Power Infrastructure Requirements for Road Transport Electrification

Doros Nicolaides
Girton College, University of Cambridge
September 2018

Supervisor: Professor David Cebon
Advisor: Professor John Miles

This dissertation is submitted for the degree of Doctor of Philosophy
Abstract

Power Infrastructure Requirements for Road Transport Electrification

Doros Nicolaides, September 2018

Deep decarbonisation of road transportation is challenging. One of the most potentially beneficial approaches is electrification which is the subject of this PhD thesis. A widespread penetration of electric vehicles (EVs) across a large proportion of road transport demand is needed to realise the benefits of an electrified transport sector. However, this is dependent on overcoming significant barriers. This study performs a systematic analysis of how proven power charging technologies could be used to unlock the barriers to widespread electrification of road transportation.

Various road transport sectors and type of journeys are explored including aspects of autonomous operations and novel wireless power transfer technologies. For each operation, a framework is proposed that allows the exploitation of current and potential future electrification technologies to enable shifting towards EVs. Based on that, simulation tools and methods are developed to calculate the power requirements of EVs and determine a suitable charging infrastructure. The additional power demand, electric load and the implications for the electricity supply network are explored. The total expenditure needed and the CO$_2$ emission savings are also calculated for each investigated operation.

Transitional strategies include the electrification of bus routes, refuse collection functions, home deliveries and aspects of autonomous operations for public transportation within the boundaries of the cities. In the long-term, focus is given on passenger cars and freight vehicles for both urban and inter-urban journeys.

A nationwide adoption of all electrification strategies proposed in this thesis would increase the peak power demand of Great Britain by approximately 38 GW (72% of the current peak) and the electricity consumption by 180 TWh per year (45% of current consumption). The total capital cost required is calculated at £225 billion which is similar to the cost of other large infrastructure projects of the country. The impact would be a significant aggregate saving of approximately 2,000 MtCO$_2$ between the numbers calculated for today’s norms (2018) and those calculated for 2050.
«... Χρειάζεται προσπάθεια τζαί χρόνο να ξοδιάσεις ν'αξιωθείς στην κορυφή με Άριστα να φτάσεις. Γιατ'εν τζαι παίξε γέλασε γνώσεις ν'αποθηκεύσεις πνεύμα τζαι σώμα άγρια πρέπει να τα παιδέψεις... »

Ανδρέας Χριστοφή
(Χαρτζιώτης)
12/7/2017
Preface

1.1 Scope
This dissertation is submitted for the degree of Doctor of Philosophy.

1.2 Declaration
This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text.

It is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my dissertation has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text.

The dissertation does not exceed the word limit of 65,000 words, including appendices, bibliography, footnotes, tables and equations, and 150 figures.

1.3 Biography
This dissertation has been written by Doros Nicolaides, a PhD Candidate at the Department of Engineering University of Cambridge. Doros has been working on the power requirements for road transport electrification. His research aims to outline the performance requirements for an electrified road transport sector and determine a suitable charging infrastructure for various road operations and type of journeys. Transitional strategies include the electrification of bus routes, refuse collection functions, home deliveries and aspects of autonomous operations for public transportation within the boundaries of the cities. In the long-term, focus is given on ‘charge-on-the-move’ technologies, because a nationwide infrastructure of this type has the potential to achieve the deep levels of decarbonisation needed in the long-term. Previously he was an MPhil student in the Department of Engineering University of Cambridge attending the course Engineering for Sustainable Development. His undergraduate studies were completed in the Department of Electrical and Computer Engineering University of Cyprus.
1.4 Dissemination of Research Findings

The work presented in this dissertation has been made widely available. Various platforms have been used for this purpose including publication to peer reviewed academic journals, conference proceedings and presentation to international conferences. Dissemination of research findings has been achieved as follows:

1.4.1 Academic Journals


(iv) D. Nicolaides, R. McMahon, D. Cebon, and J. Miles, “The potential for supplying charging coils by capacitive coupling for charge-on-the-move,” to be re-submitted to IEEE Transactions on Intelligent Transportation Systems

1.4.2 Conference proceedings


(ii) D. Nicolaides, D. Cebon, and J. Miles, “An autonomous taxi service for sustainable urban transportation,” in 2017 Smart City Symposium Prague (SCSP), 2017, pp. 1–6, DOI: 10.1109/SCSP.2017.7973353

1.4.3 Conference talks


(ii) “How can academic research contribute to policy making?”, Talk in Professional Development Policy Workshop for Department for Transport, Cambridge UK, Oct 2017
1.5 Acknowledgments

I would like to express my sincere gratitude to my supervisor David Cebon, Professor with the University of Cambridge. This PhD thesis would not have been possible without his continuous support and guidance. I am grateful for his feedback, contribution and maintenance support which have made my PhD experience productive and interesting.

I am also thankful to my advisor John Miles, Professor with the University of Cambridge. He has always been a source of motivation for an interesting PhD. I thank him for his maintenance support and the opportunities he gave me to develop different skillsets.

I am grateful to Richard McMahon, Professor with the WMG University of Warwick. Our meetings were always inspiring and constructive that helped me in all the time of my PhD studies. He has always been supportive and I thank him for the opportunity he gave me to access his laboratory facilities at WMG.

Many thanks to Dr Xiaoxiang Na, Research Associate with the Centre for Sustainable Road Freight. The analysis of existing road transport operations in this PhD thesis was possible due to his research on developing systems for in-service monitoring of road vehicles.

Special thanks also to Elizabeth Howard, Research Group Administrator with the Transitional Energy Strategies Team University of Cambridge, for her continuous administrative support. She was always helpful providing me with her prompt assistance.
I acknowledge the funding sources that made this PhD possible which are the i) ‘EPSRC Doctoral Training Grant’ (Wireless Electric Charge-on-the-move: An appraisal for the UK transport application, Doctoral Training Award Reference 1497982), ii) ‘Centre for Sustainable Road Freight Transport EPSRC Grant’ (EPSRC Grant EP/K00915X/1), iii) ‘A.G. Leventis Foundation Scholarship’, iv) Transport Research Laboratory (TRL) Partial PhD Sponsorship and v) ‘CAPCO Future Cities Prize Fellowship’.

I am indebted to my auntie Helen and uncle Sotiris in London who opened their home to me during my studies. Their unconditional love, advice and support without obligation have made me feel special. I could not have imagined a better family far from home.

Lastly, I am thankful for my very own family, my parents and siblings. They were behind me in every step of the way and I would not be here without them. Their support and love have always been the strength of my heart. They have seen me at my worst, yet they love me the best. They should know that they mean the world to me. I am blessed and I thank God for everything.
# Table of Contents

Abstract.................................................................................................................................................. iii

Preface ..................................................................................................................................................... vii

1.1 Scope .............................................................................................................................................. vii

1.2 Declaration ...................................................................................................................................... vii

1.3 Biography ...................................................................................................................................... vii

1.4 Dissemination of Research Findings .............................................................................................. viii
  1.4.1 Academic Journals ................................................................................................................... viii
  1.4.2 Conference proceedings ........................................................................................................... viii
  1.4.3 Conference talks ..................................................................................................................... viii

1.5 Acknowledgments ........................................................................................................................... ix

Table of Contents ................................................................................................................................. xi

List of Figures ........................................................................................................................................ xvii

List of Tables .......................................................................................................................................... xxi

Nomenclature .......................................................................................................................................... xxiii

Chapter 1  Introduction .......................................................................................................................... 1

  1.1 Electrification as an alternative .................................................................................................... 3

  1.2 Main research question ................................................................................................................ 5

  1.3 Methodology .................................................................................................................................. 6

  1.4 Structure of thesis ........................................................................................................................ 7

Chapter 2  Literature Review .................................................................................................................. 11

  2.1 Power charging systems .............................................................................................................. 11

    2.1.1 Inductive Power Transfer .................................................................................................... 12

    2.1.2 Overhead Catenary systems ............................................................................................... 15

    2.1.3 In-road conductive systems ............................................................................................... 16
2.2 System Level Studies ..............................................................................................................17
2.3 Research Questions ..............................................................................................................18

Chapter 3  Prospects for Electrification of Road Freight .........................................................19
3.1 Introduction .............................................................................................................................19
3.2 Logistics concept and opportunities ..................................................................................23
3.3 Modelling ...............................................................................................................................24
  3.3.1 System characterisation .................................................................................................25
  3.3.2 Charging Simulation tool ...............................................................................................32
3.4 Case studies ...........................................................................................................................35
  3.4.1 Long-Haul ......................................................................................................................35
     Driving on Trunk Roads .........................................................................................................35
     Driving on Local Roads ........................................................................................................39
  3.4.2 Urban Delivery ...............................................................................................................40
  3.4.3 Home delivery ...............................................................................................................42
  3.4.4 Refuse collection ............................................................................................................43
3.5 Conclusions ...........................................................................................................................45

Chapter 4  An Urban Charging Network: A case study for Cambridge UK .........................47
4.1 Introduction .............................................................................................................................47
4.2 Methodology ..........................................................................................................................49
  4.2.1 Data collection ...............................................................................................................49
  4.2.2 Simulation Tools .............................................................................................................50
  4.2.3 Selection of charge-on-the-stop points (CoSP) ...............................................................51
4.3 Buses .....................................................................................................................................54
  4.3.1 Energy requirements .......................................................................................................54
  4.3.2 A case study for Trumpington .......................................................................................56
  4.3.3 City’s Park and Ride bus routes ......................................................................................61
| 4.3.4 Carbon emissions savings | ................................................................. | 63 |
| 4.4 Refuse Collection Vehicles | ........................................................................ | 64 |
| 4.4.1 Domestic Waste Collection | ........................................................................ | 64 |
| 4.4.2 City’s Waste Collection Operations | ...................................................... | 68 |
| 4.5 Home Deliveries | ........................................................................... | 69 |
| 4.6 City Scale | ........................................................................... | 73 |
| 4.6.1 Routes with available data | ........................................................................ | 73 |
| 4.6.2 Urban deliveries | ........................................................................... | 75 |
| 4.6.3 Passenger cars | .................................................................................. | 76 |
| 4.6.4 City Overview | .................................................................................. | 79 |
| 4.7 Conclusions | .................................................................................. | 79 |

**Chapter 5**  An autonomous taxi service for future cities ..................................................................... 83

| 5.1 Introduction | .................................................................................. | 83 |
| 5.2 Sustainability Assessment | .......................................................................... | 85 |
| 5.2.1 Environmental Impact | .......................................................................... | 85 |
| 5.2.2 Social Sustainability | .......................................................................... | 86 |
| 5.2.3 Infrastructure needs | .......................................................................... | 88 |
| 5.3 Levels of Demand | ........................................................................... | 89 |
| 5.3.1 Trip Generation | ........................................................................... | 89 |
| 5.3.2 Trip Distribution | ........................................................................... | 90 |
| 5.3.3 Modal Split | .................................................................................. | 91 |
| 5.4 System Performance Requirements | ......................................................................... | 93 |
| 5.4.1 Size of fleet | .................................................................................. | 93 |
| 5.4.2 Energy requirements – Battery Capacity | .................................................................. | 94 |
| 5.4.3 Power demand | .................................................................................. | 95 |
| 5.4.4 Charging Infrastructure | .......................................................................... | 95 |
5.4.5 Implications for the grid ........................................................................................................ 96
5.5 Financial Analysis ..................................................................................................................... 96
  5.5.1 Biomedical Campus ............................................................................................................ 97
  5.5.2 West Cambridge ................................................................................................................ 99
  5.5.3 North West Cambridge ..................................................................................................... 100
5.6 Conclusions .......................................................................................................................... 101

Chapter 6 A National Infrastructure for Charge-on-the-move: An appraisal for GB ............ 103
  6.1 Introduction ............................................................................................................................ 103
  6.2 System Characterisation ........................................................................................................ 106
  6.3 Charging Simulation Tool ..................................................................................................... 111
  6.4 Charging Layout .................................................................................................................... 112
  6.5 Assessment of National Infrastructure ................................................................................... 117
    6.5.1 Solution Schemes ........................................................................................................... 118
    6.5.2 CoM for electrified Cars transportation ......................................................................... 120
    6.5.3 CoM for electrified Freight transportation ..................................................................... 126
    6.5.4 CoM for electrified Cars and Road Freight transportation ........................................... 127
    6.5.5 CoM infrastructure overview ....................................................................................... 129
  6.6 Conclusions ............................................................................................................................ 132

Chapter 7 Conclusions and Future work .................................................................................. 135
  7.1 Conclusions ............................................................................................................................ 135
  7.2 Future Work ............................................................................................................................ 149

Appendix I The potential for supplying coils by capacitive coupling ........................................ 153
  I.1 Introduction ............................................................................................................................ 153
  I.2 Assumptions ........................................................................................................................... 159
    I.2.1 Road pavement electric properties ............................................................................... 159
    I.2.2 Power density ................................................................................................................ 161
I.2.3 Electromagnetic field exposure limits ................................................................. 161
I.3 Road capacitive coupling......................................................................................... 162
  I.3.1 Unipolar Approach............................................................................................ 162
  I.3.2 Bipolar Approach ........................................................................................... 169
    Bipolar vertical design.......................................................................................... 177
    Lateral bipolar design......................................................................................... 183
  I.3.3 Supplementary Work......................................................................................... 185
    Hard-shoulder EMF exposure ............................................................................. 185
    Wet conditions.................................................................................................... 187
I.4 Conclusions........................................................................................................... 188
References ................................................................................................................ 191
List of Figures

Figure 1-1: Projected carbon Intensity of GB electricity supply network [23] .........................4
Figure 2-1: Typical IPT system for EVs power delivery ..............................................................................13
Figure 2-2: Siemens overhead catenary system (adapted from SIEMENS website) .................15
Figure 2-3: In-road conductive systems (from [66]) .................................................................16
Figure 3-1: Logistics concept for electrified road freight. Not to scale ..................23
Figure 3-2: Driving cycles for light good vehicles (LDV_PVU 3.5 t Vans from [86]) .............26
Figure 3-3: Driving cycles for heavy good vehicles (from [86]) .................................................27
Figure 3-4: Density of HGVs per km of motorway in East Midlands ...............................30
Figure 3-5: Power requirements of HGVs per km of motorway ..............................................30
Figure 3-6: Charging simulation tool input interface .................................................................32
Figure 3-7: Simulation results for HGV38 travelling on the HWFET drive cycle (Figure 3-3c) 33
Figure 3-8: Long-haul SOC of HGV38 for various levels of MECR ..................................36
Figure 3-9: Simulation results for HGV38 travelling on local roads for long-haul operations 39
Figure 3-10: Results of Urban delivery journey for HGV10 .....................................................41
Figure 3-11: Results of Home delivery journey for LGV ...........................................................42
Figure 3-12: Results of Refuse Collection operations for eRCV .............................................45
Figure 4-1: ‘Charging Infrastructure’ flowchart to choose CoSP for opportunity charging ....51
Figure 4-2: ‘Calculate Battery’ flowchart to calculate the capacity of the on-board battery .52
Figure 4-3: ‘Rank locations’ flowchart to calculate value of each route’s locations .......53
Figure 4-4: Park and Ride bus routes at Cambridge UK with the chosen CoSP .................54
Figure 4-5: Trumpington Park and Ride logged drive cycle ......................................................55
Figure 4-6: Trumpington Park and Ride - Energy diagrams for the OnC and CoS options .....56
Figure 4-7: Park and Ride routes performance overview .........................................................58
Figure 4-8: Power demand of the Trumpington Park and Ride route .....................................59
Figure 4-9: Annual outcomes over a 10-year lifetime period ..................................................61
Figure 4-10: Power demand of Park and Rides routes ..............................................................62
Figure 4-11: Domestic route performed on Day 11 by RCV no 2 ..............................................64
Figure 4-12: Domestic route, charging infrastructure and energy on-board .......................66
Figure 4-13: Daily power demand profile for Cambridge refuse collection .........................69
Figure 4-14: Home delivery performed on Day 3 by Retailer B – speed profile ..................70
Figure 4-15: Home delivery performed on Day 3 by Retailer B - Battery energy (kWh)............72
Figure 4-16: Home Delivery Retailer B - Daily power demand profile (kW) of the fleet............73
Figure 4-17: Daily power demand at Cambridge for electrified road freight operations ........74
Figure 5-1: Concept of Autonomous Pods at the centre of Milton Keynes UK ..................85
Figure 5-2: Entry and exit to the pod .................................................................................87
Figure 5-3: Autonomous Pods infrastructure needs [124] ...............................................88
Figure 5-4: Biomedical Campus Site map and on-site access [128] .................................89
Figure 5-5: Daily profile of trips generated in the Biomedical Campus .........................90
Figure 5-6: Biomedical Campus Trip Distribution process .............................................91
Figure 5-7: People demanding autonomous pods through a typical day ..........................92
Figure 5-8: Number of autonomous pods required through a typical day .....................94
Figure 5-9: Daily power demand at the Biomedical Campus ...........................................95
Figure 5-10: Biomedical Campus – Peak Trips per hour relative to ticket price ............98
Figure 5-11: West Cambridge Site Masterplan [134] ......................................................99
Figure 5-12: West Cambridge site – Peak Trips per hour relative to ticket price .............100
Figure 5-13: North-West Cambridge Site access plan [136] ........................................101
Figure 5-14: North West Cambridge site – Peak Trips per hour relative to ticket price ....101
Figure 6-1: Mean power required and density of EVs on motorways of London by hour ...109
Figure 6-2: Motorway SOC of ‘compact car’ for various levels of MECRs ......................112
Figure 6-3: CoM infrastructure design variables ..............................................................112
Figure 6-4: Power demand profile for a) an EV per km and b) 28 EVs per km ...............114
Figure 6-5: Power demand variance for possible CoM infrastructure configurations ....115
Figure 6-6: Power demand variance for CoM charging segments up to 5 m in length ....116
Figure 6-7: Chosen CoM infrastructure for motorways .................................................116
Figure 6-8: CoM layout for motorways for electrified car and freight transportation ....117
Figure 6-9: Conceptual power distribution configuration for CoM (not to scale) ............118
Figure 6-10: Costs to install IPT devices relative to electrified car-miles covered in GB ......122
Figure 6-11: Cash flow for electrified CoM car transportation – IPT on GB’s motorways ....124
Figure 6-12: Profit margin for electrified CoM car transportation system ......................125
Figure 6-13: Profit margin for electrified CoM car and freight transportation ..................128
Figure 7-1: Comparison between electrification solutions for road transportation .........147
Figure 7-2: Transport sector carbon footprint ................................................................149
List of Figures

Figure I-1: Typical layers of road pavement – not to scale .............................................................. 154
Figure I-2: Trench based method – supplying wires through the ‘top layer’ not to scale .................... 155
Figure I-3: Full lane method - supplying wires through the ‘base’ layer - not to scale ..................... 155
Figure I-4: Wireless connections to supply road charging coils - not to scale .............................. 156
Figure I-5: Capacitive Coupling methods a) Unipolar b) Bipolar method ....................................... 158
Figure I-6: Electric properties for ‘base’ materials obtained from [167] ............................................ 159
Figure I-7: Unipolar capacitive coupling equivalent circuit .............................................................. 162
Figure I-8: Unipolar vertical design simulation model ........................................................................ 164
Figure I-9: Unipolar vertical design simulation results at 85 kHz .................................................... 166
Figure I-10: Stray field of the Unipolar vertical design at 85 kHz ..................................................... 167
Figure I-11: Mesh convergence of the unipolar vertical design ....................................................... 167
Figure I-12: Unipolar lateral design simulation model ........................................................................ 168
Figure I-13: Bipolar vertical design with car included in the model .................................................. 170
Figure I-14: Mutual capacitance between electrodes ....................................................................... 170
Figure I-15: Bipolar capacitive coupling equivalent circuit .............................................................. 172
Figure I-16: Bipolar capacitive coupling equivalent circuit – second stage .................................... 173
Figure I-17: Bipolar capacitive coupling circuit with compensating inductors ............................... 174
Figure I-18: Bipolar capacitive coupling equivalent circuit – third stage ....................................... 174
Figure I-19: ‘Delta’ to ‘y’ transformation technique .......................................................................... 174
Figure I-20: Bipolar capacitive coupling equivalent circuit – third stage .................................... 175
Figure I-21: Bipolar capacitive coupling equivalent circuit – fourth stage .................................... 176
Figure I-22: Bipolar capacitive coupling circuit ............................................................................... 177
Figure I-23: Minimising parasitic capacitance for the bipolar vertical design ................................ 178
Figure I-24: Normalised parasitic capacitance for various model designs ........................................ 179
Figure I-25: Efficiency of the bipolar capacitive coupling system ................................................... 180
Figure I-26: Mesh convergence of the bipolar vertical design .......................................................... 181
Figure I-27: Electric field above 614 V/m at 85 kHz for the 6.32 kW power transfer ....................... 182
Figure I-28: Bipolar lateral simulation model ................................................................................... 184
Figure I-29: Electric field higher than 614 V/m – bipolar vertical design at 85 kHz ....................... 186
Figure I-30: Simulation model - bipolar vertical design with metal strip ........................................ 186
Figure I-31: Electric field higher than 614 V/m – bipolar vertical design at 85 kHz ....................... 187
List of Tables

TABLE 3-1: Components of simulated EFVs for electrified freight operations .......................... 26
TABLE 3-2: Average Power Requirements of EFVs ................................................................ 27
TABLE 3-3: Category 1 (LGV) average number of vehicles per km of road in 2013 ................. 28
TABLE 3-4: Category 2 (HGV10) average number of vehicles per km of road in 2013 .......... 29
TABLE 3-5: Category 3 (HGV38) average number of vehicles per km of road in 2013 .......... 29
TABLE 3-6: Peak power demand in GW of electrified road freight transportation ................. 32
TABLE 3-7: Long-haul case study overview .............................................................................. 40
TABLE 3-8: Urban Delivery case study overview ....................................................................... 42
TABLE 3-9: Home Delivery case study overview ....................................................................... 43
TABLE 3-10: Refuse Collection case study overview ................................................................. 45
TABLE 4-1: Components of simulated EVs for electrified urban freight operations ............... 51
TABLE 4-2: Cambridge Park and Ride bus routes - Drive Cycles and energy requirements .... 55
TABLE 4-3: Park and Rides - Bus fleet, energy requirements and capacity of battery .......... 56
TABLE 4-4: Cost Assumptions for urban opportunity charging ............................................... 58
TABLE 4-5: Cambridge Park and Ride bus routes electrification solutions ......................... 62
TABLE 4-6: Electrified Park and Ride bus routes annual overview .......................................... 63
TABLE 4-7: Energy requirements (kWh) over a two-week cycle for domestic waste .......... 65
TABLE 4-8: Domestic Waste operations – possible charging infrastructure ......................... 67
TABLE 4-9: Performance overview of refuse collection operations ......................................... 68
TABLE 4-10: Performance overview of home delivery operations ........................................... 70
TABLE 4-11: Overview of electric routes with available data at Cambridge ......................... 74
TABLE 4-12: Overview of electric road transportation at Cambridge ..................................... 79
TABLE 5-1: Levels of demand for autonomous pod operation on Biomedical Campus .......... 93
TABLE 5-2: Cost model assumptions for an autonomous pod operation ................................. 97
TABLE 5-3: Balance sheet for autonomous pods operation ..................................................... 98
TABLE 5-4: Biomedical Campus – ticket price sensitivity analysis ......................................... 99
TABLE 6-1: EVs power requirements over various drive cycles ............................................. 107
TABLE 6-2: Average number of cars per km of major road in 2014 ....................................... 108
TABLE 6-3: Peak power demand in GW of electrified passenger car transportation .......... 110
TABLE 6-4: Peak power demand in GW of electrified road freight transportation ............. 110
TABLE 6-5: Cost assumptions for the CoM ................................................................. 119
TABLE 6-6: Cost per km of road in £m for electrified cars transportation .................. 121
TABLE 6-7: Road length data (both directions) and traffic statistics in GB .................. 122
TABLE 6-8: Summarised cash flow figures for a CoM system for cars ......................... 125
TABLE 6-9: Cost per km of road in £m for electrified road freight ............................ 126
TABLE 6-10: Cash flow figures for CoM freight transportation (motorway network only) ... 127
TABLE 6-11: Cost per km of road in £m for a CoM system for cars and road freight ........ 128
TABLE 6-12: Cash flow figures for a CoM system for cars and road freight vehicles ...... 129
TABLE 6-13: CoM for cars and freight vehicles on motorways and rural ‘A’ roads .......... 129
TABLE 6-14: Possible CoM infrastructure and annual Profit Margin overview .......... 130
TABLE 7-1: Overview of Road Transport Electrification ............................................ 146
TABLE 7-2: CO₂ emission savings per year for the explored electrification strategies .... 149
TABLE I-1: Electric properties for ‘base’ materials obtained from [167] ....................... 159
TABLE I-2: Assumed electric properties of road pavement for dry and wet conditions ... 160
TABLE I-3: Reference levels for general public exposure to electric fields (RMS values) .. 162
TABLE I-4: Circuit components determined by the geometry - unipolar vertical design .... 166
TABLE I-5: Circuit components for the two charging layouts - unipolar vertical design ... 168
TABLE I-6: Circuit components of the unipolar lateral design .................................. 169
TABLE I-7: Minimising parasitic capacitance for the bipolar vertical design ............... 179
TABLE I-8: Circuit components and simulation results - bipolar vertical design with car ... 180
TABLE I-9: Circuit components and simulation results - bipolar lateral design with car ... 185
Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advisor</td>
<td>Advanced Vehicle Simulator by NREL</td>
</tr>
<tr>
<td>BEIS</td>
<td>Department for Business, Energy and Industrial Strategy</td>
</tr>
<tr>
<td>C</td>
<td>Charge Rate</td>
</tr>
<tr>
<td>CoM</td>
<td>Charge-on-the-move</td>
</tr>
<tr>
<td>CoS</td>
<td>Charge-on-the-stop</td>
</tr>
<tr>
<td>CoSP</td>
<td>Charge-on-the-stop point</td>
</tr>
<tr>
<td>CSC</td>
<td>City Suburban Cycle</td>
</tr>
<tr>
<td>CSRF</td>
<td>Centre for Sustainable Road Freight</td>
</tr>
<tr>
<td>DECC</td>
<td>Department of Energy and Climate Change</td>
</tr>
<tr>
<td>DfT</td>
<td>Department for Transport</td>
</tr>
<tr>
<td>eBus</td>
<td>Electric Bus</td>
</tr>
<tr>
<td>EFW</td>
<td>Electric Freight Vehicles</td>
</tr>
<tr>
<td>EMF</td>
<td>Electromagnetic Field</td>
</tr>
<tr>
<td>eRCV</td>
<td>Electric Refuse Collection Vehicle</td>
</tr>
<tr>
<td>EV</td>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>HGV</td>
<td>Heavy Good Vehicles</td>
</tr>
<tr>
<td>HGV10</td>
<td>Heavy Good Vehicles up to 10 T</td>
</tr>
<tr>
<td>HGV38</td>
<td>Heavy Good Vehicles up to 38 T</td>
</tr>
<tr>
<td>HS2</td>
<td>High Speed 2</td>
</tr>
<tr>
<td>HWFET</td>
<td>Highway Fuel Economy Test</td>
</tr>
<tr>
<td>IPT</td>
<td>Inductive Power Transfer</td>
</tr>
<tr>
<td>LDC</td>
<td>Local Distribution Centre</td>
</tr>
<tr>
<td>LGV</td>
<td>Light Good Vehicle</td>
</tr>
<tr>
<td>MECR</td>
<td>Mean Effective Charging Rate</td>
</tr>
<tr>
<td>MPGe</td>
<td>Miles per Gallon Gasoline Equivalent</td>
</tr>
<tr>
<td>OhC</td>
<td>Overhead Catenary Systems</td>
</tr>
<tr>
<td>OnC</td>
<td>Overnight Charging</td>
</tr>
<tr>
<td>Pr</td>
<td>Principal sections of road</td>
</tr>
<tr>
<td>RDC</td>
<td>Regional Distribution Centre</td>
</tr>
<tr>
<td>RSSB</td>
<td>Rail Safety and Standards Board</td>
</tr>
<tr>
<td>SOC</td>
<td>State of Charge</td>
</tr>
<tr>
<td>SRF</td>
<td>Sustainable Road Freight</td>
</tr>
<tr>
<td>SRF Logger</td>
<td>Logger for in-service monitoring of road vehicles</td>
</tr>
<tr>
<td>Tr</td>
<td>Trunk sections of road</td>
</tr>
<tr>
<td>TRL</td>
<td>Transport Research Laboratory</td>
</tr>
<tr>
<td>UCC</td>
<td>Urban Consolidation Centre</td>
</tr>
<tr>
<td>UDDS</td>
<td>EPA Urban Dynamometer Driving Schedule</td>
</tr>
<tr>
<td>ULEZ</td>
<td>Ultra-low Emission Zone</td>
</tr>
</tbody>
</table>
Chapter 1  Introduction

The prospect of irreversible climate change has raised the obligation for governments to embark on substantial programmes of decarbonisation [1]. The UK is legally committed “to ensure that the net UK carbon account for the year 2050 is at least 80% lower than the 1990 baseline” [2]. Many possible pathways have been suggested over the last few years. Decarbonisation of the transport sector is a necessary step for achieving this target.

The transport sector in Great Britain (GB) accounts for over a quarter of national CO$_2$ emissions [3], 93% of which are due to road transport [4]. According to [4], 63% of road transport emissions emanate from passenger cars, 17% from heavy good vehicles$^1$ (HGVs), 16% from light duty vehicles$^2$ (LGVs) and 3.5% from buses; the remainder 0.5% is due to motorcycles, mopeds and emissions from vehicles running on liquefied petroleum gas. Because road transport is a critical component of human mobility and economic growth, most studies project that the proportion of total greenhouse gas emissions due to road transport will rise significantly in the future.

One response to this challenge would be to introduce social and economic policies which discourage passenger travel by changing the behaviour of individual drivers and travellers. Several strategies were reviewed in [5], including road pricing, car sharing, education campaigns, etc. It was shown that combination of such measures could reduce travel use and greenhouse gas emissions by only 15% [5]; they cannot achieve the deep levels of decarbonisation needed in the long-term.

By contrast, adoption of innovative technologies and radical approaches to system design could allow future mobility needs to be met in sustainable way. Such systems that would have significantly lower energy demand and CO$_2$ emissions than current transportation systems are investigated in this study.

Some technologies have been recently introduced by the automotive industry to reduce fuel consumption and CO$_2$ emissions. ‘Stop-start’ systems switch off the engine of the vehicle when it is at a standstill for saving fuel. The use of smaller size and more efficient internal

---

$^1$ Over 3,500 kg gross vehicle weight  
$^2$ Not exceeding 3,500 kg gross vehicle weight
combustion engines reduces the overall mass and fuel consumption of vehicles without compromising performance. Furthermore, the adoption of lighter materials, improved aerodynamics and lower rolling resistance tyres reduce the energy needed for acceleration and cruising. The combination of these measures could potentially deliver up to 30% reduction of fuel consumption and CO₂ emissions [6].

Consumer choices also plays an important role in decarbonising road transportation. Demanding low-carbon vehicle technologies, adopting fuel-efficient driving techniques, keeping tyres correctly inflated, using air conditioning sparingly, etc. could reduce fuel consumption and CO₂ emissions by 10-15% [7].

Most of these measures can be adopted at relative low cost but they cannot achieve the deep levels of decarbonisation needed in the long-term. Indeed, the UK average figure of CO₂ emissions for a new conventional car in 2016 was around 25% lower than then 2000’s figure; but only 1% lower than the 2015’s figure [8]. This reveals the increasing challenge of delivering further environmental benefits. For CO₂ emission reductions beyond that level alternative energy sources need to be investigated.

Hydrogen is a possible alternative energy vector but the technology has not been shown to be the promising disruptive technology for road transportation. Widespread deployment of the required infrastructure and hydrogen storage are major barriers for shifting towards hydrogen vehicles [9], [10]. Furthermore, in a future green economy, Hydrogen has to be generated from electricity and the overall efficiency of a hydrogen generation and distribution system is only 21-26% [11]–[13].

Another alternative to fossil fuels is biofuels. These require only limited investment in infrastructure and the performance of a vehicle powered by biofuels is similar to the performance of a conventional vehicle [10]. However, there is not sufficient biomass globally to replace more than 20% of the total vehicle fuel consumption, and even this would be at the expense of land for food crops being used for fuel [10]. The EU aims to have 10% of the transport fuel come from renewable sources such as biofuels by 2020, with a corresponding reduction of the greenhouse gas intensity of the EU fuel mix of 6% [14]. There are no EU targets for higher levels of biofuel after 2020.
Natural gas can also be used for road vehicles and the technology has the potential for marginal environmental benefits [15]. This is possibly a worthwhile interim measure capable of achieving a 3-10% reduction in CO$_2$ emissions but it can never achieve the deep levels of decarbonisation needed in the long-term [15]. Again, there is insufficient natural gas for significant decarbonisation of road transport on a national scale.

Hybrid drivetrains are one possibility for making a significant difference. This technology allows the vehicle to run more effectively as the internal combustion engine is supported by an on-board electric motor. Significant reduction of 10-25% fuel consumption and CO$_2$ emissions is feasible depending on the drive cycle and the adoption of regenerative braking [16], [17], taking into consideration the extra mass of electric motors and batteries on-board.

1.1 Electrification as an alternative

Deep decarbonisation of road transportation is challenging. One of the most potentially beneficial approaches is electrification which can achieve the deep levels of decarbonisation needed by 2050. Electric propelled vehicles (EVs) offer significant environmental advantages over conventional vehicles. Firstly, significant reduction of CO$_2$ emissions in comparison with conventional vehicles can be achieved. A modern diesel engine for road vehicles operates up to 50% [18] which means that 2 kWh input energy is required for every delivered kWh. This, combined with the 2.678 kgCO$_2$ per litre carbon intensity of diesel, which can be converted to 252 gCO$_2$ per kWh based on the calorific value of diesel [19], show that a conventional vehicle is responsible for 504 gCO$_2$ for every delivered kWh. By contrast, an EV accounts for 330 gCO$_2$ due to the fact that an electric drivetrain operates efficiently around 90% [18] and the carbon inherent in the electricity grid is 300 gCO$_2$ per kWh (GB figures in 2017) [20]. This corresponds to approximately 35% reduction in comparison with a conventional vehicle. In the long-term, an almost complete decarbonised road transport sector is possible if the electricity supply network is significantly decarbonised as projected.

Secondly, electricity as an energy source enables energy diversity. This ensures security of energy supply and a broad use of carbon-free energy sources [21]. Electricity can reduce significantly the constant extraction of fossil fuels to supply the transport sector and therefore prevents further depletion of natural resources. Thirdly, the necessary infrastructure for delivering electricity is sufficiently mature, although a significant upgrade may be required to
accommodate the additional power demand of electrifying transport. In addition, EVs offer zero tailpipe emissions, minimising the release of noxious pollutants (EVs still produce some particulates from tyres and brake discs). This, coupled with low operational noise make EVs an attractive solution particularly for urban areas.

The adoption of electric road transportation offers opportunities for zero emissions at the point of use, which is particularly attractive for urban areas. Yet, there are still substantial CO₂ emissions at the point of generation – the power plants. Consequently, shifting towards EVs will only deliver significant CO₂ reductions if the electricity supply network is decarbonised. For GB, around 300 gCO₂ was emitted for every kWh of electricity generated in 2017 [20]. According to national objectives this value has to be as low as 70 gCO₂ per kWh by 2030 and even lower values are aimed by 2050 around 40 gCO₂ per kWh [22]. If electrification is to be an effective measure for decarbonising road transport, almost complete decarbonisation of the electricity grid is a pre-requisite. This will have to be achieved in the face of significantly increased electricity demand for running transport systems, in addition to the conventional uses of electricity for light, heat and power.

The projected carbon intensity of the electricity supply grid by the Department of Energy and Climate Change (DECC) is shown in Figure 1-1 [23]. It is noticed that the projected emissions intensity in 2030 is 100 gCO₂/kWh; a figure close to the national objective of 70 gCO₂/kWh.

Widespread penetration of EVs is dependent on overcoming significant barriers. The largest of these are the high cost, mainly due to the batteries; the limited range; the long battery
recharging times\[3\] [24], [25], and the lack of public charging infrastructure [26]. Indeed, Lithium-Ion batteries, the most attractive technology for electric vehicle propulsion [27], have energy densities around 0.1-0.15 kWh/kg, which is an order of magnitude lower than for gasoline at 12 kWh/Kg [28]. This imposes a significant challenge especially for long distance journeys, such as long-haul freight operations. This means that battery-power alone is not a practical proposition for all vehicles and type of journeys.

### 1.2 Main research question

Shifting towards EVs has been recognised as a beneficial approach for achieving an almost complete decarbonised road transport sector in the long-term. It was shown in the ‘King Review of low-carbon cars’ [6] that a widespread penetration of EVs could be capable of delivering 90% reduction per km emissions by 2050 across the fleet. If road transport continues to grow as projected by Eddington [29], then an 80% reduction in total road transport CO\(_2\) emissions would be feasible [6], [29]. However, the real benefits would only be realised if the electricity supply network gets decarbonised as projected and a widespread penetration of EVs is achieved across a large proportion of road transport demand.

This study is focused on the latter condition and specifically, whether the barriers to EVs adoption could be addressed in a way that could make electrification a feasible approach towards more sustainable road transportation. The approach is to perform a systematic analysis of how proven power charging/delivering technologies could be used to unlock novel possibilities for enabling the electrification of road transportation.

Various road transport sectors and type of journeys are explored in this dissertation with particular focus on passenger cars, LGVs, HGVs and buses; because they are responsible for 95% of total road transport CO\(_2\) emissions in the UK [4]. Aspects of autonomous operations for public transportation and novel wireless power transfer technologies are also explored.

Overall, the work aims to outline the performance requirements for a practical system and determine a suitable charging infrastructure for each investigated transport operation. According to the suggested framework, large and expensive on-board batteries are not

---

\[3\] Battery recharging times can be over 8 hours whereas filling a liquid fuel tank requires only a few minutes. Though it might be argued that a number of fast recharging technologies have been proposed recently [175], there is no scientific consensus regarding battery degradation and reduction of life span.
necessary and recharging times are preserved to minimum. This ensures that EVs can be used for similar duty cycles as conventional vehicles without compromising the effectiveness of the system. The recommendations aim to be technically feasible, financially viable and firmly anchored within the realms of practical delivery.

1.3 Methodology
The methodology used in this study involves investigations of the ways that key enabling technologies might be used to unlock the barriers to widespread electrification of road transportation. For each transport operation, a framework is proposed that allows the exploitation of current and potential future electrification technologies to enable shifting towards EVs. Such systems appear to be technically feasible, since significantly smaller and lower-cost on-board batteries are required for operation within the proposed framework. The recharging times of on-board batteries are also limited to the minimum that allows EVs to be used in a similar way to conventional vehicles.

Simulations tools and methods are developed to calculate the power requirements of EVs travelling on specified driving cycles. The ‘Advanced Vehicle Simulator’ (Advisor) is used for this purpose and any additional simulation tools are built on top of Advisor. Advisor is an open source software tool that was developed at the National Renewable Energy Laboratory for the US Department of Energy [30]. The latest version of the software was released in 2003. Its accuracy has been validated by several authors and international laboratories [31], [32].

The derived energy requirement figures are combined with national data to set the performance requirements for a practical system. Appropriate charging infrastructures are suggested for each operation. The additional power demands and electric loads are calculated and any implications for the electricity supply network are explored. In addition, a financial analysis is conducted for each case study to assess the financial viability of each operation. The aim is to examine whether such systems could be financially reasonable rather than developing an accurate business model.

Up to date data was obtained from reliable sources, including the Department for Transport (DfT) [33], Department of Energy and Climate Change UK (DECC) [34], the National Electricity Transmission System [35], etc. In addition, useful data was obtained from trial projects that have already built and demonstrated like the Electric Bus Milton Keynes Project [36] and the
LUTZ Pathfinder Project in Milton Keynes for self-driving autonomous pods [37]. Moreover, regular meetings and discussions with experts on the field of electric transportation have been performed to assess the propositions and keep up to date with recent advances of technology and policy strategies. Industrial input and feedback has been obtained from the Transport Research Laboratory (TRL), ARUP, Peter Bret Associates, members of the Centre for Sustainable Road Freight (CSRF), etc.

The study is focused on the case of GB which has been eager to adopt measures to reduce substantially its CO₂ emissions by 2050. Nevertheless, the methodology presented in the study could be considered as a framework to assess the prospects for electrification of road transport in other similar countries as well. Alternative national traffic statistics, road length data, drive cycle profiles, etc. could be processed by similar simulation tools and methods to those presented in the study.

1.4 Structure of thesis

Chapter 2 provides a literature review which explores power charging systems for EVs and system level studies for electric road transport systems. The review shows that the development of individual charging devices for EVs has been rapid but research into the characteristics of charging systems is still in need of more comprehensive consideration.

Chapter 3 explores the ‘Prospects for Electrification of Road Freight’. A logistics concept to provide a framework for the electrification of most road freight transport operations is considered and based on that, simulation tools and methods are presented to set the performance requirements for a practical system. Four case studies are developed for assessing the feasibility of electrification of various road freight operations. It is concluded that electrification of road freight is a viable route for more sustainable transportation. Long-haul operations would need installation of a charge-on-the-move (CoM) infrastructure on nation’s motorways. Electric road freight operations within the boundaries of cities could be electrified by battery powered electric freight vehicles that charge-on-the-stop during loading and unloading or top up at charging points installed at key locations along their routes.

Chapter 4, ‘An Urban Charging Network A case study for Cambridge UK’ explores the electrification of road freight transport operations within the boundaries of a city. This includes the auxiliary services of buses and refuse collection functions. Data about existing
operations in the city of Cambridge was collected to define accurate drive cycles and validate simulations. The number and location of charging points required, their power transfer rates and the capacity of the on-board batteries are determined for the five Park and Ride routes of the city, two home delivery operations and the refuse collection operations. The results are scaled up for the entire city and any implications for the electricity supply network are explored. It is shown that electrification of these freight operations would not increase significantly the city’s power demand and electricity consumption. Such a system is financially viable and would deliver substantial CO₂ emission savings in the short-term. The results are then combined with estimated performance requirements for electrified urban deliveries and urban travel by passenger cars to explore a complete urban charging network at Cambridge.

It is shown in Chapter 4 that the development of a charging infrastructure for passenger cars in cities is a long-term solution because it would require a substantial upgrade to the electricity supply network. Yet, congestion, accidents with pedestrians and cyclists and limited parking space are significant problems to be addressed in the short-term. This, coupled with the increasing concentration of people in urban environments (up to 70% of the world’s population will be in cities by 2050 [38]) have made the shift towards innovative and more sustainable urban transportation imperative. Such systems should reduce usage of private passenger cars to alleviate the negative side-effects of current systems and drive even higher reductions of energy demands and CO₂ emissions.

To this end, ‘An Autonomous Taxi Service for future cities’ is proposed in Chapter 5. The city of Cambridge UK was chosen for a case study. The research is focused on three large campus sites of the city, which are the Biomedical Campus, West Cambridge and North-West Cambridge. These sites combine academic, industrial and urban environments; representative of modern cities. A critical review is conducted to examine whether the proposed autonomous taxi service could alleviate the negative side effects of urban transportation. The study investigates issues related to environmental impact, social sustainability and the required infrastructure. Then, a methodology is proposed to estimate the levels of demand through a case study for the Biomedical Campus. The size of the fleet, the capacity of the on-board battery on each vehicle and a charging infrastructure are proposed. Implications for the electricity supply network are also explored. A financial analysis shows that such a system is financial viable for all three campuses.
The thesis then focuses on widespread use of EVs for long distance travel which is considered to be a necessary step for achieving the deep levels of decarbonisation in the long-term. Long-haul freight operations are responsible for 17% of the total road transport emissions and 63% of all car-miles in GB are travelled on motorways and rural sections of roads [39]. It would be impractical, and too expensive, to carry batteries on-board for these journeys. A promising solution would be to provide electricity to the vehicles whilst they are in motion.

Chapter 6, ‘A National Infrastructure for Charge-on-the-move’, outlines the performance requirements of a national power infrastructure suitable for implementing charge-on-the-move (CoM). The anticipated power demand is calculated from an estimation of EVs’ power requirements in conjunction with GB’s road traffic data. A simulation tool is then proposed to investigate the application of dynamic charging and the effects of system design variables. Based on that, a possible charging layout for GB’s motorways and rural sections of road is suggested. Conceptual power distribution configurations are developed and then an economic model is built to examine the cost needed per km of road. The results are combined with road traffic and road length data to calculate the proportion of car-miles covered relative to the size of the CoM infrastructure needed. Cash flow figures are produced including annual expenditures and incomes based on two pricing policies. For the first case, drivers buy fuel (electricity) from the network based on today’s prices of electricity whereas for the second scenario drivers are prepared to buy electricity based on today’s prices of diesel in GB. The financial viability of a charging network suitable for passenger cars, freight vehicles and both type of vehicles is explored. Overall, it is shown that a national infrastructure of this type could result in positive net profits for most of the examined scenarios and would deliver significant CO₂ emission savings in the long-term.

The findings of the dissertation are summarised in the chapter of ‘Conclusions and Future Work’. Electrification is shown to be a viable strategy that could make a big contribution towards more sustainable road transportation. Transitional strategies include the electrification of urban road freight operations, bus routes, refuse collection functions and aspects of autonomous operations for public transportation within the boundaries of the cities. Such systems require some civil engineering work, mainly for installing the chargers and establishing the required connections with the electricity supply network. The additional power demand and electric load is small and can be met by the existing electricity supply
networks. Such systems could deliver significant environmental and financial benefits in the short-term. Widespread use of EVs for long distance travel is a necessary step to achieve the deep levels of decarbonisation needed in the long-term. This would require installation of a CoM infrastructure on the nation’s trunk roads to enable widespread use of EVs for long distance travel. This appears to be technically and financially viable but a substantial upgrade to the electricity supply network would be needed to accommodate the new power demand.

Finally, Appendix I explores the potential for adopting capacitive coupling to supply road charging coils for the CoM transport application. This would be particularly advantageous for implementing CoM at national scale because it could minimise damage to the road structure and enable rapid installation of charging devices. Vertical and lateral designs are modelled using a finite element software. According to the vertical design, energy is transferred wirelessly from the lower to the top level of the road pavement across a 250mm gap; whereas for the lateral design, the charging coils are supplied wirelessly from the hard-shoulder across a 1.8 m gap. Potential capacitor modules are modelled and evaluated based on their circuit performance and electromagnetic pollution. This chapter shows that issues of losses and stray fields need to be addressed effectively before capacitive coupling becomes a viable proposal for supplying coils for charge-on-the-move.
Chapter 2  Literature Review

The transport sector in Great Britain (GB) accounts for over a quarter of national CO₂ emissions [3], 93% of which are due to road transport. Because road transport is a critical component of human mobility and economic growth, most studies project that the proportion of total greenhouse gas emissions due to road transport will rise significantly in the future. Under a “business-as-usual scenario”, road transport emissions would be projected to double by 2050 [6],[29]. The challenge is to support growth in transport use in a sustainable manner.

Shifting towards electric vehicles (EVs) has been recognised as a beneficial approach for achieving an almost complete decarbonised road transport sector in the long-term [6], [29]. A widespread penetration of EVs across a large proportion of road transport demand is needed to realise the benefits of an electrified transport sector. However, this is dependent on overcoming significant barriers. The largest of these are the high cost, mainly due to the batteries; the limited range; the long battery recharging times [24], [25]; and the lack of public charging infrastructure [26].

This chapter presents an overall literature review about the subject of electric road transportation. The first part of the chapter discusses the state of the art of power delivery/charging of electric vehicles (EVs) that could be used to unlock novel possibilities for enabling the electrification of road transportation. The second part focuses on system-level studies for charging applications and the last section summarises the research questions need to be addressed in this PhD thesis.

Overall, it is shown that the development of individual charging devices for EVs has been rapid but research into the characteristics of charging systems is still in need of more comprehensive consideration. Such a study would allow researchers, policymakers, industry and vehicle users to acknowledge the potential benefits of an electrified road transport system and support the transition towards EVs.

2.1 Power charging systems

This section discusses the state of the art of power delivery/charging of EVs with the aim of identifying ways of overcoming the challenges and enabling the shift towards electric road
transportation. It reviews some current research into technical aspects of power delivery but it also highlights the lack of research for integrating charging devices with the road infrastructure at national scale. The technologies of Inductive Power Transfer (IPT), Overhead Catenary Systems (OhC) and In-road conductive charging are discussed.

2.1.1 Inductive Power Transfer

Power transfer systems for EVs have been under development for decades. Conductive systems are well established and have high efficiency and reliability. Several plug-in chargers have been widely used for home and office charging applications [40]–[42]. They offer a simple and relative cheap solution around £140 per kW [40].

More recently, there has been considerable interest from academia and industry into non-conductive (wireless) power transfer suitable for EVs [43]. The ability to avoid plug-in cables and to use simple systems that are unaffected by weather conditions is likely to be attractive to drivers. Convenience, limited commitment from drivers and speed of connection/disconnection (near instantaneous charging) are some additional benefits of wireless charging. The technology also reduces clutter and hazards caused by trailing leads of conductive systems and offers increased durability compared to physical connectors. Finally, wireless charging would be a fundamental component of a future transportation system which includes autonomous vehicles.

The IPT technique is one of the most promising technologies for future power delivery. It has been used in numerous non-EV applications for almost 30 years. These include entertainment systems of airplanes [44] where power is distributed wirelessly to video entertainment units set in the back of each passenger seat for convenience and maintenance reasons; harsh environments like underwater and mining applications [45], [46]; applications in factories such as cable-free power supplies for moving parts on machines [47]; clean rooms like semiconductors fabrication rooms [48]; lighting applications [49]; amusement parks; etc.

IPT involves contactless energy transfer between two LC circuits which are in proximity to each other. For example, in common transformers, energy is transferred between the primary and secondary coils through a magnetic field. Energy transfer efficiencies up to 98% can be achieved when there is strong magnetic coupling between the coils. In applications where a
magnetic core cannot be used or the distance between the two circuits is large (tens of mm), high efficiency can be obtained by tuning both circuits to a single resonant frequency.

A typical IPT system for EV power delivery applications is shown conceptually in Figure 2-1. It comprises two major sub-systems: the road charging unit (primary circuit) and the vehicle charging unit (pick-up or secondary circuit). The primary circuit is supplied with AC power at a suitable operating frequency. The transmitting coil is energised and the resulting magnetic flux is captured by the vehicle charging unit, inducing an AC voltage which can be rectified to produce a stable DC power source for the electric motor, the batteries and other loads on board. Compensation is required on both sides of the system to minimise the reactive impedance of the system and maximise the power transfer delivery.

Some IPT systems have been commercially available including the 30 kW INTIS system [50], the 7.2 kW Plugless system [51] and the 3.2 kW BMW system [52]. Cost figures for these systems range around £400 per kW but the market is largely immature and prices would change greatly with volume [50].

Development of IPT devices may enable charge-on-the-move (CoM) also known as ‘dynamic charging’ to be implemented. In such a system, the road infrastructure would transfer energy wirelessly to vehicles whilst they are on move. This technology offers the opportunities for substantially reducing the installed battery capacity of EVs, eliminating ‘range anxiety’, reducing the cost and mass which are some of the major barriers for widespread adoption of EVs. The social and environmental aspects of CoM in Great Britain (GB) were assessed using sustainability principles and it was concluded that CoM could play a significant role as part of
the CO\textsubscript{2} mitigation efforts in the future without undermining social integrity, environmental stability, or economic prosperity [53], [54].

Only limited number of experimental CoM systems have been tested in practice and the performance of such a system cannot been specified accurately at the moment. Standardisation of the technology is essential before CoM becomes a viable solution. This will require agreement on technical specifications between all of the various stakeholders, handling different types and manufacturers of EVs, ground clearance height and load, electrical specifications, mounting arrangements etc. However, the IPT technology for the automotive industry has been under development for some years. High efficiencies, around 95\%, for static charging applications can be achieved in power delivery of tenths kW across hundreds of millimetres of air gap with some misalignments [55]–[57]. Moreover, ongoing research aims to maintain similar levels of efficiency for dynamic charging applications [58], [59]. This coupled with likely widespread penetration of lane keeping assistance driving aids for eliminating misalignment issues, the efficiency of potential CoM systems is expected to reach 90\% [60].

A comprehensive study of battery degradation and life in relation to CoM, has not been found in the literature. Nevertheless, it has been reported that frequent and small charging boosts (as may be provided by a CoM infrastructure) would increase the life of Lithium-Ion batteries when compared with deep charging and discharging cycles [61].

The charge-on-the-stop (CoS) concept involves installation of IPT devices at pre-determined locations along pre-defined routes, for charging commercial EVs during their journeys. Such an approach could be used for buses that charge at stops or at terminals; urban freight vehicles that charge at depots and delivery points; and refuse collection vehicles which could charge at stopping points along their routes. One such example is the Milton Keynes bus project [36], in which electric buses receive a 10 min booster charge at wireless charging points at stops located at either end of a 25 km route between the Milton Keynes suburbs of Wolverton and Bletchley. The line carries an estimated 800,000 passengers a year.

CoS could be also used for passenger cars that charge at traffic lights, shops, taxi ranks, etc. A charging infrastructure of this type distributes the charging process geographically within
cities, reducing the need for very large charging facilities in few locations. Having distributed charging, also reduces charging times at homes.

The development of IPT charging devices for EVs has been rapid but an industry-wide specification guideline that defines criteria for interoperability, electromagnetic compatibility, etc. is still needed to facilitate a widespread roll-out of EVs charging infrastructure. Some bodies were established for this purpose but issues of interoperability between static and dynamic systems, compatibility of EVs with both wireless and conductive chargers, operating frequency, power transfer rate, etc. still need to be addressed. However, standardisation must not limit the potential for future innovations.

2.1.2 Overhead Catenary systems

Overhead catenary systems (OhC) provide an alternative technology for charging electric freight vehicles on the move. Similar technology has been used for years for powering trams, trains and trolley buses but has recently been applied to electric freight vehicles. Siemens has been developing a catenary system for electric lorries since 2011 as part of the ENUBA research project [62]. The vehicles collect electrical energy from overhead wires, using a sophisticated pantograph system that can connect and disconnect autonomously as the vehicle enters and exits electrified sections of road (Figure 2-2). The energy supply consists of a two-wire overhead system, operating at around 650 VDC, with current ratings that match the characteristics of the electric motors on the vehicles.

![Siemens overhead catenary system](adapted from SIEMENS website)

The technology has been built and demonstrated around the world including, for example, the Californian city of Carson near the ports of Los Angeles and Long Beach [63]. The cost needed per km of road was obtained after personal communication with Patrik Ackerman.
who is a Business Developer of the SIEMENS’ Overhead Catenary System. This was confirmed at £1.2 million per km of motorway including the costs of overhead wires, supporting poles, and reinforcement of the electricity grid with substations, etc.

In addition, CoS power delivery systems suitable for electric buses have been developed by SIEMENS and ABB. SIEMENS’ portfolio comprises 150-450 kW conductive overhead catenary systems for en-route opportunity charging and up to 150 kW plug-in charging solutions suitable for charging solutions at the depot [64]. ABB’s technology offers power charging solutions up to 600 kW via an automated rooftop connection [65].

2.1.3 In-road conductive systems

In-road conductive systems have also been developed for delivering power to EVs on the stop or whilst in motion. Such systems use electric tracks built into the road and power could be fed to EVs via a conductive arm. The concept is shown in Figure 2-3 where EVs are constantly supplied using in-road conductive tracks. ELWAYS is developing a system suitable for electric passenger cars and road freight vehicles [66]. Significant progress has been made but there are some issues that still need to be addressed before successfully commercialising the technology. The largest of these is personal safety as energised conductors are exposed to public. There is also an issue concerned with any objects on the road, such as stones and sand. In addition, the efficiency of the system is significantly compromised under rain, snow and ice conditions. ELONROAD is another company working on in-road conductive systems. Together with Lund University in Sweden have built a 200 m test track for demonstration. Their system can be used for static and in motion charging. Power transfer rate capabilities, up to 240 kW, have been achieved with a 97% efficiency [67]. Yet, the issues of personal safety, rain, snow and ice still need to be addressed.
2.2 System Level Studies

The development of individual charging devices for CoS and CoM charging has been rapid but their integration with the road infrastructure at national scale is still in need of more comprehensive consideration. A few trials have been built around the world [68], [69] but they are still in early stages of demonstration. Such projects involve collaborators from academia and industry.

The Electric Bus project in Milton Keynes is the first of its kind in GB which demonstrates the concept of CoS for electric buses. This is a fully commercial full electric bus project involving eight vehicles that receive a 10 min charge boost at wireless IPT charging points located at either end of Route 7 in Milton Keynes [36]. Each of the charging points employs four 30 kW nominal rating IPT units installed in the road to deliver a total 120 kW power transfer rate. 20 kW chargers at the depot are used to fully recharge the vehicles overnight. Useful data for this thesis was obtained from this project, including operational requirements, technical specifications, capital cost figures, etc.

A broad analysis for introducing CoM on the roads of GB was conducted by TRL [60]. The report ‘Preparing the Strategic Road Network for increased use by Electric Vehicles’ covers topics of stakeholder engagement; functional requirements (such as review of IPT systems and identification of other services provided using the IPT technology); performance requirements (such as installation of CoM equipment on vehicles and construction methods of installing CoM); and process requirements of a CoM infrastructure (such as power demand requirements of vehicles and charging layouts). The report also makes recommendations on future trials and identifies potential economic, social, and environmental impacts of the technology. The report focuses on 12-32.5 t heavy good vehicles which regularly use particular stretches of road and are expected to be the first adopters of the technology.

Moreover, the European project FABRIC investigates the feasibility of on-road IPT charging technologies for implementing CoM [68]. The FABRIC consortium comprises 25 partners including participants from European academic institutions and technology providers. It is expected that the findings of the study will be announced in the first quarter of 2018.

Other studies include a cost effectiveness analysis of electric transit buses in Minneapolis, Minnesota [70] and a feasibility analysis on a dynamic charging system for electric buses in
California [71]. A similar analysis was conducted by researchers in South Korea for the OLEV Electric Bus demonstration project in Gumi City [72], [73] and in Vienna by [74].

It was generally shown that the exact requirements, costs and benefits of a charging infrastructure for CoS or CoM applications will depend on the specific application and the final specifications of charging technologies which are advancing rapidly. Additional significant factors include market acceptance, EVs uptake scenarios, future policies, possible funding schemes, business models, etc.

2.3 Research Questions

It was shown that the technology of individual charging systems has advanced significantly in the last few years for static and in motion charging. Both conductive and wireless systems have been sufficiently developed and commercial products already exist that deliver high power transfer capabilities and efficiencies. However, a more comprehensive analysis of system design is still needed. The performance requirements of charging systems suitable for various type of vehicles and operations have to be determined. Exploring the technical and financial impacts of an electrified road transport sector at national scale is essential.

Based on this review of literature and currently active projects, the following research questions need to be addressed:

(i) Is electrification a feasible approach for various road transport sectors and type of journeys, with particular focus on passenger cars, light good vehicles, heavy good vehicles and buses which are responsible for 95% of total road transport CO\textsubscript{2} emissions in GB?

(ii) What are the environmental benefits of an electrified transport sector?

(iii) How can novel power charging/ electricity distribution technologies be used to unlock widespread electrification of road transportation?

(iv) What charging systems are feasible in the short/ long term and for urban/ inter-urban mobility?

(v) What would be the performance requirements and charging infrastructure for a practical system and what are the implications on the electricity supply network?

(vi) What financial resources are required for each system?

The remainder of this thesis will focus on answering these questions.
Chapter 3  Prospects for Electrification of Road Freight

Substantial progress towards more sustainable transport requires a significant contribution from the freight sector. One of the most potentially beneficial approaches for reducing CO$_2$ emissions of road freight is electrification which is the subject of the chapter. A logistics concept to provide a framework for the electrification of most road freight transport operations is considered and based on that, simulation tools and methods are presented to set the performance requirements for a practical system. Four case studies are developed for assessing the feasibility of electrification of various road freight operations. Overall, it is shown that electrification of road freight is a viable route for more sustainable transportation.

3.1 Introduction

The transport sector in the UK accounts for over a quarter of national CO$_2$ emissions [3], 93% of which are due to road transport [4]. According to [4], 16% of road transport emissions emanate from LGV and 17% are from HGV; the remainder are due to cars, passenger service vehicles, etc. Because the road freight sector is a critical component of economic growth, most decarbonisation studies project that the proportion of total greenhouse gas emissions due to road freight will rise significantly in future [75]. To this end, substantial progress towards more sustainable transport requires a significant contribution from the freight sector.

Decarbonisation strategies for the road freight sector can include a wide range of measures including improvements to aerodynamics and rolling resistance of lorries, lighter weight vehicles, improvements to propulsion efficiency, higher capacity vehicles and operational factors such as reduced empty running, improved vehicle routing, platooning, etc. It was shown that combination of these strategies should be capable of reducing fuel consumption and CO$_2$ emissions by up to approximately 30% [17], [75], [76].

For CO$_2$ emission reductions beyond that level, alternative energy sources need to be investigated. Hydrogen is a possible alternative energy vector but the technology has not been shown to be the promising technology for freight transportation particularly because of the substantial inefficiencies involved in generating the Hydrogen from sustainable sources [12], [13]. The largest barriers include hydrogen storage and low overall efficiency of
hydrogen propelled vehicles [9]–[11]. Another option is biofuels. These require only limited investment in infrastructure and the performance of a vehicle powered by biofuels is similar to the performance of a conventional vehicle [10]. However, there is not sufficient biomass globally to replace more than 20% of the total vehicle fuel consumption, and even this would be at the expense of land for food crops being used for fuel [10]. Natural gas can also be used for road vehicles. The technology has the potential for modest reduction in greenhouse emissions due to the lower carbon content of methane than diesel. This is possibly a worthwhile interim measure, but it can never achieve the deep levels of decarbonisation needed in the long-term. Again, there is insufficient methane for significant decarbonisation of road transport on a national scale [15].

Hybrid drive trains are one possibility for making a significant difference. Odhams et al [17] showed that regenerative braking technologies could be capable of reducing fuel consumption of urban delivery vehicles by 25–30%. Midgley et al [77]–[79] developed a hydraulic hybrid urban semitrailer to explore this option and demonstrated 9–18% reduction in fuel consumption depending on the drive cycle. Another vehicle concept suitable for urban freight deliveries was explored and then built as part of a European project [80].

One of the most potentially beneficial approaches for decarbonising the road freight is electrification. Electric propelled road freight vehicles (EFVs) offer significant environmental advantages over conventional vehicles. Firstly, significant reduction of approximately 35% CO₂ emissions in comparison with conventional vehicles can be achieved at today’s emission rates as shown in Introduction. In the long-term, an almost complete decarbonised road transport sector is possible if the electricity supply network is significantly decarbonised as projected. Secondly, the necessary infrastructure for delivering electricity is sufficiently mature, although a significant upgrade would be required to accommodate the additional power demand of electrifying transport. Lastly, electricity as an energy source enables energy diversity and ensures security of energy supply and broad use of carbon-free energy sources.

Although decarbonisation of the transport sector is a long-term objective, electrification of freight transportation is also an interesting option for some nearer-term solutions. EFVs offer zero tailpipe emissions, minimising the release of noxious pollutants. This feature, coupled with low operating noise and straightforward implementation of regenerative braking make EFVs attractive for start-stop urban operations, particularly in cases where the required
operating range is short and predictable. Examples are deliveries to city centre stores from urban consolidation centres (UCCs), e.g. the ‘Regent Street UCC’ operation in London [81].

Aspirations for electric urban deliveries are shared by some established freight companies and European funded projects. In particular, UPS (package delivery company and provider of supply chain management solutions) has been investigating the adoption of alternative fuel engine vehicles for their operations. EFVs have been identified as an alternative that could significantly contribute towards the company’s environmental objective to “deliver more while using less” [82]. The European ‘ENCLOSE’ project also aims to improve urban freight efficiency and advocates about the use of EFVs instead of conventional vehicles [83].

Moreover, several low emissions zones have been planned for the cities of the UK, such as the Ultra-Low Emission Zone (ULEZ) in London that will open in April 2019 [75]. Most vehicle including cars and delivery vans will need to meet tight exhaust emission standards or pay a daily charge to travel within the area of the ULEZ. This will create an additional tax on urban road freight businesses and disrupt supply chains across the country. EFVs with zero tailpipe emissions offer free access to low emission zones and avoidance of emissions fines. Shifting towards EFVs in cities could result in economic savings.

Widespread penetration of EFVs is dependent on overcoming significant barriers. The largest of these are the high cost, mainly due to the batteries; the limited range; the long battery recharging times [24], [25], and the lack of public charging infrastructure [26]. This, coupled with the high power and energy demands of freight vehicles means that battery-power alone is not a practical proposition for long-haul freight transport.

A prototype battery electric truck has been recently unveiled by TESLA, November 2017 [84]. The company claims that the vehicle would offer 1.25 kWh/km energy consumption and 800 km range; indicating at least 1 MWh capacity of on-board battery without allowing for any reserved energy on board. The specific energy of Lithium-Ion batteries, predominantly used in EVs, is approximately 8 kg/kWh [85]. The needed capacity of 1 MWh would therefore, add 8 t to the vehicle. Accounting for the approximately 1 t mass of the conventional components that would be removed (diesel engine, transmission and fuel tank), the conversion to electric operation will increase the unladen weight of the vehicle from 14 t to

1 Assuming 8 t for a six-axles articulated tractor unit and 6 t for a tri-axle trailer
approximately 21 t. This would reduce the payload of the vehicle by approximately 7 t which corresponds approximately to 30% of the freight carrying capacity of these Class 9 vehicles in the USA (maximum gross weight of 36 t with 22 t of carrying capacity). This would introduce significant practical issues that may compromise the performance of freight operations. Furthermore, if these trucks are to be charged in 30 mins as Tesla claims, the power required for each vehicle is about 2 MW. Each medium sized distribution centre would have to charge about 20-30 vehicles at a time (while they are loading). This means that each would require a substation able to deliver 60-90 MW. That is sufficient capacity to power a city about the size of Cambridge UK with approximately 130 thousand people (as described in the next chapter). A promising solution to avoid this barrier would be to provide electricity to the vehicles while they are in motion.

Development of charging devices would enable charge-on-the-move (CoM) also known as ‘dynamic charging’ to be implemented. In such a system, the road infrastructure would transfer energy wirelessly to road vehicles whilst they are on move. This technology offers the opportunities for substantially reducing the installed battery capacity of EVs, eliminating ‘range anxiety’, reducing the cost and mass which are some of the major barriers for widespread use of EVs. A nationwide CoM infrastructure for passenger cars and freight vehicles is explored in Chapter 6. The social and environmental aspects of CoM were also assessed using sustainability principles in [53] and it was concluded that CoM could play a significant role as part of the CO₂ mitigation efforts in the future without undermining social integrity, environmental stability, or economic prosperity. Power charging systems for EVs that can be used to implement CoM are the Inductive Power Transfer systems (IPT), Overhead Catenary systems (OhC) and In-road conductive systems.

The charge-on-the-stop (CoS) concept involves installation of IPT devices or OhC systems at pre-determined locations along pre-defined routes, for charging commercial EFVs during their journeys. Such an approach could be used for buses that charge at stops or at terminals; urban freight vehicles that charge at depots and delivery points; and refuse collection vehicles (RCVs) which could charge at stopping points along their routes. Both IPT and OhC systems (like the SIEMENS and ABB solutions) can be used for implementing CoS.
3.2 Logistics concept and opportunities

Utilisation of CoM technologies would necessitate some changes to the logistics network to enable appropriate electrification strategies to be used in the various types of operation. This section describes a modified structure of logistics network that would facilitate such a change. Figure 3-1 presents a concept for overall road freight operations in GB that could potentially be used in conjunction with current and likely future electrification technologies to provide a framework for the electrification of most road freight transportation operations.

In this concept, road freight transportation is divided into four main categories: ‘long-haul trunking’, ‘urban delivery’, ‘home delivery’, and other ‘auxiliary services’. Different vehicles and charging infrastructures would be needed for each of these operations.

‘Long-haul trunking’ is responsible for the transportation of goods between national and regional distribution centres (RDCs) and local distribution centres (LDCs) or Urban Consolidation Centres (UCCs), on the edges of cities using the national trunking network. Most journeys are travelled on motorways and principal roads by heavy good vehicles (HGV) of 35-44 t gross mass. In an electrified freight system, these trunk routes would have CoM infrastructure. Provided the logistics nodes are located near to the trunk routes, these vehicles would only need modest battery capacity to handle short off-network operations.
‘Urban delivery’ refers to deliveries within city boundaries and the supply of goods from LDCs (which could be located at supermarkets) to inner-city convenience stores, or from UCCs to individual shops. HGVs up to 10 t would be mainly exploited for this type of services. The journeys would be fairly short and predictable, and mostly take place on major urban roads. Such operations could be operated by battery-powered EFVs that charge their batteries while loading at depots and could potentially top-up at wireless charging points while unloading – e.g. at convenience stores.

Transportation of goods from LDCs to consumers would be performed by ‘home delivery’ operations, using light good vehicles (LGV), often under 3.5 t. These could be battery EVs that are routed for multi-drop operations within their available range.

‘Auxiliary services’ includes other operations within the area of municipalities, such as refuse collection functions, buses, etc. Such vehicles could use CoS technologies, with contactless or conductive ‘top-up’ charging points distributed at key locations along their routes. This would significantly reduce the necessary battery capacity.

It is unlikely that all freight operations could utilize this system. There are some other types of operation such as deliveries of large in-divisible loads or transport of fuels and hazardous liquids and construction vehicles where this approach would not be viable. However, these operations could use ‘plug-in hybrid’ propulsion systems. This would enable them to use the CoM infrastructure for fully-electric, long-haul operations, but with an internal combustion engine to charge the batteries and provide an extended range when operating off the CoM network. These operations off the network could likely be done at relatively low speeds and would therefore require less power than high-speed long-haul trunking. Consequently, the internal combustion engine could be significantly smaller than the large diesel engines in existing heavy vehicles and the CO₂ emissions of these residual hybrid operations would be much lower. These vehicles are not considered further in this chapter.

3.3 Modelling

Based on the logistics concept described above, system performance requirements can be defined and the various aspects of the freight system can be simulated to assess their feasibility for electrical operations. This is the approach taken in this chapter.
A simulation is firstly performed to estimate the average power requirements of EFVs. Then, the derived figures are combined with GB road traffic data to get an estimate of the anticipated power demands on various roads around the country. Finally, a charging simulation tool is presented to illustrate how the provision of dynamic charging could be used by long-haul freight vehicles to investigate important parameters such as mileage range and state of charge (SOC) of the vehicle’s battery.

3.3.1 System characterisation

The ‘Advanced Vehicle Simulator’ (Advisor) was used to estimate the power requirements of EFVs travelling on specified driving cycles. As it was explained in Introduction, Advisor is an open source software tool that was developed at the National Renewable Energy Laboratory for the US Department of Energy [30]. The latest version of the software was released in 2003. Its accuracy has been validated by several authors and international laboratories [31], [32]. The user models the vehicle of interest and investigates the characteristics of the journey over specific drive cycles, such as the required power from the electric motor, the state of charge (SOC) of the on-board battery, etc.

Advisor’s database includes a substantial list of standard vehicle models, including light and heavy-duty vehicles with conventional and full-electric powertrain configurations. In order to model the performance, fuel economy and emissions of a particular vehicle, the user specifies components such as motors, batteries, vehicle mass, additional electric loads etc. The simulations are executed over selected driving cycles, containing speed and elevation profiles.

The Advisor database was supplemented by driving cycles for urban, rural, and motorway roads appropriate for freight vehicles as described by [86]. The driving cycles are differentiated by vehicle type: LGV (up to 3,500 kg) and HGV (over 7,500 kg) as illustrated in Figure 3-2 and Figure 3-3 respectively.

The simulation produces a variety of output quantities. For EFVs these include the target and actual speeds of the vehicle through the driving cycle, the power required from the electric motor, and the battery SOC versus time/distance.

Three different categories of EFVs are considered in this chapter, based on the logistics concept described above. These are: i) light good vehicles up to 3.5 t (LGV); ii) heavy good vehicles up to 10 t (HGV10); and iii) heavy good vehicles up to 38 t (HGV38). Standard vehicles
provided by Advisor were adjusted appropriately and values were determined for the power rating of electric motors, the capacities of the on-board batteries, constant electrical loads (e.g. for refrigeration), and the overall masses of the vehicles. The parameter values of the vehicles are summarised in TABLE 3-1. The capacity of the on-board battery of each vehicle is dependent on the proposed charging infrastructure as designed below. This is the smallest possible battery pack in each case to reduce the weight, cost, embodied energy and rolling resistance of the vehicle and allow more mass and volume for the payload.

### TABLE 3-1: Components of simulated EFVs for electrified freight operations

<table>
<thead>
<tr>
<th>Advisor’s vehicle model</th>
<th>Motor (kW)</th>
<th>Battery (kWh)</th>
<th>Load (kW)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGV</td>
<td>75</td>
<td>27</td>
<td>2</td>
<td>3,500</td>
</tr>
<tr>
<td>HGV10 Ralphs Grocery 1998</td>
<td>75</td>
<td>42</td>
<td>4</td>
<td>10,000</td>
</tr>
<tr>
<td>HGV38 Kenworth T800 Trailer</td>
<td>277</td>
<td>85</td>
<td>4</td>
<td>38,000</td>
</tr>
</tbody>
</table>

Figure 3-2: Driving cycles for light good vehicles (LDV_PVU 3.5 t Vans from [86])
(a) Urban (b) Rural (c) Motorway
Advisor was used to determine the average power requirements for each category of EFV. The ‘LDV_PVU 3.5t vans motorway’, ‘LDV_PVU 3.5t vans rural’, and ‘LDC_PVU 3.5t vans urban’
drive cycles, as shown in Figure 3-2, were used for LGVs travelling on motorways, rural, and urban roads respectively. Similarly, the ‘Highway Fuel Economy Test (HWFET)’, ‘EPA Urban Dynamometer Driving Schedule (UDDS)’, and ‘City Suburban Cycle (CSC)’, as shown in Figure 3-3, were used for both HGV10 and HGV38 vehicles. The results are presented in TABLE 3-2 for three different road types. For example, an electric LGV demands an average power of 40 kW, 18 kW, and 11 kW on motorways, rural, and urban roads.

<table>
<thead>
<tr>
<th></th>
<th>Motorway (kW)</th>
<th>Rural ‘A’ (kW)</th>
<th>Urban (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGV</td>
<td>40</td>
<td>18</td>
<td>11</td>
</tr>
<tr>
<td>HGV10</td>
<td>61</td>
<td>38</td>
<td>25</td>
</tr>
<tr>
<td>HGV38</td>
<td>123</td>
<td>100</td>
<td>74</td>
</tr>
</tbody>
</table>

These average power requirements were combined with the numbers of EFVs on various roads, in order to estimate the total power needed from the electricity infrastructure. Average annual daily traffic flow by road class was obtained from Department for Transport.
(DfT) statistics for various types of vehicles. The base data [39] provides the number of vehicles per day that will drive on a specific stretch of road on an average day of the year. Various road freight vehicle classes merged together into three main categories. Category 1 contains vehicles up to and including 3.5 t. Category 2 contains vehicles from 3.5-19 t. Category 3 contains vehicles in the 19-44 t range. The three categories were selected appropriately to match both the vehicles considered in the logistics concept (Figure 3-1) and the three modelled EFVs (LGV, HGV10, and HGV38).

The number of vehicles per km of road for each category was estimated for each region of GB by dividing the average daily traffic by 24 (hours of the day) and the appropriate speed limits for each section of road. Practical speed limits in GB for LGV up to 3.5 t are (i) 113 km/h travelling on motorways (ii) 80 km/h on rural ‘A’ roads and (iii) 50 km/h on urban roads. For HGV over 7.5 t the assumed speed limits are (i) 90 km/h travelling on motorways (ii) 80 km/h on rural roads, and (iii) 50 km/h for urban roads. TABLE 3-3, TABLE 3-4 and TABLE 3-5 present the average number of vehicles per km of road in GB for the three categories of freight vehicles. The derived figures, which include 30% safety margin, present data for all major roads in GB. Major roads include motorways and all rural/ urban sections of class ‘A’ roads [87]. Class ‘A’ roads are classified into Trunk (Tr) and Principal (Pr) sections.

| TABLE 3-3: Category 1 (LGV) average number of vehicles per km of road in 2013 |
|-----------------|-----------------|
|                  | Motorway Tr     | Rural Tr |
|                  |                 | Pr       | Urban Tr |
| England          |                 | Pr       | Pr       |
| North East       | 4               | 2        | 1        | 9        | 3        |
| North West       | 5               | 2        | 1        | 4        | 3        |
| Yorkshire-Humber | 5               | 3        | 1        | 7        | 3        |
| East Midlands    | 7               | 3        | 1        | 6        | 3        |
| West Midlands    | 5               | 2        | 1        | 7        | 3        |
| East of England  | 7               | 4        | 2        | 5        | 3        |
| London           | 7               | 0        | 3        | 0        | 4        |
| South East       | 7               | 4        | 2        | 5        | 3        |
| South West       | 5               | 2        | 1        | 5        | 3        |
| Wales            | 5               | 2        | 1        | 5        | 3        |
| Scotland         | 4               | 1        | 0        | 5        | 2        |

A trunk road in GB is a major road between places of traffic importance. The entire trunk road network (Primary Route Network) is designed to provide easily identifiable routes to access the whole of the country [87]. The remaining sections of major roads in GB (class ‘A’) are classified as Principal roads.
The average number of vehicles per km of road across a day were shaped with daily traffic distribution data obtained from DfT [88]. As an illustration, during the peak hours of the day there are 13 HGVs per km of motorway in East Midlands; a figure which is about two times the average density of 7 HGVs per km shown with the dashed line in Figure 3-4.

It is worth mentioning that under normal conditions on motorways there is minimum 1.1 sec gap between vehicles [58], which corresponds to 27.5 m gap for HGVs travelling at 90 km/h. This, combined with the 16.5 m typical length of HGVs on the roads of GB [89] means that each HGV occupies 44 m under normal flow conditions on motorways. This corresponds to a maximum capacity of 22 HGVs per km of motorway.
The derived daily profiles were combined with the power requirements listed in TABLE 3-2 to calculate the power demand per km of road across GB throughout a typical day. The methodology assumes 100% adoption of EFVs for sizing the infrastructure, based on current traffic conditions and it does not account for future growth in the freight sector. During the peak hours of the day, the average power demand by HGVs is around 1,600 kW per km of motorway, as shown in Figure 3-5.

The average power required per km of motorway in London for LGVs, HGV10 and HGV38 during the peak hours is 570 kW, 160 kW and 1,600 kW respectively. The power demand per km of rural section of road is 100 kW for LGVs, 40 kW for HGV10 and 700 kW for HGV38.
These figures correspond to the maximum demand per km of motorway and rural section of road across all regions of GB.

Although Category 1 (LGVs) and Category 2 (HGV10) vehicles are not supplied in-motion but on-the-stop according to the logistics concept in section 3.2, the additional power demand can still be estimated based on the number of vehicles per km of road. It is assumed that the number of LGVs/HGV10 on the roads of GB, given by TABLE 3-3/ TABLE 3-4, is the same, with LGVs/HGV10 performing urban/home delivery operations. The required energy to be supplied to the vehicles (i) continuously from a CoM infrastructure or (ii) at intervals from CoS top-up points, must be the same; apart from small differences due to the proportion of electricity that is supplied directly to motors from the infrastructure compared to that when is routed through charging and discharging of batteries. The latter results in losses of approximately 10%. The power demand is calculated in hourly steps and hence, the average power within a 1-hour time slot is the same for both situations. Although the actual power demand varies within the 1-hour time slot, the study does not investigate smaller time resolutions.

The average power required to electrify road freight transportation for each type of major road and different regions of GB can be calculated. The peak power demands are summarised in TABLE 3-6. A total additional power demand of 9.4 GW would be added to the peak load during peak hours. The magnitude of the load substantially exceeds the available capacity grid of the electricity supply network in GB at peak hours, which is around 5 GW [90].

Nevertheless, various authorities have already embarked on plans to upgrade the electricity supply network around the country, because the power demand is estimated to increase significantly in future due to shifting to EVs and electric heating. To this end, the anticipated installed generating capacity in GB is estimated to be around 100-130 GW by 2050 which is approximately double the current installed capacity [91]; giving a significant capacity margin for the electrification of road freight. Furthermore, the Electricity Networks Strategy Group has defined pathways to reinforce the transmission network of GB [92] and various distribution companies have already embarked on upgrade projects to deal with the increased future demand [93], [94].
TABLE 3-6: Peak power demand in GW of electrified road freight transportation

<table>
<thead>
<tr>
<th></th>
<th>Motorway</th>
<th>Rural ‘A’</th>
<th>Urban ‘A’</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>England</td>
<td>4.8</td>
<td>2.8</td>
<td>0.6</td>
<td>8.2</td>
</tr>
<tr>
<td>Wales</td>
<td>0.1</td>
<td>0.2</td>
<td>0.04</td>
<td>0.3</td>
</tr>
<tr>
<td>Scotland</td>
<td>0.4</td>
<td>0.4</td>
<td>0.08</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.3</strong></td>
<td><strong>3.4</strong></td>
<td><strong>0.7</strong></td>
<td><strong>9.4</strong></td>
</tr>
</tbody>
</table>

3.3.2 Charging Simulation tool

A simulation tool was developed on top of the Advisor software tool to investigate the application of dynamic charging and the effects of system design variables on important performance parameters, such as the mileage range and battery SOC.

The input interface to the tool is shown in Figure 3-6. The inputs are:

(i) The type of EFV and its driving cycle.
(ii) The specification of the EFV’s batteries: cell capacity, number of cells in parallel, number of modules in series, initial SOC.
(iii) The specifications of the dynamic charging system: distance between consecutive chargers, the charging segment length, and the nominal power rating of the charger.

![Charging simulation tool input interface](image)

The example in Figure 3-6 shows the input data for investigating the journey of a HGV38 vehicle travelling on motorway, 45% of which is ‘online’ (4.5 m charging segment every 10 m) at 350 kW nominal power transfer rate.

The charging model assumes instantaneous operation of chargers when a vehicle is located within the charging segment length boundaries and 100% energy transfer efficiency - without considering any misalignments between the vehicle and the charging device. In practice,
some inefficiency (typically 90%) is expected, mainly due to power losses \([58]–[60]\), as explained in the chapter of literature review. Any tolerance on fore-aft misalignment is assumed to be included in the charging segment.

Figure 3-7 shows the results of a simulation based on the input data in Figure 3-6. The four graphs show: (a) the demand (target) speed of the vehicle during the run; (b) the power required from the electric motor to track the drive cycle; (c) the energy consumed by the electric motor, the energy received from the charging infrastructure, and the net energy demand which is the difference between the energy consumed and energy received (i.e. the energy stored by the battery); and (d) the SOC of the vehicle with and without the use CoM.

![Figure 3-7: Simulation results for HGV38 travelling on the HWFET drive cycle (Figure 3-3c)](image)

At the bottom of the figure additional outputs of the run are listed: (i) the battery capacity of the vehicle under investigation, (ii) the final SOC without any charging facilities, (iii) the final
SOC with CoM infrastructure, (iv) the total energy consumed (used by the electric motor) in the simulation run, (v) the energy received from the CoM system, (vi) the net energy demand during the whole journey - negative values when the vehicle receives (and stores) more energy from the charging infrastructure than the consumed energy over the drive cycle, (vii) the equivalent fuel economy of the vehicle under investigation, (viii) the average consumption of the vehicle, and finally (ix) the ‘Mean Effective Charging Rate’ (MECR), denoted $\Psi$, which is the energy delivered by the charging system per km along the road.

The speed, power, and energy were calculated by the Advisor simulation according to the parameters of the vehicle and driving cycle under investigation. The energy received from the charging system and the consequent SOC of the vehicle were determined by the charging simulation and depend on the user’s input specification for the charging system. The longer the charging segments, the smallest the distance between two charging segments and the higher the power transfer rate result in larger amounts of energy transferred and higher SOC at the end of the journey. It can be seen from the third graph of Figure 3-7c that the energy consumed by the electric motor is relatively constant during the journey, whereas the energy received fluctuate between zero and a constant value. This is due to the fact that charging devices are installed periodically along the road and energy is transferred only when the vehicle is located over the charging device. The upper value of transferred energy is influenced by the power rating of the charging device and the speed of the vehicle; since the longer the vehicle spends within the effective boundaries of the charging system, the higher the received energy. The net energy demand is the difference between the energy consumed and energy received from the CoM infrastructure. It is plotted with negative values when the energy supplied to the vehicle is greater than the energy consumed by the electric motor. The vehicle stores energy under this condition.

Finally, the fourth graph in Figure 3-7 shows that HGV38 would have 33% SOC on battery power alone after 25 km on this driving cycle, whereas with a dynamic charging system capable of delivering $\Psi = 2.5 \text{ kWh/km}$, it could run indefinitely. The vehicle receives more energy, on average, than it uses in motorway driving and the final SOC for this condition is around 10% more than the initial SOC (the vehicle stores energy).
3.4 Case studies

This section develops four case studies for assessing the feasibility of electrification of road freight transportation. Our selection of the particular electrification system for each of the logistics operations is based on using the smallest possible battery pack in each case. This would reduce the weight, cost, embodied energy and rolling resistance of the vehicle and allow more mass and volume for the payload. Where charging can be performed practically during the journey, to enable use of a smaller battery (e.g. charging while loading or unloading), this is the chosen option.

3.4.1 Long-Haul

The first case study is concerned with ‘long-haul’ freight transport which enables the transportation of goods between distribution centres located on or near to trunk routes. Articulated HGVs in the range 33-44 t are mainly used for this type of deliveries in Europe and the analysis assumes the HGV38 articulated vehicle described in TABLE 3-1. In the simulation, each vehicle is assumed to have a 277 kW electric motor, 85 kWh battery capacity, 4 kW constant consumption for on-board loads, and 38 t overall mass.

In the logistics model shown in Figure 3-1, long-haul journeys are assumed to occur predominantly on trunk routes, with just a few km of local roads between highway exits and the delivery points (distribution centres). To this end, the investigation for long-haul deliveries is divided in two parts: (i) the trunk roads themselves, where a CoM system must be provided to enable steady-state operation, with the on-board batteries running at a constant (or increasing) state of charge; (ii) the journey from the end of each trunk road to nearby delivery points / distribution centres and back to the motorway, using battery power.

Driving on Trunk Roads

The charging simulation tool was used to determine the MECR level $\Psi$ needed to balance out the energy consumed by the vehicle on a motorway based on the HWFET drive cycle, shown in Figure 3-3c, which is repeated five times. Figure 3-8 shows the SOC of the HG38 vehicle model, for various MECR values $\Psi$. For $\Psi = 0$, no energy is transferred to the vehicle and it can be seen that the SOC is depleted rapidly after approximately 35 km journey on a motorway. When $\Psi = 2.3 kWh/km$ the energy received from the dynamic charging system largely balances the energy consumed by the vehicle and the SOC remains around 100%
throughout the whole trip. For $\Psi = 2.5\ kWh/km$, the vehicle receives more energy, on average, than it uses in motorway driving and the final SOC for these conditions is around 10% more than the initial SOC.

![Figure 3-8: Long-haul SOC of HGV38 for various levels of MECR](image)

Although charging is continuous, it can be noticed that the SOC varies throughout the journey. This is due to the fact that the vehicle does not have a constant speed over the modelled drive cycle. The energy received from the CoM infrastructure is not sufficient to balance out the energy consumed when the HGV38 travels relatively fast (faster than the average speed) thus decreasing SOC. By contrast, an increasing SOC is possible when the speed is relatively slow and steady. Overall, a steady and an even increasing SOC is achieved over the entire cycle.

These values can be compared with Tesla’s recent claim of 1.25 kWh/km (2.0 kWh/mile) for the prototype Tesla truck [84], which has a gross weight of 36 t (80,000 lbs). The Tesla claim is assumed to be for a steady speed at 96 km/h (not the more realistic drive cycle in Figure 3-7a) and would require much lower rolling resistance and aerodynamic drag than for a normal HGV. Tesla claims 0.36 drag coefficient which is similar to the coefficient factor of sports cars (e.g. Bugatti Chiron as compared by Tesla).
Both OhC systems and IPT devices could be exploited to deliver 2.5 kWh/km or alternatively 140 kW per metre\(^3\). Many of the practical challenges of OhC systems are well understood, but there are still some technical and operational issues that would need to be resolved:

(i) The catenary system would not be suitable for cars – so the infrastructure and operating costs would have to be borne by the freight industry alone;

(ii) High voltage wires carried above the roadway might pose a threat to safety, in the event of a collision between a vehicle and a roadside support pole.

(iii) Maintenance of exposed wiring located above the carriageway would be challenging although this is not a significant issue according to SIEMENS.

IPTs would eliminate all the above-mentioned issues but they have their own drawbacks when compared with overhead catenary systems:

(i) No IPT device with a power transfer rating over 30 kW is commercially available (some IPT systems have been commercially available which are the 30 kW INTIS system [50], the 7.2 kW Plugless system [51] and the 3.2 kW BMW system [52]). This is significantly lower than the required power transfer rating for HGVs. Even with 100% coverage of the road surface, a power of 140 kW is needed, which is about five times higher than any existing device. It would be possible to have multiple pick-up devices underneath each truck, each of which could receive power from a single transmitter on the ground. However, having multiple receiving systems on each truck would add some mass to the vehicle (no data is currently available to calculate precisely the added mass). Nevertheless, it is expected that the extra mass would be compensated by the lighter electric motor and transmission system in EFVs compared to conventional freight vehicles.

(ii) Installation of the charging devices would require digging-up much of the existing motorway network – at least in the ‘slow lane’, where HGVs mostly travel.

(iii) The installation would have to be durable, long lasting and not cause excessive surface roughness. This would not be straightforward for asphalt pavements, which are prone to crack around devices mounted in the surface [95], [96].

\(^3\) The average speed of the vehicle following the HWFET drive cycle, shown in Figure 3-3c, is 55 km/h. The power required then is calculated as \( P = \Psi \times U = 2.5 \text{ kWh/km} \times 55 \text{ km/h} = 140 \text{ kW} \)
(iv) There may be human health issues associated with the high magnetic fields generated by the charging system [97]. Research is needed to ensure that the human exposure is maintained within acceptable, safe limits.

(v) Ideally, HGV, LGV, and passenger cars would be able to use the same IPT infrastructure. This would improve the prospect of a privately financed system for distributing the large amounts of energy involved. The business case for this system is explored in Chapter 6.

Additional issues for both OhC and IPT systems include identification of vehicles, metering and payment transactions. Several ideas have been suggested for charging users including i) customers pay for energy (electricity) based on the current prices of electricity, ii) customers pay for energy based on the current prices of diesel and iii) customers pay a membership but they do not pay for energy. Indeed, the latter method is similar to the Tesla’s business model in the UK whereby the owners of Tesla cars use the Tesla charging network around the country without paying for recharging (regardless the amount of energy delivered to the vehicle). Charging costs could be also combined with road use pricing which refers to direct chargers levied for the use of road. Payment methods should be a topic of further research.

Finally, long-haul trunking is dependent on a nationwide CoM infrastructure which might impose concerns about the reliability of the system in case of CoM breakdown. However, it is unlikely to have a complete failure of the CoM network, which would undoubtedly have an architecture with multiple independent charging segments. Therefore, the on-board battery of freight vehicles should be sufficient to perform the short off-network operations. This, combined with battery improvements and faster charging solutions in the future mean that the performance of long-haul operations would not be compromised. Besides, a series hybrid configuration could be used with an internal combustion engine ‘range extender’ to charge the battery on-board and provide an extended range for off-grid operations. This standby combustion engine could be significantly smaller than the large diesel engines in existing heavy vehicles and the CO₂ emissions of these short, lower speed journeys would be much lower.
Driving on Local Roads

This section considers the energy used by the HGV driving on the local roads at the ends of each motorway segment. The driving cycle is assumed to be a combination of two consecutive UDDS driving profile shown in Figure 3-3b. The long-haul vehicle (HGV38) is assumed to exit the motorway with 100% SOC, travel up to 9 km to the delivery point under battery power and then return back to the motorway. The simulation results are shown in Figure 3-9.

As shown in Figure 3-9, this can be achieved with a battery capacity of 85 kWh and a safety margin of 36% SOC. Once the vehicle re-enters the motorway, the CoM infrastructure will recharge the on-board battery during the subsequent highway driving provided the infrastructure delivers MECR greater than 2.3 kWh/km. Optionally, the vehicle could be partially re-charged during the delivery process, using fixed IPT devices or OhC systems located appropriately at each loading bay in the destination centre.

This case study has shown that shifting towards electrification of long-haul deliveries is not an unreasonable proposal, provided the logistics infrastructure could be changed to the configuration shown in Figure 3-1. This kind of operation could be undertaken by purely electric HGVs with 85 kWh of on-board batteries – which is a practical size.

Using the ‘Advisor’ model the fuel economy of a 38 t diesel-powered lorry was calculated to be 36.2 l/100 km when travelling the overall long-haul delivery trip (including driving both on trunk and local roads). About 2.69 kgCO₂ are produced from burning a litre of diesel fuel [98]. As a result, a conventional 38 t vehicle emits around 974 gCO₂/km. The HGV38 model
consumes an average of 2.4 kWh/km on the same combined drive cycle on trunk and local roads for the long-haul delivery trip. Using the carbon intensity of the UK electricity supply network in 2017 of approximately 300 gCO₂/kWh [20], this corresponds to approximately 720 gCO₂/km – which is 25% lower than that of the diesel vehicle. However, using DECC’s projected CO₂ intensity of 100 gCO₂/kWh [23] for the significantly decarbonised UK electricity grid in 2030, the CO₂ emissions of the 38 t vehicle would be only 240 gCO₂/km. This corresponds to a very significant reduction of 75%. Using the CO₂ intensity of 40 gCO₂/kWh in 2050 [22], reduction of 90% CO₂ emissions is feasible. TABLE 3-7 shows an overview of the long-haul delivery case study.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Driving on trunk network: CoM at 2.5 kWh/km MECR</th>
<th>Possible power delivery systems: OhC and IPT</th>
<th>Driving on local roads: Energy provided by the 85 kWh on-board battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel 2017</td>
<td>974</td>
<td>720</td>
<td>240</td>
</tr>
<tr>
<td>gCO₂/km Reduction (%)</td>
<td>-</td>
<td>25</td>
<td>75</td>
</tr>
</tbody>
</table>

### 3.4.2 Urban Delivery

Under the logistics scenario shown in Figure 3-1, urban delivery vehicles would transport goods between LDCs and UCCs, on the edge of cities, to convenience stores and urban shops. HGV10 is assumed to be the backbone of such urban deliveries. A typical journey is assumed to have two delivery points on a 29 km round trip, driven on major regional and urban roads.

The assumed driving cycle is illustrated in Figure 3-10a. It consists of a combination of a rural driving cycle (CSC in Figure 3-3a), followed by an urban driving cycle (UDDS in Figure 3-3b) and then a repeat of the rural driving cycle. The vehicle is assumed to have the components shown in TABLE 3-1, with a 75 kW electric motor, 42 kWh battery, 4 kW constant on-board load (e.g. refrigerator) and 10 t overall mass.

The results of the simulation are illustrated in Figure 3-10. It is apparent that this urban delivery journey could be undertaken by the specified vehicle. It commences its journey with 100% SOC and return to the starting point after the 29 km round trip with 28% SOC. One hour charging is needed at the depot using a 30 kW charger to return to 100% SOC.

Another option is that the vehicles could be charged en-route, in order to reduce recharging times at the depot and allow continuous operation. Taking advantage of the fact that such
urban deliveries take place on pre-determined routes with known delivery points the CoS approach could be used for charging EFVs during unloading at delivery points.

The energy consumed by the vehicle on the journey is 1.05 kWh/km. Over the 29 km journey, this corresponds to a total energy consumption of about 30 kWh. Assuming that a static charging station is located at the main distribution centre and at the two delivery points, the three charging stations would each need to deliver around 10 kWh of energy to the vehicle’s battery in order to return to 100% SOC (Figure 3-10). This could be achieved using 30 kW chargers, running for 20 min on average while the vehicle is stopped during each loading and unloading process. This appears to be practical and would allow continuous urban deliveries throughout the day.

![Graph showing speed and SOC](image)

**Table 3-8** shows an overview of the Urban Delivery case study.

The average CO₂ emissions of a conventional ten tonnes diesel vehicle is around 420 gCO₂/km based on the computed equivalent fuel economy of 15.6 l/100 km. The average energy of HGV10 is 1.05 kWh/km on this drive cycle (Figure 3-10a). Assuming 300 gCO₂/kWh for the electricity grid (2017 levels) [20], this corresponds to 315 gCO₂/km – again, 25% lower than the conventional diesel. Assuming a decarbonized grid with 100 gCO₂/kWh (2030 levels) [23], the impact would be 105 gCO₂/km (not too different to a good mid-size car in 2017). Again, this corresponds to at 75% reduction of CO₂ emissions in comparison with urban operations by conventional vehicles. Similarly, reduction of 90% CO₂ emissions by 2050 is feasible. TABLE 3-8 shows an overview of the Urban Delivery case study.
TABLE 3-8: Urban Delivery case study overview

<table>
<thead>
<tr>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>42 kWh battery with a single charge at the depot</td>
</tr>
<tr>
<td><strong>or</strong></td>
</tr>
<tr>
<td>Charge-on-the-stop at delivery points</td>
</tr>
<tr>
<td>20 minutes charging boost at 30 kW power transfer</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Diesel 2017</th>
<th>EFV 2017</th>
<th>EFV 2030</th>
<th>EFV 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>gCO₂/km</td>
<td>420</td>
<td>315</td>
<td>105</td>
<td>42</td>
</tr>
<tr>
<td>Reduction (%)</td>
<td>-</td>
<td>25</td>
<td>75</td>
<td>90</td>
</tr>
</tbody>
</table>

3.4.3 Home delivery

The prospects for electrification of ‘home delivery’ are discussed in this part of the chapter. Under the assumed logistics system in TABLE 3-3, home delivery operations would transport goods from LDCs and city-edge supermarkets to consumers. LGVs up to 3.5 t are mostly used for this task today. The electric versions of today’s delivery vans are assumed to be equipped with a 75 kW electric motor, 27 kWh battery, and a 2 kW refrigerator, as stated in TABLE 3-1. A typical home delivery journey might have ten delivery points on urban roads, as it is shown in Figure 3-11a. The assumed driving profile is a combination of a rural driving cycle (Figure 3-2b) followed by ten consecutive urban delivery cycles (Figure 3-2a), completed with another rural driving cycle.

The results of the simulation are illustrated in Figure 3-11. The vehicle leaves the depot with 100% SOC and returns back with a safety margin of 26% SOC after consuming 20 kWh of energy. This means that a 40 min charging boost, using a 30 kW charger during the loading process at the LDC would be sufficient to fully charge the battery before the next delivery trip.

Figure 3-11: Results of Home delivery journey for LGV
(a) Requested speed of vehicle (b) State of charge history
Using the calculated average energy consumption of 0.37 kWh/km (Figure 3-11) and the same assumptions as before for the carbon content of the electricity grid, this would correspond to 110 gCO₂/km in 2017 and 37 gCO₂/km in 2030 and 15 gCO₂/km in 2050, based on [20], [23]. Again, a significant reduction of 75% CO₂ emissions when compared to conventional diesel vans (148 gCO₂/km) is possible by 2030 and 90% by 2050. TABLE 3-9 shows an overview of the Home Delivery case study.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Charge-on-the-stop at LDC</th>
<th>40 minutes charging boost at 30 kW power transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel 2017</td>
<td>EFV 2017</td>
<td>EFV 2030</td>
</tr>
<tr>
<td>gCO₂/km</td>
<td>148</td>
<td>110</td>
</tr>
<tr>
<td>Reduction (%)</td>
<td>-</td>
<td>25</td>
</tr>
</tbody>
</table>

3.4.4 Refuse collection

For the final case study, the possibility of shifting to electric refuse collection vehicles (eRCVs) is explored. Refuse collection vehicles need power for the bin-lifters, refuse compaction, for lighting indicators, and various other systems on board. Furthermore, an eRCV with an overall mass around 27 t (8 t unladen mass plus 19 t carrying capacity) has to undertake many rapid accelerations and decelerations using energy from the battery on board.

A typical refuse collection driving profile is illustrated in Figure 3-12a. The driving profile is based on the ‘William H. Martin Refuse Hauler Drive Cycle’ provided by ‘Advisor’ but the cycle was modified to increase the number of stops to approximately 60 within 10.5 km in a 1.7-hour drive cycle. The drive cycle includes driving from the depot to the collection area and back to the depot. The vehicle under investigation is equipped with a 147 kW electric motor, a 32 kWh battery and it has 27 t overall mass, which is the fully-loaded mass to provide a worst case scenario. Furthermore, the vehicle is assumed to have a 2 kW constant load for on-board equipment, of which 0.2 kW is accounted for the bin lifting and compaction system.

In particular, the auxiliary energy requirements for EFVs is calculated as follows. It is assumed that an eRCV executes one lift at every stop and two refuse bins up to 160 kg apiece⁴ are elevated by 1 m in each lift. The work \( W_L \) needed to lift two bins of combined mass \( m \) through a height \( h \) is given by \( W_L = mgh/n \), where \( g \) is the acceleration due to gravity and \( n \) is the

---

energy efficiency of the lifting motor and mechanism. So, with \( m = 320 \text{ kg} \), \( h = 1 \text{ m} \) and assuming \( n = 0.8 \), this gives a work per lift of approximately 4,000 J. Assuming 60 stops in a 1.7-hour drive cycle (19 t carrying capacity) the energy required per drive cycle is approximately 240 kJ or 0.07 kWh.

Similarly, the work done by the compaction system is given by \( W_C = Fd/n \), where \( F \) is the compaction force, \( d \) is the compaction stroke and \( n \) is the efficiency. Assuming the compaction force \( F = 10 \text{ kN} \), stroke \( d = 5 \text{ m} \) and \( n = 0.8 \), the work done per stroke is 62.5 kJ. If there is one compaction stroke every four stops (every 1.3 t of waste), the energy required per shift is approximately 940 kJ or 0.26 kWh.

Hence, the total energy required for the bin lifting and compaction system over the 1.7-hour trip is approximately 1,200 kJ or 0.33 kWh. This could be modelled as an average constant power of 0.2 kW.

The results of the simulation are illustrated in Figure 3-12. The vehicle leaves the depot with 100\% SOC and returns back with a safety margin of 20\% SOC after consuming 25 kWh of energy. This means that a 50 min charging boost using a 30 kW charger during the un-loading process would be sufficient to fully recharge the battery before each refuse collection trip.

Wireless IPT or conductive automatic charging devices could be distributed at key locations along the route to reduce recharging times at the depot. Based on a maximum 30 min charging at the depot using 30 kW chargers (15 kWh charging boost), 10 kWh is still needed to be supplied to vehicles en-route to return to 100\% SOC. Indeed, 10 ‘top-up’ charging points at 30 kW each would be sufficient to deliver the needed energy of 10 kWh provided vehicles are stationary for 2 min for charging during bin lifting or compaction procedures (Figure 3-12).

The average \( \text{CO}_2 \) emissions of a conventional 27 t diesel vehicle is around 1,022 g\( \text{CO}_2 \)/km based on the computed equivalent fuel economy of 38 l/100 km. The average energy of eRCV is 2.5 kWh/km on this drive cycle (Figure 3-12a). Assuming 300 g\( \text{CO}_2 \)/kWh for the electricity grid (2017 levels), this corresponds to 750 g\( \text{CO}_2 \)/km – again, 25\% lower than the conventional diesel. Assuming a decarbonized grid with 100 g\( \text{CO}_2 \)/kWh in 2030 levels), the impact would be 250 g\( \text{CO}_2 \)/km. Again, this corresponds to 75\% reduction of \( \text{CO}_2 \) emissions in comparison with refuse collection functions by conventional vehicles. Similarly, reduction of 90\% \( \text{CO}_2 \)
emissions is feasible using the figures for 2050 levels. TABLE 3-10 shows an overview of the Refuse collection case study.

<table>
<thead>
<tr>
<th>Battery Capacity (kWh)</th>
<th>Energy Requested (kWh)</th>
<th>Energy Received (kWh)</th>
<th>Final SOC (%)</th>
<th>Average consumption (kWh/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>25</td>
<td>0</td>
<td>20</td>
<td>2.5</td>
</tr>
<tr>
<td>Equivalent fuel economy (l/100 km)</td>
<td>38.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3-12: Results of Refuse Collection operations for eRCV**
(a) Requested speed of vehicle (b) State of charge history

**TABLE 3-10: Refuse Collection case study overview**

<table>
<thead>
<tr>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 minutes charging boost at 30 kW power transfer or 10 ‘top-up’ charging points along the route 2 minutes charging boost at 30 kW power transfer</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diesel 2017</th>
<th>EFV 2017</th>
<th>EFV 2030</th>
<th>EFV 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>gCO₂/km</td>
<td>1022</td>
<td>750</td>
<td>250</td>
</tr>
<tr>
<td>Reduction (%)</td>
<td>25</td>
<td>75</td>
<td>90</td>
</tr>
</tbody>
</table>

It is worth mentioning that a more detailed analysis based on existing operations is performed in Chapter 4 for determining the charging infrastructure of refuse collection vehicles. It is shown that driving between the depot and the collection area is considerably longer than the 4 km assumed in this chapter. The necessary capacity of the on-board battery is therefore greater. Nevertheless, the same methods for determining the charging infrastructure are still valid.

### 3.5 Conclusions

It was shown in this chapter that deep decarbonisation of the national road freight system by electrification is feasible. It would require installation of a backbone CoM network on the nation’s motorways. This could be achieved with either OhC systems or IPT devices.
A logistics concept was proposed that, in conjunction with current and likely future electrification technologies, could provide a framework for the electrification of most road freight operations. The proposed logistics concept is divided into four operations which are the ‘long-haul trunking’, ‘urban delivery’, ‘home delivery’, and other ‘auxiliary services’ such as refuse collection functions within the area of municipalities. Different vehicles and charging mechanisms were suggested for each of these operations.

Three vehicle models were developed using an advanced vehicle simulator including electric light good vehicles (LGV), electric heavy good vehicles up to 10 t (HGV10) and electric heavy good vehicles up to 38 t gross mass (HGV38). The power requirement of each vehicle model was calculated over appropriate driving cycles. The outcomes were then combined with GB traffic data in order to set the baseline of the required power demand across GB. It was shown that an additional electrical load of 9.4 GW would be added on the power demand during the peak hours of commuting due to the electrification of road freight transportation.

A charging simulation tool was developed to investigate the application of dynamic charging. The tool shows how various CoM layouts affect the SOC and the mileage range of the vehicle under investigation. The performance of the charging system was quantified by the MECR.

Four case studies were developed for assessing the feasibility of electrification of road freight. It was shown that shifting towards EFVs appears to be technically and financially feasible since large and expensive on-board batteries are not required. Significant reduction of 75% CO₂ emissions when compared with conventional freight vehicles could be achieved by 2030 for all case studies examined. Even higher reduction of 90% CO₂ emissions by 2050 is feasible provided the current projections for decarbonisation of the UK electricity grid are achieved.
Chapter 4    An Urban Charging Network: A case study for Cambridge UK

An urban charging infrastructure for electric road freight operations is explored in this chapter. The city of Cambridge UK was chosen for demonstration but the same methodology could be used for other cities. The five Park and Ride bus routes, the refuse collection operations and two home delivery operations are investigated. Real data about existing operations were collected to define accurate drive cycles. Different vehicles are modelled for each operation and their performance is evaluated over the defined drive cycles. Different charging infrastructures are proposed for each operation. The additional power demand, additional load, capital cost needed and the CO\(_2\) emissions savings for each case are calculated. The results are scaled up for the entire city and the implications for the electricity supply network are explored. It is shown that electrification of these operations would increase the city’s power demand by 6.3% based on current figures and the electricity consumption by 2.0%. This increase can be met by the current electricity supply network in the short-term. Such a system would cost £57.5 million at today’s prices and would result in accumulated savings of 205 ktCO\(_2\) by 2050. The results are then combined with estimated performance requirements for electrified urban deliveries and urban travel by passenger cars at Cambridge. In the long-term, a complete urban charging network at Cambridge would increase the power demand of the city by 20.6 MW (19.5% of the current peak) and the energy consumption by 117 GWh per year (14.6% of current consumption). The total capital cost is calculated at £222 million which is similar to the cost of other city’s projects.

4.1 Introduction

Substantial progress towards more sustainable transport requires a significant contribution from the freight sector which accounts for approximately 33% of road transport emissions in Great Britain (GB) [3]. However, deep decarbonisation of road freight by conventional means is difficult. Strategies for that purpose can include a wide range of measures including improvements to aerodynamics, higher capacity vehicles, driver performance, regenerative braking, etc. Combination of these measures should be capable of reducing fuel consumption and CO\(_2\) emissions approximately by 30% [17], [76]. For CO\(_2\) emission reductions beyond that level, alternative energy sources need to be investigated.
Chapter 3 showed that shifting towards electric freight vehicles would be technically feasible. A logistics concept was proposed, that could be used in conjunction with current and future electrification technologies, to provide a framework for the electrification of most road freight transport operations. Based on that, simulation tools and methods were presented to set the performance requirements for a practical system. Finally, four case studies were developed for assessing the feasibility of electrification of various road freight operations, including Long-Haul Journeys, Urban Deliveries, Home Deliveries and Refuse Collection. Different vehicles were modelled and appropriate charging infrastructures were considered for each of these operations.

It was shown that long-haul journeys would require installation of a charge-on-the-move network on the nation’s motorways. Such infrastructure appears to be technically and financially feasible and it could be significant driver for substantial CO$_2$ emissions reductions in the long-term [53], [54]. However, extensive road infrastructure modifications are needed.

A shorter-term solution is the electrification of road freight operations within the boundaries of a city. Road freight could be transported by battery-powered electric vehicles (EVs) that charge their batteries while loading at depots and could potentially top-up at charging points while unloading, e.g. at convenience stores. Other heavy vehicles operating within the area of cities, such as buses and refuse collection vehicles, could top-up their batteries from charging points distributed at key locations along their routes. This ‘charge-on-the-stop’ (CoS) approach reduces significantly the necessary battery capacity and vehicle costs which makes the shift towards EVs possible. It also distributes the charging process geographically, reducing the need for very large charging facilities in few locations.

Power charging systems for EVs have been under development for some decades. Conductive systems are well established and have high efficiency and reliability. Non-conductive (wireless) chargers suitable for EVs have also been developed and high efficiencies, over 90%, can be obtained for static charging applications [43], [99], [100]. The ability to avoid plug-in cables and to use simple systems that are unaffected by weather conditions is likely to be attractive to drivers and cities.

High power transfer rates have been achieved, which makes wireless chargers relevant to road transport operations performed by freight vehicles, buses and refuse collection vehicles.
For example, 120 kW wireless chargers are used in Milton Keynes where electric buses receive a 10 min booster charge at wireless charging points located at either end of Route 7 [36]. In addition, 150-600 kW conductive overhead catenary systems suitable for electric buses have been developed by SIEMENS and ABB for en-route opportunity charging at the stop [64], [65].

This chapter explores the electrification of road freight operations within the boundaries of a city, including the auxiliary services of buses and refuse collection functions. The city of Cambridge UK has been chosen for demonstration. The local council is keen to promote the adoption of emerging technologies and solutions towards more sustainable cities, as disclosed by the recent introduction of the ‘Smart Cambridge’ programme [101]. Nevertheless, the methodology presented in this chapter could be considered as a framework to assess the prospects of electric freight operations in other cities as well.

The five ‘Park and Ride’ bus routes of the city, the refuse collection operations and two home delivery operations were investigated. Operational data about speed, location and engine performance, were used to define accurate drive cycles and validate simulations. A vehicle simulation tool was used to estimate the power requirements of EVs over the defined drive cycles. The performance requirements for a practical system were set and an appropriate charging infrastructure for the city was proposed. The number and location of charging points required within the city, their power transfer rates and the capacity of the on-board battery for each vehicle were determined by solving an optimisation problem. The additional power demand for such a system was calculated and the implications for the electricity supply network were explored. A cost model was also built to assess the financial viability of the infrastructure. The results were then combined with estimated performance requirements for electrified urban deliveries and urban travel by passenger cars at Cambridge to explore the impacts from a complete urban charging network in the city.

4.2 Methodology

In this section, the methods of data collection, the simulation tools used in the study and the process for selecting en-route charging points are described.

4.2.1 Data collection

An electronic logging device, developed in the Department of Engineering University of Cambridge for the Centre for Sustainable Road Freight (CSRF), was used for logging the routes
of buses and delivery vans. The device, known as ‘SRF Logger’, is based on a mobile phone which is connected to the vehicle’s on-board diagnostics (OBD) port. The SRF Logger starts collecting data automatically without intervention of the driver, when the vehicle’s engine starts. All stored data is transmitted wirelessly to a server located in the Department of Engineering. Limited data was also collected using the GPS signal of the device (GPS location and speed) without connecting it to the vehicle. This was particularly useful for logging operations quickly as installation in the vehicle was not needed. However, the user had to physically ride the route under investigation.

For the case of refuse collection operations, a tracking device was already installed on the vehicles. Real-time data for each vehicle was available in an online database, including information about time, GPS location, speed and the operational status of the bin lift and compaction systems [102].

4.2.2 Simulation Tools
The ‘Advanced Vehicle Simulator’ (Advisor) was used to estimate the power requirements of EVs. Advisor is an open source software tool that was developed at the National Renewable Energy Laboratory for the US Department of Energy [30], as it was explained in Introduction. Its accuracy has been validated by several authors and laboratories [31], [32]. The user models the vehicle of interest and investigates the characteristics of the journey over specific drive cycles, such as the required power from the electric motor, the state of charge (SOC) of the on-board battery, etc.

Different EVs were modelled for each operation using Advisor. These were: 1) ‘eBus’, 2) ‘eVan’ and 3) ‘eRCV’ for electric buses, electric delivery vans and electric refuse collection vehicles respectively. Standard vehicles provided by Advisor were adjusted appropriately and values were determined for the power rating of electric motors, constant electrical loads (e.g. refrigeration, bin lifting, etc.) and the overall masses of the vehicles. The final parameter values are summarized in TABLE 4-1. The capacity of the on-board battery of each vehicle is dependent on the proposed charging infrastructure as designed below.
### Table 4.1: Components of simulated EVs for electrified urban freight operations

<table>
<thead>
<tr>
<th>Advisor’s vehicle model</th>
<th>Motor (kW)</th>
<th>Load (kW)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>eBus Orion VI Transit Bus</td>
<td>150</td>
<td>0.5</td>
<td>18,000</td>
</tr>
<tr>
<td>eRCV Kenworth T800 Vehicle</td>
<td>150</td>
<td>1</td>
<td>26,000</td>
</tr>
<tr>
<td>eVan Full size cargo van</td>
<td>75</td>
<td>2</td>
<td>3,500</td>
</tr>
</tbody>
</table>

#### 4.2.3 Selection of charge-on-the-stop points (CoSP)

The ‘Charging Infrastructure’ tool, shown in Figure 4.1, uses the logged data and the results of the simulations to select the most appropriate en-route charging points. This includes speed profiles, stop durations, energy consumption figures, etc. for all vehicles performing operations in each case (i.e. bus routes, refuse collection functions and home deliveries). The tool evaluates each position along the route (as described below) and creates a ranked list of all possible charge-on-the-stop points (CoSP). The first available location is selected and the process is repeated until the required number of CoSP is reached (this number was usually used as variable in our analysis). The capacity of the on-board battery and the SOC as a function of distance (saw-tooth profile) is then calculated, based on the proposed charging infrastructure.

![Figure 4.1: ‘Charging Infrastructure’ flowchart to choose CoSP for opportunity charging](image)

The process of ‘Calculate Battery’ (Figure 4.2), calculates the capacity of the on-board battery based on the proposed charging infrastructure. The maximum power transfer capability of each CoSP was set at 200 kW. The required minimum SOC and the maximum allowed charge rate (C) were chosen as 20% and 1.5C respectively for maximising the life span of the on-
board batteries [103]. In every cycle, the energy received is calculated at each CoSP based on the duration of the stop, the maximum C and the power transfer rate. The tool ignores any instantaneous charging boosts and allows half a minute lost charging time due to any alignments requirements and ‘build up’ of power electronics. It also takes into consideration any over-charging situations. If necessary the process is repeated, until an adequate battery capacity has been achieved. The effect of ambient temperature on battery performance is not considered in this study.

![Flowchart](image)

**Figure 4-2: ‘Calculate Battery’ flowchart to calculate the capacity of the on-board battery**

The ranking of each CoSP position is processed by the ‘Rank locations’ calculations, shown in Figure 4-3. In addition to the duty cycles and Advisor’s energy figures, the recommended battery size has to be provided by the user. This allows the tool to get a perspective about an acceptable size of the on-board battery. The value of each \( k_{th} \) location to install a CoSP charger is calculated based on the concept of utility function. This concept has been widely used as a comparison model between various modal choices for transport forecasting [104].

The utility function of each location \( k \)

\[
u_k = w_1 t + w_2 d = w_1 (t_1 + t_2 + \cdots + t_{ith}) + w_2 (d_1 + d_2 + \cdots + d_{ith}) \quad (4-1)
\]
is a function of $t$ and $d$, the variables affecting the choice and $w_i$, the weighting factors for each variable. Variable $t$ and $d$ are both vectors including information for the $i$ vehicles involved. Variable $t$ refers to the stop duration of each vehicle $i_{th}$ at each location $k$. Vehicles stop longer at bus stops and depots which therefore provide suitable locations for the installation of a CoSP. The higher the number of vehicles use the same location the higher its overall priority. Variable $d$ refers to the distance travelled to reach each location. Locations closer to the origin or close enough to other previously selected CoSP get lower priority because they are within the expected mileage range of EVs; which is calculated according to the ‘battery recommended’ value provided by the user. The weighting factors were equally chosen as $w_1 = w_2 = 0.5$.

The process of ‘Calculate battery’ is used to calculate the capacity of the required on-board battery for all EVs performing the investigated route. This takes into consideration any previously selected CoSP and therefore, some vehicles might have already achieved a ‘battery recommended’ capacity. These vehicles get minimum priority and therefore another CoSP is not likely to be introduced along their routes. By contrast, higher priority is given to locations which are used by vehicles that still require batteries larger than the recommended capacity.
4.3 Buses

Buses perform journeys on predefined routes and specified timetables. This allows researchers to analyse precisely the performance of the vehicles and calculate their energy requirements over these journeys. A CoS type charging infrastructure appears to be a promising concept for electric buses in cities. Charging the eBuses en-route reduces significantly the capacity of the battery and mass of the vehicle. Recharging times are also limited but multiple and smaller charging boosts are needed throughout the day.

The five Park and Ride bus routes in the city of Cambridge UK were chosen to investigate the procedure. The routes are the 1) Trumpington, 2) Newmarket, 3) Milton, 4) Madingley and 5) Babraham, which all run within the boundaries of Cambridge, as shown in Figure 4-4. Consequently, only one City Council is needed for the development of a potential charging infrastructure. In addition, the buses, which are all Double Decker, run on relative simple timetables. The ‘Bus graph’ for the Trumpington Park and Ride was obtained from the route operator. This shows the size of the fleet and the duty cycles of each vehicle, including journeys from the depot to the first bus stop. It was a useful guideline for predicting the bus graphs of the other Park and Ride bus routes.

4.3.1 Energy requirements

The author physically rode the buses under investigation and logged the GPS coordinates and speed profiles of the routes using the SRF Logger. The elevation profile was also calculated from the GPS coordinates using Google Maps. The logged drive cycle of the Trumpington Park
An Urban Charging Network: A case study for Cambridge UK

and Ride route is shown in Figure 4-5. The bus departs from the city centre at 10:30 and arrives at the Trumpington Park and Ride stop at 10:47. It then returns back to the city centre after a 3 min stop. The length of this trip was computed at 9.3 km.

The ‘bus graph’ was then derived from publicly available timetable. The graph shows the size of the fleet and the duty cycle of each bus. The Trumpington Park and Ride route involves four buses with up to 220 km maximum mileage per day.

The performance of the modelled eBus (TABLE 4-1) was simulated over the defined duty cycles using Advisor. The average energy consumption of the Trumpington Park and Ride route was calculated at 1.7 kWh/km. TABLE 4-2 summarises the energy requirements of all Cambridge Park and Ride bus routes.

TABLE 4-2: Cambridge Park and Ride bus routes - Drive Cycles and energy requirements

<table>
<thead>
<tr>
<th></th>
<th>Number of buses</th>
<th>Distance per bus (km)</th>
<th>Avg. Speed (km/h)</th>
<th>Energy (kWh/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trumpington</td>
<td>4</td>
<td>9.3 Trip / 220 Max</td>
<td>15.8</td>
<td>1.68</td>
</tr>
<tr>
<td>Newmarket</td>
<td>4</td>
<td>10.5 Trip / 300 Max</td>
<td>18.2</td>
<td>1.42</td>
</tr>
<tr>
<td>Madingley</td>
<td>3</td>
<td>9.7 Trip / 390 Max</td>
<td>18.2</td>
<td>1.55</td>
</tr>
<tr>
<td>Milton</td>
<td>4</td>
<td>12.2 Trip / 325 Max</td>
<td>15.9</td>
<td>1.49</td>
</tr>
<tr>
<td>Babraham</td>
<td>5</td>
<td>12.1 Trip / 335 Max</td>
<td>10.9</td>
<td>1.36</td>
</tr>
</tbody>
</table>

TABLE 4-3 shows the energy requirements per day for each bus route as function of the number of buses on each route. It is noticed that the energy requirements per day varies for each bus on the same route because they perform slightly different daily duty cycles as a result of the bus graphs. The capacity of the on-board battery needed without any charging boosts en-route was calculated based on the most demanding bus of each route. A 20% safety margin was considered for maximising the life span of the batteries. It can be seen that very
large batteries would be needed if there are no CoSPs, particularly for the Madingley route which would need batteries of 755 kWh.

| TABLE 4-3: Park and Rides - Bus fleet, energy requirements and capacity of battery |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
|                                | Trumpington     | Newmarket       | Madingley       | Milton           | Babraham        |
| Energy per day (kWh)           | 1,380           | 1,610           | 1,750           | 1,850            | 2,015           |
| Bus 1                           | 370             | 390             | 605             | 440             | 455             |
| Bus 2                           | 320             | 425             | 540             | 440             | 405             |
| Bus 3                           | 370             | 370             | 605             | 485             | 350             |
| Bus 4                           | 320             | 425             | -               | 485             | 375             |
| Bus 5                           | -               | -               | -               | -               | 430             |
| Battery (kWh)                   | 460             | 530             | 755             | 605             | 570             |

4.3.2 A case study for Trumpington

In this section, the concepts of Overnight Charging (OnC) and charge-on-the-stop (CoS), usually known as ‘opportunity charging’, are investigated through a case study for the Trumpington Park and Ride route. For the former, buses are equipped with a battery big enough to supply the energy requirements for the entire day. The batteries get recharged overnight when the vehicles return back to the depot. In contrast, smaller batteries are used when opportunity charging is available because the buses get multiple small charging boosts during operation from CoSP installed along their routes. The stored energy on-board is shown in Figure 4-6 for both electrification options for the Trumpington Park and Ride route. A 460 kWh battery and a 65 kWh battery are needed for the OnC and CoS approaches respectively. For the CoS solution, a 100 kW charger is installed at either end of the route.

![Figure 4-6: Trumpington Park and Ride - Energy diagrams for the OnC and CoS options where the CoS system has one charging point at either end of the route](image-url)
Both approaches have advantages and drawbacks. The main advantage of the OnC solution is that vehicles do not depend on the infrastructure of the specific route. The bus operator can potentially use the same buses for various routes. However, the large batteries needed introduce significant practical and engineering issues that undermine the feasibility of the system. The specific energy of Lithium-ion batteries predominantly used in EVs is approximately 8 kg/kWh [85]. This means that the 460 kWh battery needed for the Trumpington Park and Ride route (including the 20% safety margin) adds 3 t to the vehicle; reaching an overall mass of approximately 21 t. This assumes a 400 kg saving from the lighter electric motor and transmission system (obtained from Advisor’s components) and a 300 kg saving from not carrying the 300 litre fuel tank of Double-Decker buses. This mass is well above the maximum gross mass of 18 t. As a result, the bus operator would need to reduce the number of passengers on-board to avoid exceeding the maximum load limit. The additional mass of 3 t corresponds to approximately 40 passengers (one deck), assuming an average weight of 75 kg per person. Furthermore, the massive size of the battery imposes technical concerns because the largest battery that has been used in the automotive industry to date is 324 kWh, on the BYD eBuses [105].

The CoS approach eliminates the problems related with the massive batteries. An eBus with the necessary 65 kWh battery on-board would be lighter than a conventional bus by approximately 200 kg (65 kWh X 8 kg/kWh – 400 kg - 300 kg). Having distributed charging also dramatically reduces the charging infrastructure needed at the depot and the charging bottleneck cause by having to charge many buses overnight, as described later.

The number of CoSP and the capacity of the on-board battery is a major trade-off in the design of a charging infrastructure for eBuses. This concept is revealed in Figure 4-7a which shows the number of CoSP installed en-route relative to the capacity of the on-board battery. The size of the battery drops significantly whilst introducing additional CoSP. Yet, it quickly reaches saturation, mainly because the buses only stop long enough for significant charging at either end of their route (see Figure 4-5). The charging boost at other locations is not enough to reduce the capacity of the battery.

The total capital cost of the system was calculated from the cost of EVs and their batteries plus the charging infrastructure, which includes the cost of equipment, installation and grid connection. The purchase and connection of the chargers needed at the depot are considered
as well. Most of the cost figures were obtained from the Milton Keynes Electric Bus project [36]. Additional cost sources were also wireless charging systems that have been commercially available like the INTIS [50], Plugless [51] and BMW systems [52]. The cost assumptions are summarised in TABLE 4-4. The results shown in Figure 4-7b indicate that the most cost effective option for the Trumpington bus route is the installation of two CoSP (one at either end of the route) combined with a 65 kWh battery.

The charging infrastructure of an OnC solution includes only chargers at the depot. The battery energy of the most demanding bus of the route is shown in Figure 4-6 with the dark line. It returns to the depot with 95 kWh stored energy (20% of the 460 kWh battery) where has to get fully recharged within a minimum period of 7 hours, taking into consideration 3 hours for cleaning and maintenance. At least 55 kW power chargers are needed per vehicle at the depot to fully recharge the 460 kWh batteries. The daily power demand profile is shown in Figure 4-8. It is constant at 220 kW for most of the night hours and drops to zero when all

---

**TABLE 4-4: Cost Assumptions for urban opportunity charging**

<table>
<thead>
<tr>
<th></th>
<th>£k</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicles</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>eBus</td>
<td>375</td>
<td>Including a 150 kWh battery, receiving unit and power electronics [36]</td>
</tr>
<tr>
<td>Battery</td>
<td>0.5</td>
<td>Per extra kWh [36], [85]</td>
</tr>
<tr>
<td><strong>Infrastructure – CoSP</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation</td>
<td>20</td>
<td>Per CoSP [36]</td>
</tr>
<tr>
<td>Equipment</td>
<td>0.7</td>
<td>Per kW peak power [36], [50]–[52]</td>
</tr>
<tr>
<td>Grid connection</td>
<td>20</td>
<td>Per CoSP [36]</td>
</tr>
<tr>
<td><strong>Infrastructure – Depot</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chargers</td>
<td>10</td>
<td>Per charger up to 20 kW [36], [40]</td>
</tr>
<tr>
<td>Grid connection</td>
<td>40</td>
<td>Less than 200 kW is needed [36]</td>
</tr>
<tr>
<td>Grid connection</td>
<td>200</td>
<td>More than 200 kW is needed [36]</td>
</tr>
</tbody>
</table>
four buses leave the depot in the morning. Then it gradually increases in the evening as buses return to the depot. An upgrade to the electricity supply at the depot would be needed to meet the additional demand of 220 kW (4 buses X 55 kW).

The CoS infrastructure includes two CoSP at either end of the route and less powerful chargers at the depot. The saw-tooth diagram for this option is shown in Figure 4-6 with the grey line where the vehicle gets multiple charging boosts throughout the day. The two CoSP are rated at 100 kW, since a maximum 1.5C was assumed for maximising the life span of the battery. The bus performing the most demanding route returns to the depot with 27% SOC. 7 kW chargers are needed in the depot to fully recharge the 65 kWh batteries overnight. The power demand profile of this electrification solution (shown in Figure 4-8) is constant at 28 kW at early morning and evening hours when buses are in the depot. Over the day, the power demand is a rectangular wave because the 2 CoSP deliver power intermittently. For the case of Trumpington Park and Ride route this is every 5 min. Each CoSP delivers a maximum power of 100 kW but simultaneous operation at either end of the route demands up to 200 kW power from the electricity network of the city. Although the power demand is distributed at two locations, it is still a considerable additional demand to be delivered. Some work has to be done to connect the chargers with the supply network of the city. The experience from the Milton Keynes Electric Bus project showed that this is not complicated. In addition, no upgrade is required to the electricity supply network of the depot for meeting the additional demand of 28 kW.

Figure 4-8: Power demand of the Trumpington Park and Ride route
OnC is financially less attractive than the CoS approach, mainly due to the capital cost of the massive batteries required on-board (Figure 4-7). However, Figure 4-8 shows that the power demand of the OnC solution may be more favourable for the electricity grid when compared with the demand profile of a CoS system. A constant power is needed overnight when there is substantial grid power availability. It is therefore possible that electricity prices for OnC might be more attractive than prices during the day (due to commercial or government subsidies); a possible incentive for using power overnight to help balance the load on the grid.

To this end, the total costs of an electrified system is calculated, including capital, maintenance and operating costs, to examine whether an OnC system could be financially more attractive than a CoS system due to lower operating costs. The cumulative annual expenditures of an electrified system are shown in Figure 4-9 for three cases: i) OnC based on the current grid electricity price, ii) OnC combined with zero electricity costs and iii) CoS solution (2 CoSP) at current grid electricity costs. The annual expenditures are calculated using the following expression

\[
\text{Annual expenditures} = \frac{\text{Capital cost} \times \text{Rate}}{1 - (1 + \text{Rate})^{-\text{Years}}} + \text{Maintenence cost} + \text{Operating cost},
\]

where a 3% interest rate over a ten-year payment period is assumed. Maintenance accounts 5% of the annual spend on capital cost and operating costs are calculated according to the use and price of electricity. The annual energy requirement for the Trumpington Park and Ride route is about 500 MWh, as the daily energy needed was calculated at 1,380 kWh (TABLE 4-3). This combined with a £0.10 electricity price per kWh result in an annual cost of £50k for operating purposes and £500k over the ten-year period – this was assumed as zero for the second scenario of OnC combined with zero electricity costs. Overall, an electrified bus system for the Trumpington Park and Ride route would cost £3.3 million in total over the ten-year period for the OnC solution, £2.8 million for the OnC solution combined with zero operating costs and £2.5 million for the CoS solution.

1 The Department for Business, Energy and Industrial Energy in the UK estimates that the average cost for every generated kWh would be £0.09 on average after 2020 [146]. This combined with a typical profit margin for supplying electricity in the UK around 5-10% [147], allows us to assume a wholesale price of electricity at £0.10 per kWh.
It is apparent that the potential operating savings from an OnC system, even if electricity is available for free overnight, are not sufficient to reach the lower expenditures of a CoS system. The total expenditure is the same for the two systems when the cost of battery drops from £500 per kWh (used in this study) as low as £100 per kWh. However, BYD, one of the largest manufactures of electric buses with 324 kWh on-board batteries, estimates that the battery cost for heavy-duty vehicles by 2025 would be no less than £445 per kWh [85]. Besides, the OnC buses would have restricted passenger capacity of approximately 40 passengers instead of 90 because of the battery mass. This would require twice as many buses to maintain the same passenger capacity which means that the system would require twice as much energy and would introduce considerable additional capital cost.

4.3.3 City’s Park and Ride bus routes

The same analysis was conducted for all Park and Ride bus routes at Cambridge (Figure 4-7). The results are summarised in TABLE 4-5, for the two electrification options. For the CoS approach, it was found that 2 CoSP is the most cost-effective solution for every bus route. This is because the buses do not stop long enough at locations except the two ends of the route and the cost to install an additional CoSP is higher than the savings from reducing the capacity of the on-board battery. Such a charging infrastructure is shown in Figure 4-4 where a CoSP is installed at either end of each bus route.

The power demand for all Park and Ride bus routes at Cambridge was calculated and shown in Figure 4-10. The daily profiles have similar trends to the power demand of the Trumpington
Park and Ride bus route shown in Figure 4-8. In particular, the peak power demand for OnC of all cities’ Park and Rides buses reaches 1,400 kW during the early morning and late evening hours. It remains zero throughout the day because all the power is needed overnight at the depot. The daily profile of the CoS for all routes shows that 255 kW is needed at the depot overnight. Throughout the day, the power demand fluctuates up to 1,300 kW as multiple CoSP become active at different locations within the city.

**TABLE 4-5: Cambridge Park and Ride bus routes electrification solutions**

<table>
<thead>
<tr>
<th></th>
<th>OnC</th>
<th></th>
<th>CoS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Battery (kWh)</td>
<td>Cost (£m)</td>
<td>Battery (kWh)</td>
<td>CoSP (kW)</td>
</tr>
<tr>
<td>Trumpington</td>
<td>460</td>
<td>2.2</td>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>Newmarket</td>
<td>530</td>
<td>2.6</td>
<td>115</td>
<td>175</td>
</tr>
<tr>
<td>Madingley</td>
<td>755</td>
<td>2.4</td>
<td>130</td>
<td>195</td>
</tr>
<tr>
<td>Milton</td>
<td>605</td>
<td>2.8</td>
<td>265</td>
<td>200</td>
</tr>
<tr>
<td>Babraham</td>
<td>570</td>
<td>3.3</td>
<td>105</td>
<td>160</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>13.3</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The peak power demand of GB was around 53 GW in the winter of 2017-2018 [106]. The city of Cambridge accounts for 0.2% of the total population of the country; 130 thousand people in Cambridge from a total 65 million people [107]. Assuming that the peak power demand at Cambridge is 0.2% of that of GB, the peak power demand of Cambridge is estimated at 106 MW. In addition, the electricity consumption of Cambridge was assumed at an annual 800 GWh. This also corresponds to 0.2% of the total 400 TWh GB’s electricity consumption in 2015 [108].
The new peak power demand up to 1.4 MW, due to the electrification of all Park and Ride bus routes at Cambridge, represents an additional demand of 1.3%. In terms of energy, the electrified Park and Ride bus routes need 8.6 MWh per day, as this can be derived from TABLE 4-3. This corresponds to an annual energy consumption of 3,141 MWh which represents an insignificant additional load of only 0.4% based on current figures.

4.3.4 Carbon emissions savings
Using the eBus model, the fuel economy of an 18 t diesel powered bus was calculated to be 29.4 l/100 km on average when travelling the Park and Ride bus routes of Cambridge. About 2.69 kgCO₂ are produced from burning a litre of diesel fuel [98]. As a result, a conventional 18 t bus emits around 790 gCO₂/km. The eBus model consumes an average of 1.42 kWh/km as this can be derived from TABLE 4-6 (annual energy over annual mileage). Using the carbon intensity of the UK electricity supply network in 2017 of approximately 300 gCO₂/kWh [20], this corresponds to 430 gCO₂/km and a substantial reduction of 45%. Using DECC’s projected CO₂ intensity of 100 gCO₂/kWh [23] for the significantly decarbonized UK electricity grid in 2030, the CO₂ emissions of the 18 t bus would be only 142 gCO₂/km. This corresponds to a very significant reduction of 82%. Using the CO₂ intensity of 40 gCO₂/kWh by 2050 [22], reduction of 92% CO₂ emissions is feasible.

The impact of the electrified Park and Ride routes in Cambridge would be to save 805 tCO₂ per year at today’s emissions rates (see TABLE 4-6). Provided the emission rate for every generated kWh drops from 300 gCO₂/kWh to 40 gCO₂/kWh by 2050, 1,621 tCO₂ per year could be achieved. This corresponds to accumulated savings of 38 ktCO₂, assuming a 2.2% annual increase rate each year between 2018 and 2050.

<table>
<thead>
<tr>
<th>TABLE 4-6: Electrified Park and Ride bus routes annual overview</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Trumpington</td>
</tr>
<tr>
<td>Newmarket</td>
</tr>
<tr>
<td>Madingley</td>
</tr>
<tr>
<td>Milton</td>
</tr>
<tr>
<td>Babraham</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>
4.4 Refuse Collection Vehicles

Various categories of refuse collection operations exist at Cambridge. These are i) Domestic Waste, ii) Trade Waste, iii) Dry Recycling, iv) Green Recycling and v) Bin Deliveries. Different vehicles are assigned to each operation. According to Cambridge Waste Management, each vehicle has a two-week duty cycle. Hence, we investigated each vehicle for a two-week period to record all refuse collection routes at Cambridge and design a charging infrastructure for the entire city.

The refuse collection vehicles of the city are equipped with GPS trackers, collecting real-time operational data. Based on this data, the drive cycles were defined along with information about the bin lift and compaction systems. The Advisor eRCV model (TABLE 4-1) was used for the simulations. A constant load of 2 kW was included in the simulations, of which 0.2 kW was accounted for the bin lift and compaction procedures. The remaining power demand was included for other loads on-board such as safety lights. It was assumed that the vehicle leaves the depot empty (unladen mass at 7 t). The cargo increases progressively during each shift and this can be modelled using data from the monitored bin lift and compaction functions.

4.4.1 Domestic Waste Collection

Eight refuse collection vehicles are assigned to the domestic waste collection operations in Cambridge. Figure 4-11 shows a typical route and drive cycle which was performed on Day 11 by RCV no 2 (the most energy demanding route of the two-week period). There are parts of the route dedicated for driving between collection areas (relatively high speed) and parts of route used for refuse collection (relatively slow speed and multiple start-stops).

Figure 4-11: Domestic route performed on Day 11 by RCV no 2
a) route b) speed profile during operation
The simulation was performed over the defined drive cycles and TABLE 4-7 summarises the energy required for each route during the two-week period.

<table>
<thead>
<tr>
<th>Day 1</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 2</td>
<td>133</td>
<td>50</td>
<td>115</td>
<td>54</td>
<td>66</td>
<td>137</td>
<td>58</td>
<td>613</td>
<td></td>
</tr>
<tr>
<td>Day 3</td>
<td>41</td>
<td>44</td>
<td>58</td>
<td>42</td>
<td>58</td>
<td>79</td>
<td>18</td>
<td>340</td>
<td></td>
</tr>
<tr>
<td>Day 4</td>
<td>44</td>
<td>72</td>
<td>39</td>
<td>55</td>
<td>59</td>
<td>32</td>
<td>105</td>
<td>-</td>
<td>406</td>
</tr>
<tr>
<td>Day 5</td>
<td>34</td>
<td>43</td>
<td>33</td>
<td>42</td>
<td>70</td>
<td>87</td>
<td>-</td>
<td>309</td>
<td></td>
</tr>
<tr>
<td>Day 6</td>
<td>68</td>
<td>-</td>
<td>-</td>
<td>72</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>140</td>
</tr>
<tr>
<td>Day 7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Day 8</td>
<td>115</td>
<td>75</td>
<td>139</td>
<td>71</td>
<td>84</td>
<td>-</td>
<td>-</td>
<td>484</td>
<td></td>
</tr>
<tr>
<td>Day 9</td>
<td>28</td>
<td>70</td>
<td>40</td>
<td>21</td>
<td>102</td>
<td>66</td>
<td>75</td>
<td>-</td>
<td>402</td>
</tr>
<tr>
<td>Day 10</td>
<td>71</td>
<td>39</td>
<td>50</td>
<td>46</td>
<td>66</td>
<td>-</td>
<td>-</td>
<td>272</td>
<td></td>
</tr>
<tr>
<td>Day 11</td>
<td>141</td>
<td>77</td>
<td>34</td>
<td>47</td>
<td>61</td>
<td>51</td>
<td>-</td>
<td>411</td>
<td></td>
</tr>
<tr>
<td>Day 12</td>
<td>60</td>
<td>54</td>
<td>32</td>
<td>53</td>
<td>39</td>
<td>112</td>
<td>-</td>
<td>349</td>
<td></td>
</tr>
<tr>
<td>Day 13</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Day 14</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4,126</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A performance overview of this category was performed to examine the trade-off between the number of CoSP relative to the necessary capacity of the on-board battery. The initial assumption was that any charging en-route had to be accomplished without changing the duration of stops in the drive cycle as measured. With this assumption and by contrast with the Trumpington Park and Ride bus route, the size of the battery does not change significantly with the introduction of additional CoSP. This is mainly because the vehicles do not stop long enough at any common locations where a CoSP would deliver a useful charging boost to all vehicles. Hence, the OnC electrification solution is the most cost-effective option. Such a system involves eight eRCVs with a 180 kWh on-board battery in each, designed to meet the energy requirement of the most demanding route with recharging overnight at the depot.

The required 180 kWh on-battery weights 1,440 kg according to the 8 kg/kWh specific energy. This, corresponds to an extra mass of 800 kg on the vehicle, assuming a 400 kg saving due to lighter electric motor and transmission system and a 250 kg saving from removing the fuel tank (capacity of 250 litres). This means that an eRCV would have lower payload capacity by approximately 800 kg in comparison with a conventional vehicle.

An alternative strategy is to allow the duration of same stops to be increased slightly to make the CoS approach to be a more effective solution. This would allow eRCVs to get a charging
boost along their routes and reduce the size of the on-board battery. Such modifications to the drive cycles of refuse collection operations are less critical than for buses, as RCVs do not follow strict timetables.

The analysis shows that domestic refuse collection operations share common segments of road where a possible CoSP could deliver sufficient energy to a number of eRCVs. The necessary capacity of the on-board battery drops to 80 kWh, requiring a number of stops to be extended by 5 min during the shift. Figure 4-12a shows a possible charging location marked by the circle on the most demanding route of the two-week period (Day 11 performed by RCV no 2). However, this approach might impose practical challenges to existing operations. Depending on the route, it might be necessary to allow 5 min charging boost every time the vehicle travels by the charging location. This would probably not cause difficulty unless a number of different RCVs needed to use the same charger simultaneously, causing queuing delays. Solving this problem would require detailed knowledge of the individual RCV timetables, which should be a topic for further research. The route of Day 11 in particular, includes two outbound-inbound journeys throughout the shift (Figure 4-11b). It is noticed in Figure 4-12b that multiple charging boosts are required throughout the day; even if collection of waste is not always required.

A further alternative would be to allow 5-10 min charging at the depot when the vehicles are unloading, but with no additional stops en-route. This approach reduces the capacity of the on-board battery from 180 kWh to 110 kWh, which is larger than the lowest possible capacity of 80 kWh for CoS. However, it eliminates any practical issues as a single 5-10 min additional
stop duration at the depot would be more attractive for both drivers and logistic operators. The unloading area which is located within the size of the depot (about 500 m from the starting location) is shown in Figure 4-12a marked with the square mark and the energy of the on-board battery for this case is shown in Figure 4-12b.

The three possible charging infrastructures for Domestic Waste Operations, which are the i) OnC, ii) CoS and iii) CoSP at the depot, are compared in TABLE 4-8. The CoS option appears to be the most financially attractive solution without reducing the carrying capacity of the vehicle. The added mass due to on-board battery is compensated by the lighter electric motor, transmission system and fuel tank compared with a conventional vehicle. Yet, it might impose practical challenges that may undermine the efficiency of the system. Charging at the depot during unloading it is further assumed in this study.

TABLE 4-8: Domestic Waste operations – possible charging infrastructure

<table>
<thead>
<tr>
<th></th>
<th>OnC</th>
<th>CoS</th>
<th>CoSP at the depot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery (kWh)</td>
<td>180</td>
<td>80</td>
<td>110</td>
</tr>
<tr>
<td>Depot Charger (kW)</td>
<td>20</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>CoSP (kW)</td>
<td>NA</td>
<td>120</td>
<td>165</td>
</tr>
<tr>
<td>Cost (£m)</td>
<td>3.4</td>
<td>2.9</td>
<td>3.1</td>
</tr>
<tr>
<td>Reduced Capacity (kg)</td>
<td>790</td>
<td>0</td>
<td>230</td>
</tr>
</tbody>
</table>

Overall, an electrified system for domestic refuse collection operations include eight eRCV with a 110 kWh on-board battery. This size reduces the carrying capacity of vehicles by 230 kg (taking into consideration the 650 kg savings), which corresponds to about 1.5 bins of waste (assuming 160 kg apiece\(^2\)). 15 kW chargers are needed at the depot for each vehicle for overnight charging based on a minimum of 7-hour recharging period. If needed, vehicles could get a charging boost from a 165 kW charger during unloading (based on a 1.5C charge rate for the 110 kWh battery).

Such a system is expected to cost £3.1 million, based on the cost assumptions presented earlier in TABLE 4-4 (it is assumed that an eRCV would cost the same as an eBus which is valued at £375k [36]). Indeed, modification of drive cycles combined with the introduction of the CoSP at the depot reduces the overall cost of the system by £300k in comparison with the OnC solution. The cost savings from the smaller batteries are larger than the additional cost needed for the extra charging infrastructure at the unloading area.

---

4.4.2 City’s Waste Collection Operations
The same analysis was followed for all refuse collection operations of the city and the energy requirements, battery needed, capital costs and CO₂ emission savings are summarised in Table 4-9. The OnC solution is best for the Bin Collection operations at the city of Cambridge. The cost for installing a CoSP, even with modified drive cycles, is larger than the potential savings from using smaller batteries on-board (only one vehicle is used). By contrast, the installation of a CoSP at the unloading area combined with an additional stop duration of 5 min is the best solution for Dry Recycling operations. The necessary capacity of the on-board battery is reduced substantially from 160 kWh to 110 kWh. This reduces the overall cost of the system, regardless the additional cost for the extra charging infrastructure at the depot. Green Recycling vehicles can perform all routes with only overnight charging and finally, the introduction of a CoSP at the unloading area of Trade vehicles combined with an additional 5 min stop is financially the most attractive solution for Trade operations. The battery of these vehicles drops from 210 kWh to 110 kWh which results in significant cost savings. In total, three 165 kW CoSP are needed at the unloading areas for Domestic Waste, Dry Recycling and Trade Waste operations.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Annual Energy (MWh)</th>
<th>Annual Mileage (10³ km)</th>
<th>No eRCV</th>
<th>Battery (kWh)</th>
<th>Cost (£m)</th>
<th>tCO₂ savings by 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic</td>
<td>107.3</td>
<td>126</td>
<td>8</td>
<td>110</td>
<td>3.1</td>
<td>129</td>
</tr>
<tr>
<td>Bin</td>
<td>14.7</td>
<td>19</td>
<td>1</td>
<td>110</td>
<td>0.4</td>
<td>19</td>
</tr>
<tr>
<td>Dry</td>
<td>54.5</td>
<td>62</td>
<td>4</td>
<td>110</td>
<td>1.6</td>
<td>64</td>
</tr>
<tr>
<td>Green</td>
<td>32.7</td>
<td>46</td>
<td>2</td>
<td>110</td>
<td>0.8</td>
<td>47</td>
</tr>
<tr>
<td>Trade</td>
<td>124.7</td>
<td>170</td>
<td>9</td>
<td>110</td>
<td>3.4</td>
<td>174</td>
</tr>
<tr>
<td>Total</td>
<td>334</td>
<td>423</td>
<td>24</td>
<td>-</td>
<td>9.3</td>
<td>433</td>
</tr>
</tbody>
</table>

The daily power demand profile was calculated for the most demanding day during the two-week period. This is Day 3 when 23 refuse collection trips are performed across all categories of refuse operations. The profile is shown in Figure 4-13. It is similar to a combination of the OnC and CoS profile of the Trumpington Park and Ride bus route shown in Figure 4-8. The power demand is constant in the early morning and late evening hours when vehicles are recharged in the depot. It fluctuates up to 200 kW during the day when charging boosts are needed during unloading. Although the power demand from a CoSP at the unloading area does not go above 165 kW, it is noticed that 200 kW is drawn from the grid as some power is needed for overnight charging of other vehicles.
The peak power demand corresponds to an additional peak demand of 0.19% of the current power demand of Cambridge. Similarly, the extra load of 334 MWh per year for such a system (TABLE 4-9) represents an additional load of only 0.04%.

![Daily power demand profile for Cambridge refuse collection](image)

**Figure 4-13**: Daily power demand profile for Cambridge refuse collection

The average CO₂ emissions of a conventional 26 t diesel vehicle is around 1,056 gCO₂/km based on the real fuel economy of 39.2 l/100 km (obtained from the operator). The average energy consumption of eRCV was calculated as 0.79 kWh/km (TABLE 4-9). Assuming 300 gCO₂/kWh for the electricity grid (2017 levels), this corresponds to 237 gCO₂/km and represents a significant reduction of 78%. Assuming a decarbonized grid with 40 gCO₂/kWh (in 2050 levels), the impact would be 32 gCO₂/km. This corresponds to 97% reduction of CO₂ emissions in comparison with refuse collection functions by conventional vehicles.

The impact would be to save 347 tCO₂ per year at today’s emissions rates and 433 tCO₂ per year by 2050. This corresponds to accumulated savings of 13 ktCO₂ between 2018 and 2050 (based on a 0.7% annual increase rate each year between 2018 and 2050).

### 4.5 Home Deliveries

In this section, the home delivery operations of two grocery suppliers at Cambridge are explored. A light goods vehicle up to 3.5 t overall mass was monitored for each retailer using the SRF Logger. The Advisor eVan model (TABLE 4-1) was used to calculate the energy requirements over the logged drive cycles. No data was available about the cargo load of the vehicles and therefore, it is assumed that vehicles are half loaded in average throughout the
journey reaching an overall mass of 2.8 t. Moreover, a 2 kW constant load was included in the analysis to model the power drawn from the refrigeration unit.

The results for each vehicle are summarised in TABLE 4-10 over a one-week cycle. It can be seen that Retailer B generally travels further than Retailer A because many of Retailer B’s customers are in nearly villages; whereas Retailer A’s customers are mainly concentrated in the city centre. The delivery van of Retailer A did not perform deliveries on all days over the one-week cycle. In particular, no data was recorded (NR) on days 5-8. The annual mileage and energy requirements of Retailer A were extrapolated based on the available data. Figure 4-14 shows the drive cycle of the most demanding route, performed on Day 3 by Retailer B.

TABLE 4-10: Performance overview of home delivery operations

<table>
<thead>
<tr>
<th></th>
<th>Retailer A</th>
<th>Retailer B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy weekly (kWh)</td>
<td>88</td>
<td>273</td>
</tr>
<tr>
<td>Day 1</td>
<td>26</td>
<td>36</td>
</tr>
<tr>
<td>Day 2</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>Day 3</td>
<td>17</td>
<td>49</td>
</tr>
<tr>
<td>Day 4</td>
<td>23</td>
<td>46</td>
</tr>
<tr>
<td>Day 5</td>
<td>NR</td>
<td>22</td>
</tr>
<tr>
<td>Day 6</td>
<td>NR</td>
<td>17</td>
</tr>
<tr>
<td>Day 7</td>
<td>NR</td>
<td>48</td>
</tr>
<tr>
<td>Day 8</td>
<td>NR</td>
<td>35</td>
</tr>
<tr>
<td>Aver. daily distance (km)</td>
<td>47</td>
<td>63</td>
</tr>
<tr>
<td>Aver. Energy (kWh/km)</td>
<td>0.47</td>
<td>0.55</td>
</tr>
<tr>
<td>Annual energy (MWh)</td>
<td>8.1</td>
<td>12.6</td>
</tr>
<tr>
<td>Annual mileage (10^3 km)</td>
<td>17</td>
<td>23</td>
</tr>
<tr>
<td>tCO2 savings 2018</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>tCO2 savings 2050</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Capital Cost (£k)</td>
<td>220</td>
<td>310</td>
</tr>
</tbody>
</table>

Figure 4-14: Home delivery performed on Day 3 by Retailer B – speed profile
The unladed mass of the vehicle has to be similar when replacing a conventional vehicle with an eVan. This assures that the same amount of cargo could be delivered by both vehicles without violating the upper limit of 3.5 t. In that case, the mass savings from the lighter electric motor and transmission system compensates the mass of the on-board battery. In particular, an eVan is likely to be lighter by 355 kg in comparison with a conventional vehicle, based on a 300 kg saving due to lighter electric motor and transmission system (Advisor) and a 55 kg saving from not carrying the typical 55 litre fuel tank [109]. Consequently, a 45 kWh on-board battery was proposed for eVans, based on the specific energy of 8 kg/kWh.

The OnC electrification option was proposed for the Retailer A. The proposed battery of 45 kWh is sufficiently big to provide the energy needed for the entire day. The batteries SOC do not go below the recommended safety margin of 20% and they get fully recharged overnight at the depot (store). Based on a minimum recharging time of 10 hours (based on the logged data), 3 kW power chargers are needed at the depot for each vehicle.

Up to four delivery vans are used every day, according to the supplier. This means that the power demand at the depot during the night is expected to increase by 12 kW. No upgrade is needed to the electricity supply network of the store for meeting the new additional demand. There is substantial available capacity in the early morning and late evening hours.

The cost assumptions of TABLE 4-4 were used in this section as well. The cost of eVans was assumed as £35k per vehicle\(^3\). An electrified system for Retailer A, which includes four eVans with a 45 kWh on-board battery and four 3 kW chargers for overnight charging, would cost £220k.

As shown in TABLE 4-10, the suggested 45 kWh battery is not adequate to deliver the daily energy needed by the vehicles of Retailer B. The CoS electrification approach has to be adopted for that case using chargers located at the depot. The analysis showed that the installation of one CoSP at the depot would deliver sufficient charging boost to the eVans during loading. Figure 4-15 shows the energy of the on-board battery of the modelled eVan performing the route of Day 3, which was the most demanding day throughout the week,

\[^3\] Based on the Nissan E-NV200 electric light good vehicle which costs £20k [109]. Increasing the battery from 24 kWh to 45 kWh (as it is recommended in this study) would add approximately £10k to the current price \((45 - 24 \text{ kWh}) \times 500 \frac{\text{E}}{\text{kWh}} = £10.5k\). This combined with the installation of a special refrigerated body around £5k, the overall cost of the vehicle would be £35k.
based on OnC and CoS solutions. For the latter case, a CoSP at the depot is used to fully recharge the vehicle during reloading which lasts approximately for 45 min. The power transfer rate of the charger is 68 kW, based on the maximum charge rate of 1.5C. Vehicles return to the depot with SOC levels as high as 80%. 3 kW chargers are needed for each eVan to fully recharge the batteries overnight. The capital cost for this system, including four vehicles plus chargers, was calculated at £310k based on the cost assumptions of TABLE 4-4.

Figure 4-15: Home delivery performed on Day 3 by Retailer B - Battery energy (kWh)
for i) Overnight Charging ii) CoSP at the depot

Retailer B uses up to four vehicles per day. The daily power demand profile is shown in Figure 4-16 which is similar in form to the power demand of refuse collection operations in Figure 4-13. The demand is constant during early morning and late evening hours at 12 kW (4 eVans X 3 kW chargers) and fluctuates up to 76 kW during the day (due to the CoSP at the depot). The additional peak demand of 76 kW represents only 0.07% of the current peak demand of the city. The combined additional load of both retailers was calculated at 21.4 MWh per year as shown in TABLE 4-10. This corresponds to an insignificant load of less than 0.01% based on the current electricity consumption of Cambridge.

The average CO₂ emissions of a conventional 3.5 t diesel vehicle is around 300 gCO₂/km based on the computed equivalent fuel economy of 11 l/100 km. The average energy consumption of each eVan was calculated as 0.51 kWh/km. Assuming 300 gCO₂/kWh for the electricity grid (2017 levels), this corresponds to 153 gCO₂/km and represents a substantial reduction of 49%. Assuming a decarbonized grid with 100 gCO₂/kWh (in 2030 levels), the impact would be
51 gCO₂/km. This corresponds to 83% reduction of CO₂ emissions in comparison with home delivery operations by conventional vehicles. Using the national objectives for 2050 levels, reduction of 93% CO₂ emissions is feasible.

The impact would be to save 5 tCO₂ per year at today’s emissions rates and 11 tCO₂ per year by 2050. This corresponds to accumulated savings of 252 tCO₂ between 2018 and 2050 (based on a 2.5% annual increase rate each year between 2018 and 2050).

Figure 4-16: Home Delivery Retailer B - Daily power demand profile (kW) of the fleet

4.6 City Scale

4.6.1 Routes with available data

In this section, the results are scaled up for the entire city and the implications for the electricity supply network are explored. The impact of a total shift towards electric road freight operations in Cambridge, which involves electrification of all bus routes, refuse collection and home delivery operations, is summarised in TABLE 4-11. This assumes that the explored bus routes, refuse collection and home delivery operations, which were investigated in this study, account 20% (in total 100 buses in Cambridge), 100% and 20% (in total 10 retailers in Cambridge) respectively of all city’s operations.

The current and expected daily power demand profile of Cambridge are shown in Figure 4-17a. The current profile of the city corresponds to 0.2% of the nation’s power demand as described earlier. The base data was obtained from the National Grid website for a typical day in winter 2017 [110]. The shift towards these electric road transport operations would
increase the peak power demand of the city by 6.7 MW. In terms of energy, the additional load was calculated at 16.1 GWh per year. This increase corresponds to 6.3% and 2.0% based on the current figures of power and energy respectively.

| TABLE 4-11: Overview of electric routes with available data at Cambridge |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
|                | Demand          | Annual Load          | ktCO₂ savings          | Capital Cost          |
|                | kW              | % of current        | MWh                   | % of current   | by 2050 | £m    |
| Buses         | 7,000           | 6.60                | 15,705                | 1.96           | 190     | 45.5  |
| Refuse Collection | 200            | 0.19                | 334                   | 0.04           | 13      | 9.3   |
| Home Deliveries | 380            | 0.36                | 104                   | 0.01           | 1.3     | 2.7   |
| Total         | -               | -                   | 16,143                | 2.02           | 204.3   | 57.5  |

The additional power demand of 6.3% does not go beyond the available capacity margin of the city’s supply network. This was assumed to be 10% in accordance to the national supply network which has also 10% capacity margin [90]. Still some upgrade might be needed to accommodate the new power demand and maintain the current capacity margin. Nevertheless, the growth of population in the city, which is projected to be 10.3% by 2030 [111], would add 11 MW to the electricity network of Cambridge. The expected adoption of electric heating would increase the city’s annual consumption of electricity by 120 GWh per year by 2050 [112].

It is also worth mentioning, that electrification of buses using the OnC approach has minimum impact on the electricity supply network of the city. The current and expected daily power demand from such a system are shown in Figure 4-17b, which includes the power demand of electric buses, refuse collection vehicles and home delivery vehicles. Buses get recharged overnight when there is available grid capacity and hence, the additional peak power demand
is limited to only 0.19 MW (0.18% of the current peak). This means that OnC for buses eliminates any implications for the electricity supply network.

However, it was shown earlier that OnC is not a viable option for electrifying the bus routes of the city. Mainly due to the large and expensive on-board batteries and the reduced passenger capacity. Possible adoption of OnC, which would have minimum impact on the grid, is dependent on overcoming these problems. Combination of government incentives such as tax relief, lower operating costs and capital cost support, need to be considered for making OnC more attractive.

The total capital cost required for a charging network for the city of Cambridge was calculated at £57.5 million. Again, this is mainly controlled by electric buses. Nevertheless, this cost is significantly smaller than other infrastructure projects of the city and could be shared between the Cambridge City Council, bus operators and grocery retailers. By comparison, the Cambridgeshire Guided Busway costs £200 million [111] and carries an estimated of 2.6 million passengers a year [113]. By contrast, only the five Park and Ride bus routes carry an estimated of 3.8 million passengers per year [114]. Electrification of these operations would reduce CO₂ emission by approximately 205 ktCO₂ by 2050.

4.6.2 Urban deliveries

Data about urban deliveries was not collected in this study. Some assumptions were made to estimate the performance requirements for an electrified system at Cambridge.

In the future logistics model, it is assumed that Urban deliveries are performed by transportation of goods between urban consolidation centres and stores within the boundaries of cities, as described in Chapter 3. LGVs and HGVs up to 10 t are mainly exploited for this type of services and the journeys are mostly on urban roads. According to road traffic statistics in GB [115], 16.5 billion vehicle miles were travelled by LGVs on urban sections of road and 2.2 billion vehicle miles by HGVs; including various operations such as deliveries to grocery shops, cloth shops, parcel deliveries, etc. Based on the fact that the population of Cambridge is 0.2% of that of GB, it is assumed that 33 million of these miles were travelled by LGVs in Cambridge and 4.4 million miles by HGVs.

The estimated traffic mileage combined with the 0.51 kWh/km energy consumption of LGVs (calculated in section 4.5) and 1.05 kWh/km of HGVs performing urban deliveries (Chapter 3)
result in an overall additional electricity demand of 34,500 MWh per year. This corresponds to 4.3% of the current energy consumption at Cambridge.

The additional power demand from electrified urban deliveries would depend on the exact charging infrastructure of the system which cannot be determined at this stage due to missing information, such as number of vehicles performing deliveries, length of routes, frequency of deliveries, etc. The power demand for eBuses was scaled up to estimate the power demand for electrified urban deliveries. Assuming that the same power usage profile is generated by the urban delivery vehicles as for the eBuses, then the peak power required by the delivery vehicles would be approximately 14 MW (because approximately twice as much energy is required by urban deliveries than eBuses).

This additional power demand corresponds to 13% of current figures. It goes beyond the available capacity margin of the city’s supply network which is assumed to be 10%. This means that a small adoption of electrified urban deliveries is possible in the short-term. A complete electrification of urban deliveries at Cambridge would require an upgrade to the electricity supply network to meet the additional power demand.

The cost needed for an electrified system for urban deliveries was estimated at £91 million based on the calculated cost of £45.5 million for eBuses. Again, this cost is substantially lower than the cost of the Cambridge Guided Busway (£200 million).

The impact from an electrified system for urban deliveries in Cambridge would be to reduce CO₂ emissions by 9 ktCO₂ per year at today’s norms⁴ and by 18 ktCO₂ per year by 2050⁵. An aggregate saving of 430 ktCO₂ is calculated over the intervening period⁶.

4.6.3 Passenger cars

The exact charging network for electric passenger cars in cities is less of concern, mainly because urban trips of this type are fairly short and predicable. According to [116], the

---

⁴ Assuming 33 million miles by LGVs and 4.4 million miles by HGVs; 300 gCO₂/km for a conventional LGV (section 4.5) and 420 gCO₂/km for a conventional HGV (section 3.4.2); 153 gCO₂/km for a LGV (0.51 kWh/km X 300 gCO₂/kWh) and 315 gCO₂/km for a HGV (1.05 kWh/km X 300 gCO₂/kWh)

⁵ Assuming 33 million miles by LGVs and 4.4 by HGVs; 300 gCO₂/km for a conventional LGV (section 4.5) and 420 gCO₂/km for a conventional HGV (section 3.4.2); 20 gCO₂/km for a LGV (0.51 kWh/km X 40 gCO₂/kWh) and 42 gCO₂/km for a HGV (1.05 kWh/km X 40 gCO₂/kWh)

⁶ Based on a constant 2.2% increase in annualised savings between the numbers calculated for today’s norms (2018) and those calculated for 2050
average trip length in urban environments is around 12 km and the energy required for these journeys, around 2.3 kWh\(^7\), could be provided by the capacity of the on-board battery. Besides, a well-developed charging network in cities with chargers installed at houses, offices, etc. would be sufficient for the charging of electric passenger cars in urban environments.

Nevertheless, the additional power demand, electric load and any implications for the electricity supply network are explored in this section to investigate a complete urban charging network at Cambridge. Some assumptions have been made: The average number of people per household in GB is 2.3 people according to national statistics [117]. This, combined with the average 1.3 passenger cars per household provide an estimate of approximately 73,500 passenger cars based in Cambridge. Secondly, the annual average mileage of a passenger car in GB is about 13,000 km, of which 37% are driven on urban roads [115]. This means that the average use of passenger cars on urban roads is about 4,800 km per year. Thirdly, 7 kW plug-in chargers are assumed for recharging, as such systems have been widely used for home charging applications. They offer a simple and relative cheap solution around £1,000 per charger [40].

Initially, the study assumes that the electricity supply network of Cambridge has to provide all the energy needed for the passenger cars of the city, including energy consumed for urban and inter-urban journeys. Based on the average mileage of 13,000 km per year and an average energy consumption of 0.19 kWh/km (as shown in Chapter 6), the additional load from each passenger car was calculated at 2.47 MWh per year. For the city of Cambridge, this corresponds to a substantial increase of 182 GWh per year (500 MWh per day) which corresponds to 23% of the current load consumption of the city which is 800 GWh per year. It is assumed that the additional daily load of 500 MWh is delivered overnight when there is substantial available grid capacity, as shown in Figure 4-17. Assuming an 8-hour recharging period the average power demand added to the system was calculated at 62 MW. This demand goes beyond the available grid capacity by approximately 24 MW which corresponds to about 23% increase. This power demand could not be met by the existing supply network of the city and substantial reinforcement would be needed.

\(^7\) Assuming 0.19 kWh/km average energy consumption of EVs as shown later in Chapter 6
In the long-term, it is expected that a charge-on-the-move (CoM) infrastructure would be available on the nation’s trunk roads to enable electrification of long distance travel. The electricity supply network of cities would therefore, have to provide a smaller proportion of the total energy requirements of EVs and specifically, the energy needed for urban journeys. The energy needed for long distance journeys would be provided by the CoM charging network. The additional load for the city of Cambridge is calculated at 66 GWh per year. This corresponds to 8.3% of the current energy demand. Again, assuming an 8-hour overnight recharging period, the additional power demand for charging passenger cars is calculated at 22 MW. This power demand can be accommodated by the current electricity supply network since there is approximately 38 MW grid availability overnight.

In any case, an electrified system for passenger cars is not a short-term solution. Such a system would need either substantial upgrade to the electricity supply network of cities for meeting the new demand or implementation of a CoM infrastructure at the nation’s trunk roads. Both options involve extensive programmes to be completed at national scale. Besides, the installation of home chargers imposes significant socio-environmental problems that need to be addressed by cities. Not all homes have private parking spaces and therefore, chargers have to be installed on public roads and spaces. This raises significant health and safety considerations.

Nevertheless, the total cost needed for such project is similar to the cost of other city’s projects like the Cambridge Guided Busway. The total cost is calculated at £73.5 million, based on the 73,500 cars and £1,000 per charger figures.

The impact from an electrified system for passenger cars in Cambridge would be to reduce CO₂ emissions by 22 ktCO₂ per year at today’s norms⁸ and by 31 ktCO₂ per year by 2050⁹. An aggregate saving of 870 ktCO₂ is calculated over the intervening period¹⁰.

---

⁸ Assuming 73,500 cars; 4,800 km average annual mileage in cities; 120 gCO₂/km for a conventional car (emissions per km for new cars registered in GB in 2016 [151]) and 57 gCO₂/km for an EV (0.19 kWh/km X 300 gCO₂/kWh [23]).
 ⁹ Assuming 73,500 cars; 4,800 km average mileage range per year; 95 gCO₂/km for a conventional car (emissions per km target by 2020 [151]); 8 gCO₂/km for an EV (0.19 kWh/km X 40 gCO₂/kWh [22])
¹⁰ Based on a constant 1.1% increase in annualised savings between the numbers calculated for today’s norms (2018) and those calculated for 2050
4.6.4 City Overview

Overall, the impact of total shift towards EVs at Cambridge in the long-term, which includes electrification of all bus routes, refuse collection vehicles, home deliveries, urban deliveries and urban travel by passenger cars, is summarised in TABLE 4-12. It is assumed that CoM is available on the nation’s trunk roads for passenger cars and the electricity supply network of Cambridge is responsible to meet the energy requirements for urban travel only. This means that the peak power demand of the city stays the same because the current electricity supply network can meet the additional demand for overnight charging.

The total power demand for the city of Cambridge is calculated at 20.6 MW (19.5% of the current peak) and the additional energy consumption at approximately 117 GWh per year (14.6% of current consumption). The latter is similar to the expected increase of energy consumption due to the adoption of electric heating, which is projected at 120 GWh. Nevertheless, the anticipated installed generating capacity and generation of electricity in GB (and in cities) is estimated to increase by 145% [91] and 200% [108] respectively. This allows a considerable margin for the electrification of transportation.

The total capital cost needed for such a project is calculated at £222 million which is similar to the cost of the Cambridge Guided Busway (£200 million). The impact would be a significant aggregate saving of 1.5 MtCO$_2$ by 2050.

TABLE 4-12: Overview of electric road transportation at Cambridge

<table>
<thead>
<tr>
<th></th>
<th>Demand kW</th>
<th>% of current</th>
<th>Annual Load MWh</th>
<th>% of current</th>
<th>ktCO$_2$ savings by 2050</th>
<th>Capital Cost £m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routes with data</td>
<td>6,600</td>
<td>6.3</td>
<td>16,143</td>
<td>2.0</td>
<td>205</td>
<td>57.5</td>
</tr>
<tr>
<td>Urban Deliveries</td>
<td>14,000</td>
<td>13.2</td>
<td>34,500</td>
<td>4.3</td>
<td>430</td>
<td>91</td>
</tr>
<tr>
<td>Urban Travel</td>
<td>-</td>
<td>-</td>
<td>66,000</td>
<td>8.3</td>
<td>870</td>
<td>73.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>20,600</strong></td>
<td><strong>19.5</strong></td>
<td><strong>116,643</strong></td>
<td><strong>14.6</strong></td>
<td><strong>1,505</strong></td>
<td><strong>222</strong></td>
</tr>
</tbody>
</table>

4.7 Conclusions

A potential charging infrastructure for electric road freight operations was explored in this chapter including the auxiliary services for buses and refuse collection functions. The city of Cambridge UK was chosen for demonstration but the same methodology could be used for other cities as well. In particular, the five Park and Ride bus routes, the refuse collection operations and two home delivery operations were investigated. Real data about existing operations was collected to define accurate drive cycles.
It was shown that the CoS approach appears to be the best solution for electrifying the Park and Ride bus routes of the city. Such a system requires an on-board battery of practical size, charging points at either end of each route and less powerful chargers at the depot to fully recharge the vehicles overnight. The size of batteries, around 135 kWh on average for all Park and Ride bus routes, would have minimum impact on the passenger capacity of the vehicle and on some cases (e.g. Trumpington Park and Ride) the electric bus would be lighter than the conventional vehicle. The additional peak power demand for such a system was calculated at 1,300 kW and the additional consumption of electricity at 3,141 MWh per year. This system would cost £9.1 million and would result to an accumulated CO\textsubscript{2} emission savings of 38 ktCO\textsubscript{2} between 2018 and 2050.

A combination of the CoS and OnC approach was considered to be the most appropriate solution for electrifying the refuse collection operations of Cambridge. In such a system, the 110 kWh on-board battery of vehicle would be large enough to provide all the energy needed for the entire day. Yet, it has a practical size which does not compromise the capacity of the vehicles. For some routes, it would be necessary to recharge the vehicles during unloading at the depot before performing the second part of the shift. It was shown that three 165 kW charging points installed at the depot (one charger for each of the Domestic, Dry Recycling and Trade vehicles) combined occasionally with an additional 5-10 min stop during unloading would deliver sufficient charging boost to the vehicles. The additional peak power demand and additional electrical load per year were calculated as 200 kW and 334 MWh respectively. A total capital cost of £9.3 million was computed for this system and 13 ktCO\textsubscript{2} emission savings are possible by 2050.

For the case of home deliveries, it was shown that a 45 kWh on-board battery would provide the needed energy for the entire day. If needed, a charging point could be installed at the depot (store) and recharge the batteries of the vehicles during re-loading. The new peak power demand was computed as 76 kW for two of the city’s retailers and the additional electricity consumption for both operations was calculated at 20.7 MWh per year. The combined system would cost £0.53 million and would save up to 0.25 ktCO\textsubscript{2} by 2050.

The results were scaled up for the entire city. It was shown that electrification of all bus routes, refuse collection vehicles and home deliveries would increase the peak power demand of the city by 6.7 MW and the electricity consumption by 16.1 GWh per year. This
increase of 6.3% and 2.0% respectively based on today’s figures, is considerably lower than the expected increase due to the growth of population and shifting to electric heating. The total cost to be shared by the Cambridge City Council, bus operators and grocery suppliers is £57.5 million which is substantially lower than other infrastructure projects of the city. Such a system would save up to 205 ktCO₂ emissions between 2018 and 2050.

It was also shown that OnC for electrifying the bus routes of the city eliminates any implications for the electricity supply network. The additional power demand of such a system is limited to only 0.19 MW which corresponds to 0.18% of current figures. However, OnC for the bus routes of Cambridge is not a viable option. Massive batteries would be needed on-board which increases significantly the capital costs of the system. OnC is financially less attractive than the CoS approach even if zero electricity cost is considered for OnC. Besides, OnC buses have restricted passenger capacity and would require twice as many buses to maintain the same passenger capacity. This means that the system would require twice as much energy and would introduce considerable additional capital cost. Possible adoption of OnC, which is particularly advantageous for the grid, is dependent on overcoming these problems. Combination of government incentives such as tax relief, lower operating costs and capital cost support, need to be considered to make OnC a more attractive solution.

An electrified system for urban deliveries at Cambridge was then explored. It was shown that the peak power demand of the city would increase by 14 MW (13.2% of the current peak) and the consumption of electricity by 34.5 GWh (4.3% of current consumption). This means that a small adoption of electrified urban deliveries is possible in the short-term. A complete electrification of urban deliveries at Cambridge would require an upgrade to the electricity supply network to meet the additional power demand. The cost needed for this system was estimated at £91 million. The impact would be an accumulated saving of 430 ktCO₂ by 2050.

The implications from an electrified system for passenger cars were also explored. It was shown that such a system would require significant upgrade to the electricity supply network at national scale. The cost to install the required home chargers was calculated at £73.5 million and the impact would be an aggregated saving of 870 ktCO₂ by 2050.

Overall, the impact of a total shift towards EVs at Cambridge, which includes electrification of all bus routes, refuse collection vehicles, home deliveries, urban deliveries and urban travel
by passenger cars, would increase the power demand of the city by 20.6 MW (19.5% of the current peak) and the energy consumption by 117 GWh per year (14.6% of current consumption). Nevertheless, the anticipated installed generating capacity and generation of electricity in GB is estimated to increase by 145% and 200% respectively. This allows a considerable margin for the electrification of transportation. The total capital cost needed for such a project was calculated at £222 million which is similar to the cost of other city’s projects like the Cambridge Guided Busway. The impact would be a significant aggregate saving of 1.5 MtCO₂ by 2050.
Chapter 5  An autonomous taxi service for future cities

An autonomous taxi service is proposed as part of an integrated sustainable urban transport system for future cities. A critical review is conducted to examine whether the proposed technology can alleviate the negative side effects of urban transportation. The study investigates issues related to environmental impact, social sustainability and required infrastructure. A methodology is proposed to estimate the levels of demand and define the system performance requirements for an autonomous taxi to serve the Biomedical Campus at the University of Cambridge UK. The size of the fleet, the capacity of the on-board battery and a charging infrastructure are suggested. Implications for the electricity supply network are also explored. A financial analysis shows that such a system is financial viable. A similar analysis for the University sites in West Cambridge and North-West Cambridge yield similar conclusions.

5.1 Introduction

Deep decarbonisation of road transportation is a necessary step towards alleviating climate change. It has been recognised that electrification is a viable strategy for achieving this purpose. An urban charging network for Cambridge was explored in the previous chapter and it was shown that transitional strategies include the electrification of bus routes, refuse collection operations and home deliveries. The additional power demand can be met by the current electricity supply network and the capital cost required for implementing such a network is considerably lower than other infrastructure projects in the city. Such a system is capable of delivering substantial environmental benefits in the short-term.

By contrast, the development of a charging infrastructure for passenger cars is a long-term solution. An electrified system of this type would increase significantly the power demand of the city and a substantial upgrade to the electricity supply network would be needed to accommodate the new power demand.

However, use of road vehicles has negative side effects that need to be addressed in the short-term. The largest of these are congestion, accidents with pedestrians and cyclists and limited parking space. The average travelling speed in big cities can be under 15 km/h [118] and 1.2 million lives are lost each year due to road accidents around the world [119]. This, coupled
with the increasing concentration of people in urban environments (up to 70% of the world’s population will be in cities by 2050 [38]) have made the shift towards innovative and more sustainable urban transportation imperative.

Successful mobility management and sustainable transportation requires an integrated urban transport system which incorporates several levels of transportation [120]. New and existing mass transit systems are expected to provide fixed route transport links for the arrival and departure of daily commuters and visitors to cities. If cars were excluded from city centres such systems would decrease traffic congestion and peak time delays on the surrounding public roads. The issue of limited parking would be also addressed effectively. For such proposals to be acceptable, an affordable and effective first/last mile transport service must be provided within the city limits. This service can be provided by underground rail, buses, trams, bicycles and under some circumstances by small autonomous vehicles that can provide flexible and on-demand transportation services within city centre zones, campuses etc. They could provide an alternative solution for commuters that is capable of removing private cars, buses and taxis from city streets.

The problem to be addressed in this chapter is whether an autonomous taxi service could be adopted as a first/last mile service and as an alternative solution for intra-site movements within an existing urban context (city centre zones and campuses). Novel features that might increase market acceptance and social equity over other possible options (i.e. rail, buses, bicycles, etc.) are autonomy, safety, comfort, all-weather operations, accessibility by disable and aged people, connectivity, etc. These features are discussed in following sections.

The city of Cambridge UK has been chosen for demonstration. In particular, the research is focused on three large campus sites of the city, which are the Biomedical Campus, West Cambridge and North-West Cambridge. These sites combine academic, industrial and urban facilities; representing a small-scale city. Expansion of these sites is putting pressure on the surrounding transport network creating both localised congestion and on-site parking problems. Moreover, they provide a closed urban environment within which autonomous vehicles can be segregated from other traffic whilst allowing sufficient access to members of the public for demonstration purposes and for building trust in their operation.
A critical review is presented to examine whether the proposed technology is capable for alleviating the negative side effects of urban transportation. The study aims to address issues related to environmental impact, social sustainability and the required infrastructure. The levels of demand are estimated and then the system performance requirements are defined. A financial analysis is presented to assess the financial viability of an autonomous taxi service on the three campuses.

Legal aspects related to testing and use of autonomous vehicles are not discussed. This is less of a concern because similar projects have been already built and demonstrated around the world [37], [121]–[123].

5.2 Sustainability Assessment

The utilisation of innovative road vehicles is proposed to establish a taxi service which meets the sustainable objectives of future cities. Autonomous Pods (Figure 5-1) are 2-seater driverless vehicles, capable of navigating a route in open space without physical guidance [124], [125]. They are an attractive solution within an existing urban context as a first/last mile transport service within the area of operation. The impact on environment, social sustainability and required infrastructure are explored in this section.

![Figure 5-1: Concept of Autonomous Pods at the centre of Milton Keynes UK](image)

5.2.1 Environmental Impact

One of the most important characteristics of autonomous pods is that they are electric-propelled vehicles. This allows them to offer significant environmental advantages over conventional vehicles. Firstly, significant reduction of CO₂ emissions can be achieved in comparison with conventional vehicles. It was showed in previous chapters that more than 90% reduction of CO₂ is feasible by 2050; provided the current projections for decarbonisation
of the electricity grid are achieved. This will substantially decarbonise the transport sector and help alleviate climate change.

Secondly, electricity as an energy source enables energy diversity. This ensures security of energy supply and a broad use of carbon-free energy sources [21]. Electricity can reduce significantly the constant extraction of fossil fuels to supply the transport sector and therefore prevents depletion of natural resources.

Thirdly, autonomous pods could potentially become part of the electricity supply network. Charging the vehicles’ batteries or utilising their stored energy could be managed in a smart way [126]. This would be particular advantageous for balancing the electricity supply network and would facilitate the penetration of renewable energy sources. Consequently, autonomous pods could help to reduce CO$_2$ emissions associated with the electricity grid.

5.2.2 Social Sustainability

The field of intelligent transport and autonomous vehicles has advanced significantly in the last decade. Some autonomous taxi services have been built and demonstrated around the world. At early stages, ‘Fixed-Path Systems’ were mostly common. These systems run on their own dedicated pathways and some examples are the ‘ULTra System’ at Heathrow Terminal 5 [121] and the ‘2GetThere’ system at Masdar City, UAE [122]. More recently, there has been a lot of interest in ‘Roaming Systems’. These vehicles are capable of navigating a route in open space without physical guidance. An example of this system is the Navya vehicle which accommodates 12 passengers and is currently under trial at several different locations around the world including Switzerland, Singapore and UK [123]. Additionally, smaller and more agile 2-4 seater autonomous pods have been recently used for the ‘LUTZ Pathfinder’ demonstration project at Milton Keynes [37]. Consequently, the technology risk for implementing an autonomous taxi service in the University’s campus is limited as many lessons can be learnt from various trial systems around the world.

A comprehensive research methodology to account behavioural factors affecting the acceptance of autonomous pods has not yet been established. However, they have a number of novel features that increase market acceptance and social equity [124].

One of them is autonomy which allows them to be driverless. The current generation of pods are designed to operate at low speeds in restricted and pedestrianised spaces, free of
conventional vehicles, where the traffic conditions are much simpler than normal city streets. Furthermore, the human error factor on driving tasks, which is the primary cause of all vehicle crashes [75], has been removed. This could lead to increased safety for both passenger, pedestrians and cyclists because reliable technology is responsible for the control of the vehicle. Although, human error is still involved in other parts of the system, such as software development and system design, researchers advocate that this is less of a concern. The technology of autonomous vehicles is advancing continuously through ongoing testing and refining. Moreover, a driverless vehicle removes any necessary interconnections between the driver and the rolling chassis. This, coupled with relative slow travelling speed eliminates the need for ‘crumple zones’ in front of the vehicle. Therefore, the exterior and interior of autonomous pods can be designed in a more flexible way for enhanced attractiveness and comfort. Entry and exit to the vehicle can be from the front or rear instead of the side. This is particularly advantageous for disabled and aged people (see Figure 5-2).

Another fundamental design concept for autonomous pods is connectivity. This enables communication between a vehicle with other vehicles, networks and the environment. It allows pods to collect and process large amounts of data for an improved experience of personal mobility in urban environments. Vehicles could determine their optimal route based on real-time information about possible road blockages, congestion, etc. This would make journeys faster, more predictable and more reliable. Travel time can be useful for other activities such as working or entertainment whilst experiencing the use of a private vehicle.
New service facilities are also feasible. Call on demand, automating pickup/drop-off transactions and door-to-door journeys would increase the attractiveness of the system.

Finally, air pollution is less of a concern for the proposed taxi system. Autonomous pods offer zero tailpipe emissions, eliminating the release of noxious pollutants. This, coupled with low operation noise make them an attractive and enjoyable solution for urban areas.

5.2.3 Infrastructure needs

In autonomous pods the conventional mechanical systems of road vehicles - the drive train, steering and braking systems - are replaced by more compact, flexible and automated electric systems. This reduces significantly the size and mass of the vehicle (see Figure 5-3a). They can run without any purpose-built infrastructure and this combined with low travelling speeds up to 20 km/h (12 mph) allows them to coexist with pedestrians and cyclists within an existing urban context. Even folding autonomous pods are possible for reducing the space needed when they are parked (see Figure 5-3b). This could be an attractive feature for cities where parking space is limited and expensive.

Autonomous taxi services could be a retrofit solution to an urban transport system through addition of local charging infrastructure, but not much else. Non-conductive (wireless) power charging systems for electric vehicles have been under development for some time [43]. The ability to avoid plug-in cables and to use simple low-profile systems that are unaffected by weather conditions is likely to be attractive for urban environments. Electricity distribution networks may need to be upgraded to deal with the increased future demand but the technology and expertise have been available for some years.

Figure 5-3: Autonomous Pods infrastructure needs [124]
a) Size comparison between an autonomous pod and other road vehicles b) Folding the autonomous pod
5.3 Levels of Demand

In this section, the levels of demand for an autonomous taxi service are estimated. Autonomous vehicles are still in the early stages of testing and therefore, a demand forecasting methodology has not been established. Nevertheless, the analysis is based on the main principles of transport planning [127] combined with personal judgement and realistic assumptions particular to the city of Cambridge. The first step was Trip Generation for forecasting travel demands. Then, Trip Distribution for matching trips’ origins and destinations and finally, Modal Split analysis for determining the degree of satisfaction to use an autonomous pod instead of other mode choices. The Biomedical Campus (Figure 5-4) was selected to illustrate the analysis but the same methodology could be used as a framework to estimate the levels of demand of similar systems in other areas as well.

![Figure 5-4: Biomedical Campus Site map and on-site access [128]
Figure not to scale – approximate area 1,100 m X 750 m (0.8 km²)](image)

5.3.1 Trip Generation

The first stage was to estimate the number of trips made in the Biomedical Campus. Three type of journeys were considered in this study. Category A includes trips generated by workers, Category B includes trips generated by visitors for business purposes (including outpatient appointments and hospital visitors) and Category C includes trips generated by
people who visit the site for leisure purposes. Access to reliable information about numbers of residents, numbers of workers, students, outpatient appointments, etc. was essential to calculate the number of trips generated. It is noted that there are significantly more Category A trips than Category B and C trips. Sources of data were the University of Cambridge Estate Management and Cambridge University Hospitals NHS Foundation Trust [129]. Our assumptions include: 15,000 working population by 2020, 1,000 bed spaces for students and key workers’ accommodation and about 3,000 visitors per day, of which 2,900 are visitors for business purposes. The remaining are visitors for leisure purposes.

The number of generated trips was also combined with travel data for creating daily profiles. Figure 5-5 shows the daily profiles (percentage) for the three categories investigated in this study. UK National Travel data was used for Category A and Category C [130] whereas online data about the arrival pattern of patients to the Prince of Wales Hospital in Hong Kong was used for Category B trips [131]. The Prince of Wales Hospital is a large public and teaching hospital. (It was the only major hospital for which this type of data was available. No equivalent data was available for a UK hospital.) It is therefore assumed that the arrival pattern of patients of the Biomedical Campus is similar to that in the Prince of Wales Hospital. A scale factor of 30%, 30% and 110% (based on personal assumptions) was applied for the generated trips during weekends for Category A, Category B and Category C respectively.

![Figure 5-5: Daily profile of trips generated in the Biomedical Campus](image)

5.3.2 Trip Distribution
The geographic area of interest was divided into zones for distributing the trips and identifying the traffic flows. Although the matching of origins with destinations was performed rather qualitatively, the analysis was based on a comprehensive overview of the site regarding
An autonomous taxi service for future cities

concentration of job positions, location of medical and community buildings, transport access to the site, parking places and provision of other public transport services. A site map of the site which shows the zones of Trip Distribution is shown in Figure 5-6. For this particular example, Zone A is the destination for 3,750 Category A trips (based on 3,750 job positions in the zone); 15% of which originate from zones A and B, 10% from zone C, 25% from zone D and 35% from zone E.

![Site map of the site showing zones of Trip Distribution](image)

**Figure 5-6: Biomedical Campus Trip Distribution process**

### 5.3.3 Modal Split

A modal split analysis was performed to calculate the number of people who would use an autonomous pod instead of walking, cycling or taking the bus. The process was based on the concept of utility function which allows the comparison of mode choices based on various modal features [104]. The utility function \( u_k = a_1X_1 + a_2X_2 + a_3X_3 \) for travel mode \( k \) is a function of \( X_i \), the variables affecting modal choice and \( a_i \), the weighting factors for each variable. Three main features were chosen to assess the mode choices. These were the Travelling Time, Waiting Time and Price whose weighting factor was chosen as -0.16, -0.30 and -0.54 respectively; using the Analytical Hierarchy Process (AHP) technique [132]. The negative signs are due to the negative impact of each variable on the mode’s value.

The AHP method is a tool to help decision makers to rank alternative options through a comprehensive and rational framework. This method enables evaluation of the elements of the problem by comparing them to each other two at a time. Rather than concrete data, the decision makers typically use their judgements about the elements’ relative strength of preference [133]. This study assumes that (i) Waiting Time is moderately more important than
Travelling Time, (ii) Price is strongly more important than Travelling Time and (iii) Price is moderately more important than Waiting Time for choosing a travel mode.

The primary travel mode of travellers was also considered during mode choice because it influences the possibility of shifting to a different mode of transport for in-site movements. For example, people who use the bus for journeys to the Biomedical Campus will probably not choose another mode of transport for in-site movements if a bus stop is available near to their final destination. Data about the primary travel choice for journeys to the campus, including Bicycle, Motorcycle, Car, Bus and Walk, was obtained from the Cambridge University Hospitals NHS Foundation Trust. Any other factors affecting the demand for a possible autonomous taxi service, such as weather conditions, student populations, proportion of elderly residents, etc., were not considered in this study.

Overall, the levels of demand for a possible autonomous taxi service on the Biomedical Campus are shown in Figure 5-7 for weekdays and weekends separately. The number of people demanding autonomous pods during the weekends is significantly lower than the weekdays. Mainly because there are less Category A trips for workers traveling to their jobs.

It is noticed that 396 people would require an autonomous pod during peak hours. This, corresponds to 276 pod-trips (trips performed by autonomous pods) per hour; assuming occupancy ratio of autonomous pods at 1.5 for Category A journeys (i.e. 1.5 people on average in a pod), 1.0 for Category B and 1.5 for Category C journeys. The levels of demand of an autonomous pod operation on the Biomedical Campus are summarised in TABLE 5-1.
TABLE 5-1: Levels of demand for autonomous pod operation on Biomedical Campus

<table>
<thead>
<tr>
<th></th>
<th>Weekday</th>
<th>Weekend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak people per hour</td>
<td>398</td>
<td>119</td>
</tr>
<tr>
<td>People per day</td>
<td>2,778</td>
<td>833</td>
</tr>
<tr>
<td>People per year</td>
<td>808,912</td>
<td></td>
</tr>
<tr>
<td>Peak pod-trips per hour</td>
<td>276</td>
<td>130</td>
</tr>
<tr>
<td>Pod-trips per day</td>
<td>2,195</td>
<td>1,076</td>
</tr>
<tr>
<td>Pod-trips per year</td>
<td>682,604</td>
<td></td>
</tr>
</tbody>
</table>

5.4 System Performance Requirements

Based on the levels of demand, the performance requirements can be defined for a practical system. The size of the required fleet, the capacity of the on-board batteries and the charging infrastructure are determined in this section. Potential impacts on the electricity supply grid are also explored.

5.4.1 Size of fleet

The number of autonomous pods required to meet the demand is firstly calculated. It was found that a pod can perform up to 5 trips in an hour; taking into consideration the average time needed for each pod-trip (calculated as 3.6 min), additional time needed for embarking and disembarking the vehicle (assumed as 3 min) and any time needed to travel between dropping-off one passenger and collecting the next customer (assumed as 1.8 min – half time of an average trip). A conservative 50% safety margin was also included in the calculations to allow circumstances of unexpected high demand, vehicle failure, etc. Congestion delays are less of a concern because the use of private cars is prohibited within the campus. In total, this model assumes a maximum waiting time of 5.4 min at peak period.

The number of pods required through the day can be therefore, calculated by dividing the demanded pod-trips by the 5 trips per pod figure. The results are shown in Figure 5-8. A fleet of 57 autonomous pods is needed to serve approximately 400 people at peak times (7am-9am) and a total number of 2,778 people per weekday.
Although a central parking and maintenance area is likely to be designated, it is expected that autonomous pods will be distributed within the area of service. This allows vehicles to be closer to customers and therefore, minimise waiting times for customers and energy consumed. The number of autonomous pods required in each zone of the site throughout the day can be calculated by the Trip Distribution and Modal Split processes.

The small size of autonomous pods combined with folding features (see Figure 5-3) reduce significantly the space needed when they are parked. It is therefore expected that such a system will not significantly affect parking availability within the area of service. Indeed, an autonomous taxi service could provide an alternative solution for commuters that is capable of removing private cars, buses and taxis from city streets. This would improve significantly parking availability.

5.4.2 Energy requirements – Battery Capacity

The average energy consumption of pods was assumed at 0.12 kWh/km (0.2 kWh/mile) according to the project findings of the Milton Keynes Autonomous Pod trial [37]. This means that the energy consumption of each pod-trip was found to be 0.22 kWh, of which 0.15 kWh is for the actual distance driven for the trip which was calculated at 1.25 km in average (3 min travelling time at an average speed of 20 km/h). The remaining energy of 0.07 kWh was added for any distance travelled to pick up a customer (0.6 km - 1.8 min travelling time).

The total number of pod-trips in a weekday was calculated at 2,195 (TABLE 5-1). Each autonomous pod is therefore responsible for 40 trips per day assuming a fleet of 57 vehicles. This, combined with the 0.22 kWh energy consumption per trip means that the total energy required for a day is 8.8 kWh per pod.
The analysis assumed that an autonomous pod is charged once per day, although smaller and frequent charging boosts could be possible throughout the day. The battery should therefore provide all the energy required for the day. A 11 kWh battery is suggested, taking into consideration a minimum discharged level of 20% for maximising the life span of the battery.

5.4.3 Power demand

Data about the power demand of the Biomedical Campus were obtained from the Estates and Facilities Management. Average power demand profiles for weekdays and weekends are summarised in Figure 5-9. Summer and winter figures are presented separately to explore any alterations due to heating/air-conditioning load. The base data was logged on the weeks starting 12 July 2016 and 12 December 2016.

![Figure 5-9: Daily power demand at the Biomedical Campus](image)

5.4.4 Charging Infrastructure

The charging infrastructure for such a system is calculated in this section. It is noticed in Figure 5-9 that there is substantial decrease of power demand during the evening and early morning hours (between 5pm-7am). This offers a substantial capacity margin of 1-3 MW for charging the batteries of autonomous pods, without increasing the peak power demand of the site.

A 1C charge rate is advised for Lithium-Ion batteries, normally used in automotive vehicles, for maximising their life span [103]. This means that a minimum 60 min charging time is needed for each vehicle using a 11 kW charger. Based on the 14-hour charging period (between 5pm-7am), a charging infrastructure with 5 chargers is needed to deliver the energy requirements of the proposed taxi service at the Biomedical Campus, which includes 57 vehicles.
It is expected that the waiting times do not change during the charging hours. Only five vehicles per hour are reserved for charging overnight which means that the rest of the fleet is fully functional. There are 52 available pods every hour and no more than 10 pods per hour are needed overnight as shown in Figure 5-8.

Installing more than five chargers can be shown to be an inferior approach. The additional power demand of the charging system increases proportionally with the number of installed chargers. The utilisation time of each charger also decreases because a single charger serves fewer vehicles. Most importantly, the cost of the system rises due to the installation of multiple charging stations which involves higher capital costs (purchase of chargers, cables, etc.) and civil engineering expenses (integrating chargers with the infrastructure, connecting charging point to the electricity distribution network, etc.).

5.4.5 Implications for the grid
The additional power demand of the proposed autonomous taxi service at the Biomedical Campus was calculated at 55 kW (5 chargers at 11 kW apiece). Charging the vehicles during the evening and morning hours (5pm-7am) does not go beyond the minimum available capacity margin of 1-3 MW. It is also possible that vehicles get recharged throughout the day when the demand for pods and the power demand of the site are both lower than peak. The peak power demand of the campus stays unaltered and therefore, no upgrade of the electricity supply is needed to accommodate the new demand.

The energy demand of the proposed autonomous taxi service was calculated at 150 MWh per year based on 682,604 pod-trips per year (as shown in TABLE 5-1) and 0.22 kWh energy consumption per trip. This additional load corresponds to less than 0.17% of the current energy consumption at the Biomedical Campus which stands currently at approximately 90,000 MWh per year; based on data obtained from the Estates and Facilities Management.

5.5 Financial Analysis
In this section, a financial analysis is presented to explore the financial viability of the proposed system. The assumptions used for the cost model are divided into capital and operating costs and summarised in TABLE 5-2. The former category includes costs for the vehicles, supporting systems and any infrastructure modifications, including installation of chargers. Furthermore, there will be significant staff costs associated with fleet operations
An autonomous taxi service for future cities

(customer care, vehicle allocation and dispatch, etc.), safety and security staff, technical support, cleaning, maintenance, etc. It was assumed that an employee would be needed for every four vehicles. There would also be further recurring costs such as electricity and maintenance. The derived cost figures were based on similar autonomous taxi services that have been already built and demonstrated around the world [37], [121]–[123]. The technology is still in the early stages and any additional market data was not available. Although the costs involved with a demonstration project might not always reflect the actual costs of a real system, they do not undermine this study which aims to examine whether such a system could be financially viable rather than developing an accurate business model.

<table>
<thead>
<tr>
<th>TABLE 5-2: Cost model assumptions for an autonomous pod operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost Variables</td>
</tr>
<tr>
<td>Capital Costs</td>
</tr>
<tr>
<td>Autonomous pods</td>
</tr>
<tr>
<td>Supporting systems</td>
</tr>
<tr>
<td>Charging Infrastructure</td>
</tr>
<tr>
<td>Operating Costs</td>
</tr>
<tr>
<td>Staff wages</td>
</tr>
<tr>
<td>Per km driven</td>
</tr>
<tr>
<td>Maintenance</td>
</tr>
</tbody>
</table>

5.5.1 Biomedical Campus

An economic analysis of the break-even ticket price showed that payback period less than five years is possible for a £2 ticket price. A balance sheet for the first ten years of operation is presented in TABLE 5-3. It was assumed that the annual demand of pod-trips increases according to the growth rate as listed in the second row of the table. Any additional pods, charging infrastructure expenses, maintenance, staff, etc. were recalculated based on the new demand. Alternative revenue streams (such as income from advertisements), and costs such as salary increases, upgrades to the pods, insurance costs and billing methods were not considered in this study. They could be included in a future financial appraisal.

It is shown in TABLE 5-3 that such a system could return positive profits of approximately £6 million over the ten-year period. This means that an autonomous taxi service for the Biomedical Campus could be either privately funded or provided by the local authority at an overall profit.
The effect of ticket price on demand and the financial viability of the system were also investigated. Figure 5-10 shows the number of pod-trips per hour during peak time for various ticket prices. As expected, the number of pod-trips per hour during peak times is reduced when the ticket price increases. Higher ticket price reduces the ‘value’ of the mode according to the utility function which means that the use of autonomous pods is less desirable among the other mode choices. By contrast, the demand for pod-trips increases when the ticket price is lower. For each ticket price, the size of the fleet was recalculated to meet the demand of pod-trips during the peak hours. The methodology of section 5.4.1 was followed in this section using the same assumptions (i.e. traveling and waiting times).

Figure 5-10: Biomedical Campus – Peak Trips per hour relative to ticket price

TABLE 5-4 shows the results of the sensitivity analysis. It is shown that the payback period of the system is less than five years when the ticket price is at least £2. Positive net profit is possible within the first year of operation for more than £2 ticket price.
5.5.2 West Cambridge

The levels of demand for a possible autonomous taxi service on the West Cambridge site (Figure 5-11) were estimated in conjunction with a financial appraisal of that scheme. The methodology developed for the Biomedical Campus was applied for this case as well.

Representative figures for the new area were employed. In particular, the study assumed 15,000 workers, 750 visitors for business purposes and 800 visitors for leisure purposes per
day [135]. As expected, fewer visitors for business purposes were considered for the West Cambridge site in comparison to the Biomedical Campus. By contrast, the number of visitors for leisure purposes is larger for the case of West Cambridge where the sport facilities might be an attraction to students and workers. The number of generated trips, including Category A, B and C tips, was combined with trip distribution data from the UK National Travel [130].

The ticket price is shown as function of the number of pod-trips in Figure 5-12. The net profit of an autonomous taxi service in the site of West Cambridge was estimated at £792,000 for the first year and £6,087,000 for the fifth year of business based on a £2 ticket price. The number of required pods for such a scheme would be 34 and 52 for the first and fifth year respectively. It is noticed in the figure that payback period in less than five years is also possible for a £1 ticket price.

![Figure 5-12: West Cambridge site – Peak Trips per hour relative to ticket price](image)

### 5.5.3 North West Cambridge

Similarly, the number of peak trips per hour relative to ticket price is shown for the North-West Cambridge site in Figure 5-14. For this site 4,500 workers, a residential population of 7,000 people and 4,000 visitors per day for both business and leisure purposes were assumed [136]. The increased number of visitors is justified by the large residential population and in-site facilities including school, hotel, convenience stores, etc.

The net profit of an autonomous taxi service operating on the North-West Cambridge site was estimated at £199,000 for the first year and £1,616,000 for the fifth year of business based on a £2 ticket price. The number of pods required for such a scheme would be 9 and 13 for the first and fifth year respectively.
An autonomous taxi service for future cities

5.6 Conclusions

An autonomous taxi scheme was proposed as a sustainable urban transport system for three campuses of Cambridge University. Such a system could be part of an integrated urban transportation system capable of addressing the current issues of urban transport. It offers a complimentary service to mass transit systems by providing an affordable solution for any first/last mile transport requirements and an alternative solution for any random intra-site movements within the area of operation. A critical review showed that such a system could deliver environmental benefits and improve the experience of personal mobility in closed urban environments. A methodology was proposed to estimate the levels of demand of such a system and set the performance requirements. The methodology was presented through a case study of the Biomedical Campus at Cambridge but it could be considered as a comprehensive framework for similar systems in other areas as well.
For the Biomedical Campus, it was shown that a fleet of 57 vehicles would be needed to serve a total number of 2,778 people per day. The capacity of the on-board battery was found to be 11 kWh and a charging infrastructure of 5 chargers at 11 kW was suggested to deliver the energy requirements of the system. The additional power load was calculated at 150 MWh per year which corresponds approximately to 0.17% of the current energy consumption at the Biomedical Campus. The peak power demand of the site would be unaltered, provided charging of the vehicles is performed between the evening and morning hours. A financial analysis showed that such a system is financially viable and a payback period in less than five years is possible for a £2 ticket price. For greater ticket prices, positive net profit is possible from the first year of operation. Similar results were obtained by applying the methodology to the West Cambridge and North-West Cambridge.
Chapter 6 A National Infrastructure for Charge-on-the-move: An appraisal for GB

This chapter investigates the performance requirements of a national power infrastructure suitable for implementing charge-on-the-move. From an estimation of electric vehicles’ power requirements in conjunction with Great Britain’s road traffic data the anticipated power demand is expected to be increased by 16 GW. A simulation tool is proposed to investigate the application of dynamic charging and the effects of system design variables. Based on that, a possible charging layout is suggested using the IPT technology. Such infrastructure involves 30 kW chargers, 3 m in length, installed every 4.2 m on motorways and 8.6 m on rural sections of road. Conceptual power distribution configurations are developed and then an economic model is built to examine the cost needed per km of road. The results are combined with road traffic and road length data to calculate the proportion of car-miles covered relative to the size of the charging infrastructure. Cash flow figures are produced for a charging network suitable for passenger cars, freight vehicles and both type of vehicles. The Overhead Catenary technology is also considered for freight transportation. Overall, it is shown that a national infrastructure of this type could result in positive net profits for most of the examined scenarios. Indeed, a charge-on-the-move infrastructure available on the motorways and rural sections of ‘A’ roads of the country would enable the electrification of long-haul operations and 86% of all car-miles. The capital cost required for this system is calculated at £114-128 billion depending on the technology, which is similar to the cost of other national large infrastructure projects. It would result in an annual profit margin of 30-34% and the impact would be a significant aggregated saving of 1,230 MtCO₂ emissions by 2050.

6.1 Introduction

It has been generally accepted that decarbonisation of the transport sector is a necessary step towards alleviating climate change. The shift towards electric vehicles (EVs) has been identified as one of the most beneficial approaches for achieving this target since significant reduction of CO₂ emissions in comparison with conventional vehicles can be achieved. In addition, EVs offer zero tailpipe emissions, eliminating the release of noxious pollutants.
Aspirations for better air quality coupled with low operational noise make EVs an attractive solution, particularly for urban areas.

Indeed, an urban charging network was explored in Chapter 4 for electric road transport operations. Such a network is considered to be technically feasible, financially viable and could deliver substantial CO₂ emission savings by 2050. Additionally, an autonomous taxi scheme was explored in Chapter 5. It was shown that this system could be adopted as an alternative transportation service for current and future cities and play a significant role for reducing usage of private cars and related emissions.

However, long-haul freight operations are responsible for 17% of the total road transport emissions [4] and 64% of all car-miles in GB are travelled on motorways and rural sections of roads [115]. If substantial progress is to be made towards a significantly decarbonised road transport sector, a radical solution has to be proposed for long-haul freight operations and ubiquitous use of EVs for long distance travel. It would be impractical, and too expensive, to carry batteries on-board for long distance freight journeys. The cost weight and range of EV could all be improved significantly if energy was provided to the vehicle in motion.

Charge-on-the-move (CoM), also known as dynamic charging, is considered to be a key enabling factor in moving towards the widespread use of EVs for long distance travel. It is an idea whereby the road infrastructure will be capable of transferring energy to EVs whilst they are on move. The technology offers the opportunity for substantially reducing the installed battery capacity of EVs, thereby eliminating ‘range anxiety’ and reducing the vehicle purchase price and mass, which are some of the major barriers to increasing use of EVs [24, 25].

Previous work showed that a nationwide charging infrastructure of this type in Great Britain (GB) could be a key enabling factor in moving towards EVs and a significant driver for substantial CO₂ emissions reductions in the near future [53, 54]. Additionally, a feasibility study conducted by the Transport Research Laboratory (TRL) highlights that shifting towards EVs could be accelerated by the wide availability of CoM at national scale [60].

Overhead Catenary systems (OhC) provide a technology for charging electric freight vehicles on the move. Similar technology has been used for years for powering trams, trains, and trolley buses, but has recently been applied to EVs. Siemens has been developing a catenary system for electric lorries since 2011 as part of the ENUBA research project [62]. Electric
trucks could collect electrical energy from overhead wires, using a sophisticated pantograph system that can connect and disconnect autonomously as the vehicle enters and exits electrified sections of road.

The technology has been built and demonstrated around the world including, for example, the Californian city of Carson US near the ports of Los Angeles and Long Beach [63]. The cost needed per km of road for developing a CoM infrastructure based on the Siemens OhC system was obtained after personal communication with Patrik Ackerman, a Business Developer of the SIEMENS’ eHighway System. This was confirmed at £1.2 million per km of motorway (per direction) including costs for overhead wires, supporting poles, and reinforcement of the electricity supply network (to meet an additional power demand of 3 MW per km).

A CoM infrastructure for passenger cars (and potentially for freight vehicles) could be implemented using Inductive Power Transfer (IPT) charging devices. The technology of IPT has advanced significantly over the last few years. A typical IPT system comprises two major subsystems: road charging units and vehicle charging units. Energy is transferred wirelessly between the two parts of the system when they are in proximity to each other. High efficiencies, over 90%, can be obtained for static charging applications [43], [99], [100] and similar efficiencies are expected to be achieved for dynamic charging as well [58], [59].

However, the integration of IPT road charging units with the road infrastructure on a national scale needs more comprehensive consideration. The report ‘Preparing the strategic road network for increased use by electric vehicles’ is a first of its kind comprehensive analysis for introducing CoM on the roads of GB [60]. The study covers topics of stakeholder engagement; functional requirements (such as review of IPT systems and identification of other services provided using IPT technology); performance requirements (such as installation of CoM equipment on vehicles and construction methods of installing CoM); and process requirements of a CoM infrastructure (such as power demand requirements of vehicles and charging layouts). The report also makes recommendations on future trials and identifies potential economic, social, and environmental impacts of the technology.

Additional system level studies include a cost effectiveness analysis of electric transit buses in Minneapolis, Minnesota [70] and a feasibility analysis on a dynamic charging system for electric buses in California [71]. It was generally shown that the exact requirements, costs and
benefits of a CoM infrastructure will depend on the specific application of dynamic charging and the final specifications of the IPT technology, which is advancing drastically. Additional significant factors include market acceptance, EVs uptake scenarios, future policies, possible funding schemes, business models, etc.

This chapter provides an overall understanding of the challenges of the CoM technology at the level of the system. It should be considered as a preliminary study towards the implementation of CoM at national scale. It is based on current traffic data and current/expected technical specifications of IPT and OhC systems to outline the requirements of a national power infrastructure for deployment of CoM. More detailed studies focusing on different regions of the country, local traffic and driving patterns, environmental/social factors and alternative economic cost models should be conducted in the future.

6.2 System Characterisation

Initially, the study aims to outline the system performance requirements of a CoM national infrastructure. Tools and procedures are proposed to calculate the power requirements of EVs and set the baseline of the anticipated power demand on the roads of GB.

The ‘Advanced Vehicle Simulator’ (Advisor) was used to estimate the power requirements of EVs. A medium-sized car was firstly modelled and its main vehicle components include a 75 kW electric motor, a 30 kWh on-board battery and 1,500 kg overall mass. Although various size cars are available, including small and large SUVs, this study assumes that all passenger cars have a medium size.

The simulation was performed over a variety of drive cycles including standard and real drive cycles. The SRF Logger (described previously) was used to define real drive cycles whilst driving on a variety of road types in private cars. The elevation profile was determined for each drive cycle and included in the analysis as well. The aim was to record drive cycles in different regions and times of the day to identify any potential discrepancies on power requirement and energy consumption. The outputs of the simulation are summarised in TABLE 6-1 and showed that the average power requirements are 20.3 kW, 11.2 kW and 4.3 kW for travelling on motorways, rural sections and urban sections of road respectively. Any differences on power requirements across the regions of GB were considered to be insignificant and therefore, were not considered further in this study.
According to national statistics, the average length of a journey in urban roads is about 12 km [116]. This corresponds to 2.3 kWh assuming the average energy consumption of 0.19 kWh/km as shown in TABLE 6-1. The on-board battery capacity would be sufficient to satisfy the needs of EVs on urban roadways. Charging of EVs in urban environments might be facilitated by a well-developed home and/or public infrastructure without the need of a CoM infrastructure. Even if drivers have some stretch of urban roadway to reach a motorway or a rural section of road, the CoM infrastructure on the motorway would allow a constant or increasing state of charge. CoM is therefore considered only for motorways and rural roads.

The calculated power requirements of EVs were combined with GB traffic data in order to estimate the power demands from the power infrastructure. Average daily traffic flow statistics for cars travelling on various roads were obtained from the Department for Transport (DfT) in GB [39]. The base data gives the number of vehicles per day that will drive on a specific stretch of road on an average day of the year. The number of vehicles per day was divided by 24 to obtain vehicles per hour. Then, the computed figure was divided by the speed limit of each section of road (which was assumed to be the same as the average speed) to calculate the average number of vehicles per km of road. A speed limit of 113 km/h and 96 km/h applies for cars travelling on motorways and rural sections of road respectively [137]. A conservative safety margin of 30% was included in the calculations. The average number of cars per km of major road for each region of GB are stated in TABLE 6-2. According to the
Department for Transport (Dft), “major roads include motorways and all rural/urban sections of class ‘A’ roads” [87]. Class ‘A’ roads are classified into Trunk (Tr) and Principal (Pr) roads.

| TABLE 6-2: Average number of cars per km of major road in 2014 |
|----------------------|-----------------|-----------------|
|                      | Motorway         | Class ‘A’ roads  |
|                      | Rural            | Urban           |
|                      | Tr   | Pr   | Tr   | Pr   |
| England              |      |      |      |      |
| North East           | 31   | 12   | 4    | 51   | 17  |
| North West           | 29   | 8    | 4    | 24   | 16  |
| Yorkshire & Humber   | 23   | 12   | 4    | 36   | 16  |
| East Midlands        | 33   | 14   | 4    | 39   | 16  |
| West Midlands        | 34   | 11   | 4    | 37   | 17  |
| East of England      | 33   | 15   | 6    | 28   | 16  |
| London               | 37   | 0    | 12   | 0    | 23  |
| South East           | 35   | 18   | 6    | 30   | 16  |
| South West           | 27   | 10   | 4    | 29   | 17  |
| Wales                | 25   | 5    | 3    | 25   | 15  |
| Scotland             | 16   | 4    | 1    | 26   | 14  |

The average number of vehicles per km of road across a day was shaped with daily traffic distribution data obtained from DfT [39]. The resulting daily profiles were combined with the power requirements of the cars to calculate the power demand per km of road across GB throughout a typical day. The analysis takes into account current traffic statistics and 100% uptake of EVs for sizing the infrastructure for a potential CoM system.

It is true that some EVs might not support CoM and charging will be performed while stopped from static chargers along the road infrastructure (e.g. at motorway services). However, we can still calculate the additional power demand based on the number of vehicles per km of road. The required energy to be supplied to the EVs on the roads of GB, given by TABLE 6-2, i) from a CoM infrastructure or ii) from static charging points along the road infrastructure must be the same. The power demand was calculated in hourly steps. Hence, the average power within a 1-hour time slot would be the same for both situations, regardless the proportion of EVs that charge statically or on the move. Although the actual power demand varies within the 1-hour time slot, the study does not consider higher time resolution. This means that a CoM infrastructure will distribute the charging process geographically, reducing

---

1 A trunk road in GB is a major road between places of traffic importance. The entire trunk road network (Primary Route Network) is designed to provide easily identifiable routes to access the whole of the country [87]. The remaining sections of major roads in GB (class ‘A’ roads) are classified as Principal roads.
the need for very large charging facilities in few locations, without adding an extra significant load.

As an illustration, the density of cars per km of motorway in London is depicted with the dashed line in Figure 6-1. From TABLE 6-2, the average number of vehicles on these roads is 37. During the peak hours of commuting there are around 70 passenger cars per km of road and the peak power required to propel this number of EVs is approximately 1.4 MW per km. In a similar way, the number of EVs and power required on trunk rural sections of class ‘A’ roads in South East during peak hours are 34 cars and 0.4 MW respectively. Indeed, motorways of London and rural sections of class ‘A’ roads of South East have the highest density of EVs per km of road. The selection of alternative regions leads to lower power demand per km for both road types.

A similar analysis was followed in Chapter 3 for estimating the power demand per km of road for an electrified road freight transportation. It was concluded that a maximum peak power demand of 2.3 MW per km of motorway and 0.9 MW per km of rural section of ‘A’ road is needed for all freight vehicles.

Overall, a maximum peak power demand of 3.7 MW and 1.3 MW is needed per km of motorway and rural sections of ‘A’ road respectively (both directions) for a combined electrified system of passenger cars and freight vehicles.

![Figure 6-1: Mean power required and density of EVs on motorways of London by hour](image)
The figures derived were combined with road length data [138] and the overall power demand for a CoM infrastructure for GB was estimated. TABLE 6-3 and TABLE 6-4 summarise the calculated additional peak demand for passenger cars and freight vehicles respectively.

A potential CoM infrastructure of electrified passenger car and road freight transportation would add an additional peak power load of 7.6 GW and 8.7 GW respectively. The new peak power demand represents an additional demand of 31% based on the 2017/2018 winter peak demand (around 53 GW) [106] and goes significantly beyond the capacity margin of the electricity system (5 GW) in GB [90]. However, various authorities have already embarked on plans to upgrade the electricity supply network mainly due to the shift to EVs and electric heating. The anticipated installed generating capacity in GB is estimated to be around 130 GW by 2050 [91] thus allowing a considerable capacity margin for CoM. Furthermore, the Electricity Networks Strategy Group has defined pathways to reinforce the transmission network of GB [92] and finally, various distribution companies have already embarked on upgrade projects to deal with the increased future demand [93], [94]

### TABLE 6-3: Peak power demand in GW of electrified passenger car transportation

<table>
<thead>
<tr>
<th></th>
<th>Motorway</th>
<th>Rural ‘A’</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>England</td>
<td>3.7</td>
<td>2.8</td>
<td>6.5</td>
</tr>
<tr>
<td>Wales</td>
<td>0.1</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Scotland</td>
<td>0.3</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4.1</strong></td>
<td><strong>3.5</strong></td>
<td><strong>7.6</strong></td>
</tr>
</tbody>
</table>

### TABLE 6-4: Peak power demand in GW of electrified road freight transportation

<table>
<thead>
<tr>
<th></th>
<th>Motorway</th>
<th>Rural ‘A’</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>England</td>
<td>4.8</td>
<td>2.8</td>
<td>7.6</td>
</tr>
<tr>
<td>Wales</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Scotland</td>
<td>0.4</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.3</strong></td>
<td><strong>3.4</strong></td>
<td><strong>8.7</strong></td>
</tr>
</tbody>
</table>

The figures outline the power demand requirements of a CoM infrastructure in GB. A more detailed analysis focusing on different regions of the country including local traffic conditions and driving patterns it is worth exploring. However, it is expected that the results would lie in the same order of magnitude without altering substantially the outcome of this study. Another factor influencing the power demand of a CoM infrastructure is the power transfer efficiency of the chosen IPT charging devices. Again, this does not change the main outcome of the study. Assuming a 90% efficiency for dynamic charging the additional power demand
increases from 16.3 GW to 18.1 GW. The new additional peak power demand corresponds to 34% based on the 2016/2017 peak power demand in GB.

It is also worth mentioning that some drivers might choose to charge at home or at work if they have adequate on-board capacity. However, this study assumes that all vehicles charge on the move without considering the initial value of the state of charge of the battery (SOC). This is not an unrealistic scenario as the CoM infrastructure delivers the energy needed to the vehicle for balancing out the energy consumed in real-time. This means that a steady-state SOC is possible throughout the entire journey regardless the initial SOC.

### 6.3 Charging Simulation Tool

A simulation tool was developed on top of Advisor to investigate the application of dynamic charging and the effects of system design variables on important performance parameters, such as the mileage range and the state of charge of the battery (SOC). The tool was also used for exploring the prospects of road freight electrification in Chapter 3.

The charging simulation tool produces a variety of outputs. Among others the user has access to i) the battery capacity of the vehicle under investigation, (ii) the final SOC without any charging facilities, (iii) the final SOC with CoM infrastructure, (iv) the total energy consumed (used by the electric motor) in the simulation run, (v) the energy received from the CoM system, (vi) the net energy demand during the whole journey which is the difference between the energy consumed and energy received, (vii) the average speed of the vehicle, (viii) the average consumption of the vehicle, and finally (ix) the ‘Mean Effective Charging Rate’ (MECR), denoted Ψ, which is the average energy delivered by the charging system per km along the road.

Figure 6-2 shows the motorway SOC of the modelled ‘compact car’ for various MECRs based on the ‘Artemis Motorway’ drive cycle which is repeated five times. It can be noticed that if the car was operated on battery power alone, the battery would be fully depleted after 53 km on motorways. The actual mileage range of EVs will depend on the capacity of the on-board battery. Yet, with a dynamic charging system capable of delivering Ψ equals 0.22 kWh/km they could run indefinitely, or with an increasing SOC. A similar analysis was conducted for the rural sections of roads. The required MECR for this type of journeys is 0.18 kWh/km.
Although charging is continual, it is noticed that the SOC varies throughout the journey. This is due to the fact that the ‘compact car’ does not have a constant speed over the modelled drive cycle. The energy received from the CoM infrastructure is not sufficient to balance out the energy consumed when the car accelerates at higher speeds thus drawing some current from the battery and decreasing SOC. In contrast, an increasing SOC is possible when the speed is relatively low. Overall, a steady average SOC can be achieved over the entire cycle.

![Figure 6-2: Motorway SOC of ‘compact car’ for various levels of MECRs](image)

6.4 Charging Layout

Multiple combinations of the charging infrastructure parameter configurations are possible to meet the MECR. Parameter that can be carried are: (i) charging segment length, $l$, (ii) nominal power rating, $P$, and (iii) number of charging segments, $n$, as shown in Figure 6-3.

![Figure 6-3: CoM infrastructure design variables](image)

The energy received, $E_r$, from a single charging segment is proportional to the power transfer rate of the charger, $P$, and the charging time, $t_c$. The charging time, $t_c$, is equivalent to the ratio of the charging segment length, $l$, and the average speed of the vehicle, $u$, as shown in the following expression, $E_r = P \cdot t_c = P \cdot \frac{l}{u}$. 
The total energy received from \( n \) charging segments per km of road must meet the required MECR, \( \Psi' \). For a given charging segment length and power rating, the number of required charging segments per km of road is calculated using the following expression,

\[
\Psi' = nE_r = nP \frac{l}{u} \rightarrow n = \frac{\Psi'u}{Pl} \quad (6-1)
\]

where \( \Psi' \) equals 0.32 kWh and \( u \) equals 97 km/h (based on the 60.2 mph average speed of the ‘Artemis Motorway’ drive cycle). Hence, (6-1) takes the form of

\[
n = \frac{21340}{Pl} \quad (6-2)
\]

It is worth mentioning that each charging segment might consist of multiple individual charging devices. Their number within one charging segment will depend on i) the length of the charging segment and ii) the length of individual devices. This technique, also used by TRL [60], allows the deployment of long charging segments that are not possible using a single individual device; since the length of current IPT systems is usually around 0.75 m [43], [60]. Indeed, a high-power compact IPT system is under development at the WMG, University of Warwick. It offers 50 kW nominal power transfer rate without exceeding 0.75 m in length, 0.5 m in width and 0.05 m in depth.

The required MECR of 0.22 kWh per km translates into 21.3 kW mean power transfer per metre\(^2\). However, the power drawn from the grid as function of time is a rectangular wave. This is because power is drawn periodically while EVs travel over the charging segments. Two charging layouts were chosen arbitrarily to assist us visualise the power demand profiles.

Figure 6-4a shows the power demand from an EV which travels at 97 km/h constant speed (average speed of the ‘Artemis Motorway’ drive cycle) assuming (i) 237 charging segments, 3 m in length (four individual IPT units) at 30 kW and (ii) 88 charging segments, 6 m in length (eight individual units) at 40 kW. The mean power demand of 21.3 kW, which is the same for both charging layouts, is shown in the figure as well.

The power demand for more than one EV was investigated for the two charging layouts described in the previous paragraph. The analysis assumed 28 EVs per lane per km, as this

\(^2\) The average speed of the vehicle following the ‘Artemis motorway’ drive cycle, used for the simulation is 97 km/h. The power required is calculated as \( P = \Psi \times U = 0.22 \text{ kWh/km} \times 97 \text{ km/h} = 21.3 \text{ kW} \)
The figure is the maximum density of vehicles for freeways under normal conditions [58]. This is based on a minimum 1.1 seconds gap between vehicles which corresponds approximately to 30 m at 97 km/h (average speed of ‘Artemis Motorway’ drive cycle) and an average length of 5 m per vehicle [58] – 1000/(30+5). The power demand profile for the two charging layouts are shown in Figure 6-4b. The power demand over time fluctuates around the mean power demand (28 vehicles X 21.3 kW = 600 kW) in a random way depending on the number of active charging segments at each time. The power demand for the first charging layout (dark line) fluctuates up to ±60 kW per km which corresponds to 10% of the mean power demand. In contrast, the power demand for the second charging layout (grey line) varies up to ±120 kW which corresponds to 20% of the mean power demand. Between the two options, the first charging layout appears to be a better option as it minimises the power variance per km of road.

To this end, all feasible combinations between charging segment length, power transfer and number of segments were investigated to explore the range of power demand. The length of segments was assumed to vary from 0.75 m to 30 m. The lower value was chosen based on the average length of individual IPT units, whereas the upper value was based on the 30 m spacing between two vehicles on motorways under normal conditions [58]. This assures that a charging segment is coupled with only one vehicle under normal flow conditions. However, charging segments longer than 5 m (the average length of a car [58]) have to cope potentially with more than one vehicle simultaneously. This is particularly important in heavy traffic conditions when spacing between vehicles is reduced significantly. Power transfer rates were assumed to range between 30 kW and 100 kW. The former value was selected by rounding...
up the mean power demand of 21.3 kW, whereas the latter value is an expected power transfer rate to be available from improved IPT devices in the near future. It was assumed that the installation interval is the same between any two charging segments.

Three flow conditions were considered in this study which are the ‘free’, ‘high density’ and ‘near capacity’ scenarios [139]. Each scenario assumes 8, 28 and 42 EVs per km of road (42 is the maximum density of vehicles per km of motorway before a traffic breakdown situation [139]). Assuming an average vehicle length of 5 m [58], the gap between vehicles is 120 m, 30 m and 20 m for each case. The speed of EVs is assumed at 97 km/h for the ‘free’ and ‘high density’ scenario and 50 km/h for the ‘near capacity’ scenario according to [139]. The range of power for all possible charging layouts was calculated and the average fluctuation around the mean power demand is computed for each examined scenario about the density of EVs per km of motorway. The results are summarised in Figure 6-5. Some charging layouts lead up to ± 275% variance in power demand per km whereas the smallest average fluctuation was found to be ± 7% around the mean power demand in average for the three density scenarios.

![Figure 6-5: Power demand variance for possible CoM infrastructure configurations](image)

The power demand variances per km for CoM infrastructure configurations that involve charging segments up to 5 m in length (average length of a vehicle [58]) are shown in Figure 6-6. Such configurations are particular advantageous in motorway queues with stop-start driving because no charging device would transmit energy to multiple EVs at the same time. This eliminates any technical and practical considerations such as dealing with multiple driver accounts simultaneously.
The smallest average range of power demand was calculated at ± 8% per km of motorway as shown in Figure 6-6 with the darkest colour. This is a figure close to the optimal margin of ± 7% between all investigated charging configurations shown in Figure 6-5. The CoM infrastructure which offers the smallest average range of power demand per km of motorway is shown conceptually in Figure 6-7 and involves:

(i) 3 m charging segments (combination of four IPT units)
(ii) 30 kW power transfer per unit
(iii) 237 charging segments per km of motorway - installed every 4.2 m (1000/237=4.2).
   This ensures that the minimum number of charging segments are installed to guarantee the necessary MECR.)
(iv) 116 charging segments per km of rural section of road (installed every 8.6 m)$^3$

Although the charging layout is a combination of four individual IPT units, the receiver system on the vehicle’s side is only one IPT unit as shown in Figure 6-8. This increases the charging time from each segment but not the power transfer rate between the charging infrastructure

$^3$ Based on the 58 km/h average speed of ‘Artemis Rural’ drive cycle and the necessary MECR of 0.18 kWh/km
and the vehicle. The real-time power received profile by an EV travelling at an average speed of 97 km/h on motorway is shown in Figure 6-4a with dark line.

The same charging layout could be exploited for road freight transport as well. It was shown in Chapter 3 that 2.5 kWh/km MECR has to be delivered dynamically to long-haul road freight vehicles on motorways. This is about eleven times higher than the MECR needed for passenger cars. Nevertheless, it would be possible to have multiple pick-up devices underneath each truck. Each receiving device could receive power from a single 30 kW charging segment for reaching the required power transfer levels. This concept is shown in Figure 6-8 where eleven receiving pads, 30 kW apiece, are used to meet the needed MECR of 2.5 kWh/km for long-haul operations.

It is worth mentioning that the proposed CoM infrastructure should be perceived only as a proposal. The aim is to suggest a reference solution for identifying any technical and economic limitations. The study was based on current data and robust assumptions. The process should be adjusted to include up-to-date information as this becomes available; including development of technology, business models, local traffic conditions, etc.

6.5 Assessment of National Infrastructure

In this section, the cost viability of a nationwide infrastructure for implementing CoM is explored. The development of conceptual power distribution configurations is combined with a cost model to calculate the cost needed per km of road for deploying CoM. This part of the study is focused on the IPT technology which can be compared to the cost for OhC which was confirmed at £1.2 million per km of motorway by the manufacturer (personal communication with Patrik Ackerman). The cost figures for the IPT and OhC systems are then combined with
road traffic data from DfT [115] and road length data [138] to calculate the percentage of electrified vehicle-miles in GB relative to the size of the necessary CoM infrastructure.

Cash flow figures are then produced including annual expenditures (capital, maintenance, operating and interest expenditures) and annual incomes, based on two pricing policies. For the first case, drivers buy fuel (electricity) from the CoM network based on the current price of electricity whereas for the second scenario drivers are prepared to buy energy based on the current prices of diesel. The financial viability of a CoM system suitable for passenger cars (using IPT charging devices), freight vehicles (using IPT or OhC system) and both type of vehicles (using IPT charging devices only or both IPT and OhC systems) is explored.

6.5.1 Solution Schemes

The analysis starts with the development of solution schemes for implementing a potential CoM infrastructure. Conceptual AC and DC power distribution configurations were developed for establishing the required connections between the charging transmitting devices and the electricity supply network (Figure 6-9). 3 m long charging segments at 30 kW installed every 4.2 m on motorways and 8.6 m on rural sections of road were considered according to the analysis presented earlier. The same layout was assumed for all regions in GB.

![Conceptual power distribution configuration for CoM (not to scale)](image)

Feeder stations and substations are introduced to provide flexibility and circuit protection. The size of stations is influenced by operational conditions and based on the calculated peak power demand per km of road. In particular, 2 MW sub-stations were assumed to meet the peak power demand of 1.4 MW per km of motorway and 0.6 MW sub-stations to meet the peak power demand of 0.4 MW per km of rural section of class ‘A’ road as was calculated.
earlier. It should be noted that this demand refers only to passenger cars. A CoM infrastructure suitable for passenger cars and freight vehicles, which requires 3.7 MW and 1.3 MW per km of motorway and rural section of road, is explored in a following section.

An economic model was developed to examine the financial viability of the proposed scheme. The aim was to examine whether the deployment of a CoM infrastructure at national scale could be financially reasonable rather than developing an accurate business model.

The key cost drivers of the model include the price of charging devices and cables and for the cost of cable trenching. Moreover, the cost of feeder stations and sub-stations was considered in the study, including expenditure for necessary equipment such as circuit breakers, transformers, connection switchgear and protection/metering. In addition, fees for system design and civil engineering were considered. The assumptions of the cost model are summarised in TABLE 6-5.

<table>
<thead>
<tr>
<th>TABLE 6-5: Cost assumptions for the CoM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost Variable</td>
</tr>
<tr>
<td><strong>Charging Devices</strong></td>
</tr>
<tr>
<td>Charging segments</td>
</tr>
<tr>
<td><strong>Cables</strong></td>
</tr>
<tr>
<td>Cables 132 kV</td>
</tr>
<tr>
<td>Cables 11 kV</td>
</tr>
<tr>
<td>Cables 3.3 kV</td>
</tr>
<tr>
<td>Cables 1 kV-DC</td>
</tr>
<tr>
<td><strong>Feeder Stations</strong></td>
</tr>
<tr>
<td>Circuit breaker</td>
</tr>
<tr>
<td>Switchgear/metering</td>
</tr>
<tr>
<td>Transformer 132 kV/11 kV</td>
</tr>
<tr>
<td><strong>Sub-stations</strong></td>
</tr>
<tr>
<td>11 kV circuit breaker</td>
</tr>
<tr>
<td>Rectifier 11 kV/1 kV-DC</td>
</tr>
<tr>
<td>Transformer 11 kV/3.3 kV</td>
</tr>
<tr>
<td>Booster 11kV/11kV</td>
</tr>
<tr>
<td><strong>Connections</strong></td>
</tr>
<tr>
<td>11 kV</td>
</tr>
<tr>
<td>3.3 kV</td>
</tr>
<tr>
<td>1 kV-DC</td>
</tr>
<tr>
<td><strong>Civil Engineering</strong></td>
</tr>
<tr>
<td>Cable Trenching</td>
</tr>
<tr>
<td>Construction works</td>
</tr>
<tr>
<td><strong>Additional Fees</strong></td>
</tr>
<tr>
<td>DNO design fees</td>
</tr>
</tbody>
</table>
The technology involved with CoM is still in the early stages and market data are not available. Some real projects have been built and demonstrated around the world, such as the OLEV system in Gumi City, South Korea [72]; the dynamic charging testing of Primove Bombardier in Mannheim [69]; and the testing projects of the European project Fabric in France, Italy and Sweden [68]. However, cost data have not yet been disclosed. Even if data was available, they might not be representative as the costs involved with a demonstration project do not always reflect the actual costs of a real system at national scale. Nevertheless, we have made some assumptions based on available data and personal judgment to assess the financial viability of such a large infrastructure project.

The price of the charging segments, 3 m long at 30 kW (four individual IPT units) was calculated at £10.8k. Initially, the cost of a charging device from the design point of view was estimated based on the approach followed by the authors of [140]. In particular, the total copper mass required for an individual 30 kW IPT system - about 15 kg [141] - was combined with the cost of Litz wire\(^4\) of £30 per kg [140], [142]. An additional cost of £45 per kW was added for the cost of the power electronics [140], [143] and the total material cost of an individual IPT system was calculated at £1.8k. Then, a 50% gross profit margin was added and the overall cost of a 30 kW IPT system is assumed at £2.7k, which corresponds to £90 per kW. The total cost for the 3 m charging segment, which is a combination of four 30 kW IPT systems, is therefore assumed at £10.8k.

Prices for the remaining equipment, (cables, feeder stations, sub-stations, connections, civil engineering fees and additional fees) have been mainly obtained from reports on the electrification of Britain’s railway network [144], [145]. Additional sources of cost data were reports from distribution network operators in GB, like [144], and the engineering teams from the Milton Keynes Electric Bus project [36]. Again, the actual figures will depend on the local power requirements and on-site available capacity.

6.5.2 CoM for electrified Cars transportation

The model produces the cost per km relative to the class of road and distribution approach. Three distribution approaches were considered which are (i) 1 kV-DC (ii) 3.3 kV-AC and

\(^4\) This type of wire is usually adopted for IPT systems that operate between 20-150 kHz to minimise skin effect losses [176].
(iii) 11 kV-AC. The expenditure figures include installation of IPT on one lane of road. It is also assumed that sub-stations are spaced every km as shown in Figure 6-9.

The average costs per km of road are shown in TABLE 6-6 for the three power distribution configurations. For motorways the average cost per km is around £3.6 million and for rural sections £1.9 million. The price of charging devices was identified as the most significant cost driver which accounts 70% of the total expenditure to deploy CoM. Reinforcement of the electricity supply network and setting up connections to the IPT charging devices account 10% of the total expenditure. The remainder 20% is for construction costs.

Overall, the CoM infrastructure on roads account for 87.5% of the total cost including equipment and construction expenses and the remaining 12.5% is for reinforcing the electricity supply network. Reinforcement of the electricity supply network in particular, was calculated at £450k per km of road. This can be compared with the quoted figure of £350-425k by TRL, which is the estimated cost for setting up connections from the electricity grid to IPT charging devices for one km stretch on the M6 motorway of England [60].

<table>
<thead>
<tr>
<th>Power Distribution Configuration</th>
<th>Motorway</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kV-DC</td>
<td>3.5</td>
<td>1.8</td>
</tr>
<tr>
<td>3.3 kV-AC</td>
<td>3.6</td>
<td>1.9</td>
</tr>
<tr>
<td>11 kV-AC</td>
<td>3.8</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Road length data [138] and traffic statistics [115] of GB (summarised in TABLE 6-7) were combined with the outcomes of the cost model (average cost of the three distribution configurations shown in TABLE 6-6). The results are summarised in Figure 6-10 which shows the total expenditure to install IPT devices relative to the percentage of electrified car-miles covered in GB, excluding miles driven on urban roads. An alternative view of the analysis is shown in TABLE 6-7 which gives the expenditure numbers for electrifying the various components on the road network.

A CoM infrastructure for electrifying 60% of car-miles in GB (excluding miles travelled on urban roads) would cost £26 billion (the average cost of the three distribution configurations). Such a charging infrastructure would involve installation of IPT devices on the motorways of the country which account for 1.8% of the total road length and carry 19.8% of all car-miles in GB as shown in TABLE 6-7. The expenditure to cover 70% of car-miles would be £48 billion.
IPT devices would be installed on motorways and trunk rural sections of ‘A’ roads (4.6% of the total road length). A CoM infrastructure on motorways and both on trunk and principal rural sections of ‘A’ roads would electrify up to 86% of car-miles increasing the cost to £105 billion (11.8% of the total road length). Finally, including IPT devices on rural sections of minor roads as well, would cover essentially 100% of car-miles with a national cost of £503 billion in average (64.2% of the total road length).

<table>
<thead>
<tr>
<th>Billion car-miles</th>
<th>Car-miles excluding urban roads</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kV-DC</td>
<td>25 60% 46 70% 100 86% 464 100%</td>
</tr>
<tr>
<td>3.3 kV-AC</td>
<td>26 60% 48 70% 104 86% 513 100%</td>
</tr>
<tr>
<td>11 kV-AC</td>
<td>27 60% 50 70% 108 86% 533 100%</td>
</tr>
<tr>
<td><strong>Average (£ billion)</strong></td>
<td>26 60% 48 70% 105 86% 503 100%</td>
</tr>
</tbody>
</table>

It is highlighted in Figure 6-10 that the results have similar trends for all power distribution concepts considered in the study; and therefore, the type of power distribution is not a critical factor to be addressed at this stage. Indeed, the cost required to electrify the greater part of all car-miles in the country is only a minor fraction of the total cost required to electrify the whole nation. This was calculated at £105 billion for the 86% electrification option whereas the cost for the 100% option was calculated at £503 billion (see Figure 6-10).
Cumulative expenditures, incomes and net profit figures were estimated for a possible CoM system on GB’s motorways which covers 60% of car-miles. Annual capital, maintenance, operating and interest expenditures were calculated by

\[
\text{Annual Expenditures} = \frac{\text{Capital cost} \times \text{Rate}}{1 - (1 + \text{Rate})^{-\text{years}}} + \text{Maintentance cost} + \text{Operating cost}. \quad (6-3)
\]

The capital cost was calculated in the previous section at £26 billion. A repayment period over 25 years at 3% interest is assumed. Maintenance accounts for 5% of the annual spend on capital expenditures. The operating cost represents the cost needed for the electricity supplied to vehicles. This is calculated by multiplying the total car-miles driven within the system (50 billion miles on GB’s motorways [115] -TABLE 6-7) with the average energy consumption of cars (0.19 kWh/km) and the wholesale cost of electricity (assumed 10p per kWh). The latter price is based on the report prepared by the Department for Business, Energy and Industrial Energy in GB which estimates that every generated kWh would cost 9p on average after 2020 [146]. This combined with a typical profit margin for supplying electricity in GB around 5-10% [147], allow us to assume that the operating cost for the CoM provider would be 10p per kWh. Overall, a CoM infrastructure on GB’s motorways using IPT charging devices would result in accumulated costs of £76 billion.

Two pricing options were explored in this study, pricing policy ‘A’ and ‘B’. In A, customers buy fuel (electricity) from the network according to the current retail price of electricity. This is assumed to be 14.4p per kWh [147] which corresponds to 2.74p for every driven km on motorway using equation

\[
\text{Fuel}_{\text{electricity}} = 0.19 \frac{kWh}{km} \times 14.4 \frac{p}{kWh} = 2.74 \frac{p}{km}. \quad (6-4)
\]

In price option B, customers buy fuel based on the current price of diesel in GB, which is assumed at £1.2 per litre. The equivalent cost per km driven on motorway for this pricing option is 7.54p using

\[
\text{Fuel}_{\text{diesel}} = \frac{1}{\text{mpg}} \times 4.55 \frac{\text{litrle}}{\text{gallon}} \times 1.2 \frac{\text{£}}{\text{litrle}} = 12.13 \frac{\text{p}}{\text{mile}} = 7.54 \frac{\text{p}}{\text{km}}. \quad (6-5)
\]
The miles per gallon gasoline equivalent (mpg) figure is needed for the conversion and this is assumed at 45 mpg. The total revenue from a system of this type was calculated at £54 billion for case A and £151 billion for case B.

Figure 6-11 summarises the results for a CoM system which includes IPT charging devices on GB’s motorways only (60% of car-miles is covered). The light grey dashed-dotted line shows the cumulative expenditures for the infrastructure provider. The profit for each pricing option is shown in Figure 6-11 with solid lines. The system is financially viable only when customers are prepared to buy fuel based on today’s prices of diesel in GB. In that scenario, (case B), an accumulated positive net profit of £75 billion over the 25-year period is possible. This corresponds to an annual positive profit of 50%. A negative profit is realised when customers buy fuel based at the current prices of electricity.

![Figure 6-11: Cash flow for electrified CoM car transportation – IPT on GB’s motorways](image)

Similar analysis was conducted for a CoM system which covers 70%, 86% and 100% of all car-miles in GB. The annual net profit margin for each electrification option is illustrated in Figure 6-12. The grey line refers to the pricing policy A (customers buy fuel based on today’s prices of electricity), whereas the dark line refers to case B (customers buy fuel based on today’s prices of diesel). The detailed cash flow figures are summarised in TABLE 6-9. It is shown that positive profit is mostly possible when customers are prepared to buy fuel based on today’s prices of diesel (pricing policy B) whereas negative profit is realised when the pricing policy ‘A’ is adopted.
According to pricing policy ‘B’, a CoM infrastructure would return positive annual profits of 50%, 45% and 33% for the 60%, 70% and 86% electrification options. This margin allows even a likely 20% reduction of income for fuel duty [148]. Installation of IPT charging devices additionally on rural sections of minor roads to cover 100% of all car-miles in GB returns negative profit. This is due to the fact that the greatest proportion of all car-miles (86% excluding urban road car-miles) are driven on motorways and trunk/ principal rural sections of ‘A’ roads which correspond to only 11.8% of the total road length in GB (TABLE 6-7). The extra income from the minor rural sections of road (52.4% of total road length) does not compensate the additional capital and maintenance cost needed for the much larger system.

The purpose of this study was to examine whether the deployment of a CoM infrastructure at national scale could be financially viable rather than developing an accurate business

TABLE 6-8: Summarised cash flow figures for a CoM system for cars

<table>
<thead>
<tr>
<th>Electrification of car-miles</th>
<th>60%</th>
<th>70%</th>
<th>86%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoM infrastructure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motorways</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Trunk Rural ‘A’</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Principal Rural ‘A’</td>
<td>√</td>
<td>√</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Rural minor road</td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Expenditures – 25 years (£ billion)</td>
<td>76</td>
<td>130.4</td>
<td>247.4</td>
<td>865.7</td>
</tr>
<tr>
<td>Capital</td>
<td>26</td>
<td>48</td>
<td>105</td>
<td>503</td>
</tr>
<tr>
<td>Maintenance</td>
<td>1.3</td>
<td>2.4</td>
<td>5.3</td>
<td>25.2</td>
</tr>
<tr>
<td>Operating</td>
<td>37.4</td>
<td>59.1</td>
<td>91.4</td>
<td>118.4</td>
</tr>
<tr>
<td>Interest</td>
<td>11.3</td>
<td>20.9</td>
<td>45.7</td>
<td>219.2</td>
</tr>
<tr>
<td>Incomes – 25 years (£ billion)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pricing policy A – ‘Electricity’</td>
<td>53.8</td>
<td>85.1</td>
<td>131.7</td>
<td>170.4</td>
</tr>
<tr>
<td>Pricing policy B – ‘Diesel’</td>
<td>151.1</td>
<td>239.0</td>
<td>369.8</td>
<td>478.7</td>
</tr>
<tr>
<td>Profit – 25 years (£ billion)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pricing policy A – ‘Electricity’</td>
<td>-22.2 (-41%)</td>
<td>-45.3 (-53%)</td>
<td>-115.7 (-88%)</td>
<td>-695.3 (-408%)</td>
</tr>
<tr>
<td>Pricing policy B – ‘Diesel’</td>
<td>75.1 (50%)</td>
<td>108.6 (45%)</td>
<td>122.4 (33%)</td>
<td>-387.0 (-81%)</td>
</tr>
</tbody>
</table>

Figure 6-12: Profit margin for electrified CoM car transportation system
model. Aspects of EVs uptake scenarios, market acceptance, payment methods etc. could be included in a future financial appraisal.

6.5.3 CoM for electrified Freight transportation
The financial viability of a CoM infrastructure for electrified freight transportation only is now considered. It was shown in Chapter 3 that long-haul operations would require installation of a CoM network on the nation’s motorways. Driving on local roads (between highway exits and delivery points) can be achieved using battery power or series hybrid vehicles according to the logistics concept of freight transportation described in Chapter 3. CoM for freight vehicles is therefore explored for the motorway network only.

TABLE 6-9 presents the cost per km of road of an electrified road freight system based on the IPT strategy. The results are identical with the cost per km of road of an electrified cars transportation system (TABLE 6-6); mainly because the same charging layout is considered which is responsible for 87.5% of the total cost. The different power demands per km of motorway between freight vehicles (2.3 MW per km) and passenger cars (1.4 MW per km) does not have significant impact on the calculated costs. The average cost per km of motorway is £3.6 million based on the IPT technology which can be compared with the £1.2 million figure quoted by SIEMENS for their eHighway system for trucks.

<table>
<thead>
<tr>
<th>Power Distribution Configuration</th>
<th>Motorway</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kV-DC</td>
<td>3.5</td>
</tr>
<tr>
<td>3.3 kV-AC</td>
<td>3.6</td>
</tr>
<tr>
<td>11 kV-AC</td>
<td>3.8</td>
</tr>
</tbody>
</table>

The cash flow figures for an electrified freight transportation are summarised in TABLE 6-10. The results show that a CoM system on GB’s motorways based on the IPT technology would produce a positive net profit of 17% provided the pricing policy ‘B’ is adopted. The fuel consumption of a conventional HGV, which is needed for calculating the cost per km driven on motorway in (6-5), is assumed at 7.9 mpg [149].

It should be noted that an electrified CoM system on GB’s motorways for freight vehicles produces higher incomes than a CoM system for passenger cars; even if the number of miles driven by HGVs on motorways is significantly lower than the miles driven by passenger cars (7.7 billion miles compared to 50 billion car-miles [115]). This is due to the fact that freight...
vehicles demand more fuel (energy) in comparison with passenger cars (average energy consumption of HGVs is 2.3 kWh/km whereas the energy consumption of passenger cars is 0.19 kWh/km).

OhC can be used as an alternative to IPT for implementing CoM for long-haul operations. TABLE 6-10 summarises the cost analysis of a CoM infrastructure installed on GB’s motorways based on the OhC system. The total capital cost of this system was calculated at £8.6 billion based on the £1.2 million per km figure obtained from Patrik Ackerman who is a Business Developer of the SIEMENS’ eHighways system. The system is financially viable for both pricing policies, ‘A’ and ‘B’, with a positive net profit margin of 18% and 37% respectively.

Overall, it was shown that a CoM system for electrified freight transportation for the motorway network in GB could be implemented by both IPT charging devices and OhC systems. The IPT technology requires the adoption of pricing policy ‘B’ to return positive profits; whereas an OhC system which involves lower capital requirements is financially viable for both pricing policies.

| TABLE 6-10: Cash flow figures for CoM freight transportation (motorway network only) |
|----------------------------------|----------|----------|
|                                  | IPT      | OhC      |
| **Expenditures – 25 years (£ billion)** |          |          |
| Capital                          | 26       | 8.6      |
| Maintenance                      | 1.3      | 0.4      |
| Operating                        | 71.3     | 71.3     |
| Interest                         | 11.3     | 3.7      |
| **Incomes – 25 years (£ billion)** |          |          |
| Pricing policy A – ‘Electricity’ | 102.6    | 102.6    |
| Pricing policy B – ‘Diesel’      | 132.8    | 132.8    |
| **Profit – 25 years (£ billion)** |          |          |
| Pricing policy A – ‘Electricity’ | -7.3 (-7%) | 18.6 (18%) |
| Pricing policy B – ‘Diesel’      | 22.9 (17%) | 48.8 (37%) |

6.5.4 CoM for electrified Cars and Road Freight transportation

Next, the costs per km of a CoM infrastructure suitable for both cars and long-haul road freight vehicles are calculated. Such infrastructure would involve IPT charging devices as an OhC system is not compatible with passenger cars. It is also expected that long-haul freight vehicles and passenger cars would have separate dedicated charging lanes and therefore, the analysis considers two charging lanes for each direction of motorway. Only one charging lane is considered for the rural sections of ‘A’ roads to meet the charging requirements of passenger cars. CoM for freight vehicles would not be necessary on rural sections of roads.
The needed costs per km of road for a combined electrified CoM system for passenger cars and freight vehicles are summarised in TABLE 6-11. The cost per km of motorway for this system is 87.5% higher than the CoM system designed separately for passenger cars or freight vehicles, as shown in TABLE 6-6 and TABLE 6-9. This is due to the fact that a second lane of IPT devices is deployed. It was shown that the charging devices account 87.5% of the total cost per km including construction/ installation expenses. The combined power demand of 3.7 MW per km of motorway does not have significant impact on the costs. The cost of rural sections of road has not changed, as the same charging infrastructure is considered.

Although higher capital cost is required, due to the second charging lane on motorways, revenue would be returned from both EVs and HGVs. The annual profit margin for such a system is shown in Figure 6-13. It can be seen that a positive profit margin in the range of 30-36% is possible when the pricing policy ‘B’ is adopted.

The detailed cash flow figures are summarised in TABLE 6-12. Installation of IPT devices on motorways and rural sections of road would cover long-haul operations and 86% of all car-miles in the country. It is shown in the left part of TABLE 6-13 that an annual positive profit margin of 30% is possible from an entire IPT CoM for electrified cars and freight transportation. This, results in an accumulated profit of £150 billion over the 25-year period and corresponds to approximately £85 billion at today’s prices assuming 5% inflation rate.
TABLE 6-12: Cash flow figures for a CoM system for cars and road freight vehicles

<table>
<thead>
<tr>
<th>Electrification of car-miles</th>
<th>60%</th>
<th>70%</th>
<th>86%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expenditures – 25 years (£ billion)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital</td>
<td>48.8</td>
<td>70.8</td>
<td>127.8</td>
<td>525.8</td>
</tr>
<tr>
<td>Maintenance</td>
<td>2.4</td>
<td>3.6</td>
<td>6.4</td>
<td>26.3</td>
</tr>
<tr>
<td>Operating</td>
<td>108.6</td>
<td>130.3</td>
<td>162.7</td>
<td>189.6</td>
</tr>
<tr>
<td>Interest</td>
<td>21.2</td>
<td>30.7</td>
<td>55.5</td>
<td>229.0</td>
</tr>
<tr>
<td>Incomes – 25 years (£ billion)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pricing policy A – ‘Electricity’</td>
<td>156.4</td>
<td>187.7</td>
<td>234.2</td>
<td>273.0</td>
</tr>
<tr>
<td>Pricing policy B – ‘Diesel’</td>
<td>283.9</td>
<td>371.9</td>
<td>502.6</td>
<td>611.5</td>
</tr>
<tr>
<td>Profit – 25 years (£ billion)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pricing policy A – ‘Electricity’</td>
<td>-24.6 (-16%)</td>
<td>-47.7 (-25%)</td>
<td>-118.2 (-50%)</td>
<td>-697.7 (-255%)</td>
</tr>
<tr>
<td>Pricing policy B – ‘Diesel’</td>
<td>102.9 (36%)</td>
<td>136.5 (36%)</td>
<td>150.2 (30%)</td>
<td>-359.2 (-59%)</td>
</tr>
</tbody>
</table>

As an alternative, CoM for both passenger cars and freight vehicles can be implemented by a combination of IPT charging devices and OhC systems. This would require dedicated charging lanes on motorways for passenger cars and freight vehicles implemented by IPT and OhC respectively. Yet, it is assumed that the two systems could use common sub-stations. CoM on rural sections of ‘A’ roads would involve only one lane of IPT devices to meet the charging requirements of passenger cars. CoM for freight vehicles would not be necessary on rural sections of roads.

The cost analysis of the combined system is summarised in the right part of TABLE 6-13. It is shown that a CoM infrastructure of this type, which includes one IPT charging lane for passenger cars on motorways and rural sections of ‘A’ roads and one OhC charging lane for freight vehicles on motorways, appears to be slightly more attractive in terms of profit in comparison with the entirely IPT infrastructure.

TABLE 6-13: CoM for cars and freight vehicles on motorways and rural ‘A’ roads

<table>
<thead>
<tr>
<th>CoM technology</th>
<th>IPT Motorway</th>
<th>IPT Rural ‘A’</th>
<th>Total</th>
<th>IPT Motorway</th>
<th>OhC</th>
<th>IPT Motorway</th>
<th>Rural ‘A’</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charging lanes</td>
<td>2</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Expenditures (£ billion)</td>
<td>181</td>
<td>171.4</td>
<td>352.4</td>
<td>76.0</td>
<td>84.0</td>
<td>171.5</td>
<td>331.5</td>
<td></td>
</tr>
<tr>
<td>Capital (£ billion)</td>
<td>48.8</td>
<td>79</td>
<td>127.8</td>
<td>26</td>
<td>8.6</td>
<td>79.0</td>
<td>113.6</td>
<td></td>
</tr>
<tr>
<td>Incomes (£ billion)</td>
<td>283.9</td>
<td>218.7</td>
<td>502.6</td>
<td>151.1</td>
<td>132.8</td>
<td>218.7</td>
<td>502.6</td>
<td></td>
</tr>
<tr>
<td>Profit (£ billion)</td>
<td>102.9</td>
<td>47.5</td>
<td>150.2</td>
<td>75.1</td>
<td>48.8</td>
<td>47.2</td>
<td>171.1</td>
<td></td>
</tr>
<tr>
<td>Profit Margin (%)</td>
<td>36</td>
<td>22</td>
<td>30</td>
<td>50</td>
<td>37</td>
<td>22</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>Profit after inflation (£ billion)</td>
<td>58.1</td>
<td>26.8</td>
<td>84.7</td>
<td>42.3</td>
<td>27.5</td>
<td>26.8</td>
<td>96.5</td>
<td></td>
</tr>
</tbody>
</table>

6.5.5 CoM infrastructure overview

The possible infrastructure for an electrified CoM system for passenger cars, freight vehicles and both type of vehicles is summarised in TABLE 6-14. The sections of road with installed
charging devices and the annual profit margin are shown for each investigated option. All options with positive annual profit are shaded with dark colour whereas grey colour is used for non-viable options.

Overall, it is shown that a CoM infrastructure on the roads of GB appears to be financially viable when pricing policy ‘B’ is adopted – drivers buy fuel based on today’s prices of diesel. In contrast, negative annual profit is mostly obtained when pricing policy ‘A’ is adopted – drivers buy fuel based on today’s prices of electricity. For this pricing option, the system is only viable when CoM for freight vehicles on motorways is implemented by OhC.

A CoM infrastructure on motorways and rural sections of ‘A’ roads would cover long-haul operations and 86% of all car-miles in the country. It was shown that such a system could return positive profits and therefore it could be privately funded. Alternatively, the entire infrastructure could be provided by the government. In any case, the capital cost needed for such a project, around £114-128 billion depending on the chosen infrastructure (combination of IPT and OhC systems or entirely IPT system respectively), is similar to the cost of other national large infrastructure projects such as the High Speed 2 (HS2) scheme in GB [150]. It would result in an annual profit margin of 30-34%.

Furthermore, a nationwide infrastructure of CoM offers the opportunity for substantially reducing the installed battery capacity of EVS, and therefore reducing significantly the price of EVs. The cost per vehicle of building the CoM infrastructure on the nation’s motorways and rural sections of ‘A’ roads in GB, which covers 86% of all car-miles and long-haul freight operations, is approximately £4,100 per vehicle. This figure is calculated by dividing the total

---

### TABLE 6-14: Possible CoM infrastructure and annual Profit Margin overview

<table>
<thead>
<tr>
<th>Pricing policy A (electricity) – 2.74p/ km</th>
<th>Pricing policy B (Diesel) – 7.54p/ km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorway</td>
<td>Trunk Rural ‘A’</td>
</tr>
<tr>
<td>60% cars</td>
<td>-41%</td>
</tr>
<tr>
<td>70% cars</td>
<td>-7%</td>
</tr>
<tr>
<td>86% cars</td>
<td>-16%</td>
</tr>
<tr>
<td>100% cars</td>
<td>-25%</td>
</tr>
</tbody>
</table>
infrastructure capital cost needed for such a project (£114-128 billion) by the total number of licensed cars and HGVs in GB, which was 31 million passenger cars and 160 thousand HGVs in the end of 2016 [151]. The resulting infrastructure cost per vehicle of implementing CoM corresponds to less than 8.5 kWh of battery based on the £500 per kWh cost of batteries (i.e. 4100/500) as shown in TABLE 4-4. Of course, there is also a cost to implement the charging hardware on the vehicles which is not calculated here.

This means that a CoM infrastructure would offer wider economic benefits if the capacity of on-board batteries is reduced by 8.5 kWh on average per vehicle. This is a realistic scenario because EVs for long distance travel (particularly for HGVs) would require massive batteries without CoM and therefore, they offer significant margin for battery reduction. For example, the capacity of the on-board battery of the Tesla truck can be reduced potentially from 1 MWh to 85 kWh (according to the analysis of Chapter 3) which corresponds to 915 kWh of battery reduction.

If all road vehicles were electrified as a result of the CoM system, the impact would be to reduce the total GB passenger car emissions from approximately 30 MtCO₂ per year to 14 MtCO₂ per year at today’s emission rates⁵ and 2 MtCO₂ per year by 2050⁶. This would result in GB savings of 16 MtCO₂ per year at 2018 and 28 MtCO₂ per year at 2050. An estimated aggregate saving of 710 MtCO₂ is therefore possible over the intervening period⁷.

---

⁵ Assuming 158 billion car-miles travelled on motorways and rural sections of road (TABLE 6-7); 120 gCO₂/km for a conventional car (emissions per km for new cars registered in GB in 2016 [151]) and 57 gCO₂/km for an EV (0.19 kWh/km X 300 gCO₂/kWh [23]).
⁶ Assuming 158 billion car-miles travelled on motorways and rural sections of road (TABLE 6-7); 120 gCO₂/km for a conventional car (emissions per km for new cars registered in GB in 2016 [151]); 8 gCO₂/km for an EV (0.19 kWh/km X 40 gCO₂/kWh [22])
⁷ Based on a constant 1.8% increase in annualised savings between the numbers calculated for today’s norms (2018) and those calculated for 2050.
Additionally, electrification of freight operations in GB would result about 8 MtCO₂ savings per year at today’s emission rates⁸ to 27 MtCO₂ per year at 2050⁹. This corresponds to accumulated savings of approximately 520 MtCO₂ by 2050¹⁰.

Overall, a CoM infrastructure of this type would deliver an estimated aggregate saving of approximately 1,230 MtCO₂ by 2050. In reality, the real savings are likely to be less than these figures, because the shifting towards EVs at scale is unlikely to progress either uniformly or quickly. Nevertheless, simply because road-vehicle related emissions are such a large fraction of the emissions footprint of GB, the potential for national impact is unquestionably enormous. Placing these figures in context, the HS2 scheme is expected to result around 3 MtCO₂ savings during the first 60 years of operation [152].

6.6 Conclusions

CoM is considered to be a key enabling factor in moving towards EVs. The development of individual charging devices for implementing in-motion charging has been rapid but their integration with the road infrastructure at national scale is still in need of more comprehensive consideration. The aim of this chapter was to outline the performance requirements of a national power infrastructure suitable for implementing CoM based on the IPT technology.

A medium-sized vehicle was modelled and its energy requirements were calculated over a variety of drive cycles including standard and logged drive cycles. The results were combined with the number of vehicles on roads, in order to estimate the total power demand needed from the power infrastructure. The results indicate a need for an additional 3.7 MW per km of motorway and 1.3 MW per km of rural section of road, assuming an electrified CoM system for both passenger cars and freight vehicles. For GB, an additional demand of 16.3 GW is needed, of which 7.6 GW is due to passenger cars. The remaining load is due to road freight vehicles. A charging simulation tool was developed to investigate the application of dynamic

---

⁸ Assuming 32.6 and 14.4 billion vehicle-miles by LGVs and HGVs respectively travelled on motorways and rural sections of road [115]; 148 gCO₂/km for a conventional LGV and 974 gCO₂/km for a conventional HGV (Chapter 3); 110 gCO₂/km for an electric LGV and 720 gCO₂/km for an electric HGV (Chapter 3)

⁹ Assuming 32.6 and 14.4 billion vehicle-miles by LGVs and HGVs respectively travelled on motorways and rural sections of road [115]; 148 gCO₂/km for a conventional LGV and 974 gCO₂/km for a conventional HGV (Chapter 3); 15 gCO₂/km for an electric LGV and 96 gCO₂/km for an electric HGV (Chapter 3)

¹⁰ Based on a constant 3.9% increase in annualised savings between the numbers calculated for today’s norms (2018) and those calculated for 2050.
charging. It was shown that a charging infrastructure capable of transferring 0.22 kWh/km and 0.18 kWh/km would preserve 100% SOC of the on-board battery for EVs travelling on motorways and rural sections of ‘A’ roads.

Based on that, a possible CoM layout based on the IPT technology was proposed. Such a charging layout includes (i) charging segment length at 3 m, (ii) power rating at 30 kW and (iii) distance between consecutive chargers at 4.2 m (1.2 m gap between chargers) for motorways and 8.6 m (5.6 m gap between chargers) for rural sections of road. This configuration offers minimum power demand variance per km of road for three examined scenarios about the density of EVs per km of motorway. Long-haul freight vehicles with multiple pick-up systems could exploit the same charging infrastructure on motorways for achieving the needed 2.5 kWh/km MECR.

A strategic overview for the CoM proposal for GB showed that a nationwide infrastructure of this type could be financially viable. The development of potential power distribution configurations was combined with an economic appraisal to calculate the cost needed for implementing CoM. The installation of IPT charging devices on motorways would require £3.6 million per km on average according to the three power distribution configurations investigated in this study. The cost needed for the rural sections of roads was calculated at £1.9 million per km including the cost needed for reinforcing the distribution network.

Installation of IPT charging devices on motorways would cover 60% of all car-miles in GB (excluding car-miles driven on urban roads). CoM on motorways and trunk rural sections of ‘A’ roads would cover 70% of car-miles. Installation of chargers additionally on principal rural sections of ‘A’ roads would enable 86% electrification of car-miles.

Long-haul freight operations would require installation of a CoM technology on the nation’s motorways. IPT charging devices can be used for implementing the system which can be used exclusively by road freight vehicles or shared with passenger cars. As an alternative, the OhC technology can be adopted for implementing CoM for freight vehicles only.

Cash flow figures were produced for an electrified CoM system suitable for passenger cars, for freight vehicles and for both type of vehicles. A CoM infrastructure for passenger cars would involve installation of IPT charging devices. It was concluded that such a system could be financially viable when CoM devices are installed on GB’s motorways and rural sections of
'A' roads (86% of all car-miles) as long as drivers are prepared to buy electricity based on today’s prices of diesel. The system is still financially viable even if 20% of revenue is deducted for fuel duty. Negative profit margin is realised if CoM devices are installed additionally on rural sections of minor roads or fuel is sold to drivers based on today’s prices of electricity.

A CoM infrastructure for long-haul freight vehicles could involve IPT devices or OhC systems on GB’s motorways. A system based on the IPT technology is financially viable when drivers buy fuel at today’s prices of diesel whereas diesel or electricity prices can be adopted when the OhC technology is used.

A CoM network for both passenger cars and freight vehicles could be implemented either by an IPT infrastructure (suitable for both EVs and HGVs) or a combination of an IPT (for EVs) and OhC (for HGVs) infrastructure. Both options would ultimately require two charging lanes on motorways to have sufficient capacity for all motorway traffic with passenger cars and freight vehicles using separate charging lanes. Such infrastructure could be privately funded or be paid by the government. The capital cost which was calculated at £114-128 billion, depending on the two options, is similar to the cost of other national large infrastructure projects in GB. The infrastructure cost per vehicle of implementing CoM was calculated at £4,100 which is the same to the cost of an 8.5 kWh battery. A nationwide CoM infrastructure would offer wider economic benefits if the capacity of the on-board batteries is reduced by 8.5 kWh in average per vehicle.

The impact of this system would be to reduce the combined GB passenger vehicle and freight emissions by 24 MtCO₂ per year at today’s emission rates and by 56 MtCO₂ per year by 2050. Overall, an aggregated saving of 1,230 MtCO₂ by 2050 is possible.
Chapter 7   Conclusions and Future work

7.1 Conclusions

The prospect of irreversible climate change has raised the obligation for governments to embark on substantial programmes of decarbonisation. Many possible pathways have been suggested over the last few years. It has been generally accepted that decarbonisation of the transport sector is a necessary step toward mitigating the effect of climate change.

The transport sector in Great Britain (GB) accounts for over a quarter of national CO₂ emissions, 93% of which are due to road transport. Because road transport is a critical component of human mobility and economic growth, most studies project that the proportion of total greenhouse gas emissions due to road transport will rise significantly in the future. The challenge is to support growth in transport use in a sustainable manner.

Decarbonisation strategies for the road transport sector can include a wide range of measures, including improvements to propulsion efficiency and aerodynamics, lower rolling resistance tyres, driver training, alternative fuels, etc. Most of these measures can be adopted at relative low cost but they could not achieve the deep levels of decarbonisation needed in the long-term. It was shown that combination of these strategies could reduce fuel consumption and CO₂ emissions up to 30%.

One of the most potentially beneficial approaches is electrification which is the subject of this dissertation. Electric propelled vehicles (EVs) offer significant environmental advantages over conventional vehicles. Firstly, significant reduction of CO₂ emissions in comparison with conventional vehicles can be achieved. This, coupled with a significantly decarbonised electricity supply network in the future offers the opportunity for an almost complete decarbonised transport sector. Secondly, electricity as an energy source enables energy diversity which ensures security of energy supply and a broad use of carbon-free energy sources. Thirdly, the necessary infrastructure for delivering electricity is sufficiently mature, although a significant upgrade would be required to accommodate the additional power demand for electrifying transport. In addition, EVs offer zero tailpipe emissions, eliminating the release of noxious pollutants. This, coupled with low operational noise make EVs an attractive solution particularly for urban areas.
The real benefits of an electrified transport sector would be realised if a widespread penetration of EVs is achieved across a large proportion of road transport demand. However, this is dependent on overcoming significant barriers. The largest of these are the high cost, mainly due to the batteries; the limited range; the long battery recharging times and the lack of public charging infrastructure.

To this end, the main research question in this study is to examine whether the barriers to EVs adoption could be addressed in a way that could make electrification a feasible approach towards more sustainable road transportation. This was achieved through an examination of how novel proven power charging/delivering technologies could be used to unlock some of the barriers to electrification of road transportation. Various road transport sectors and type of journeys were explored with particular focus on passenger cars, light good vehicles (LGVs), heavy good vehicles (HGVs) and buses. Aspects of autonomous operations for public transportation and novel wireless power transfer technologies were also explored.

Techno-economic studies were developed to assess the feasibility of an electrified road transport sector in the short-term and long-term horizon. The aim of the work was to outline the system performance requirements for a practical system and determine a suitable charging infrastructure for each investigated transport operation. According to the proposed framework, large and expensive on-board batteries are not necessary and recharging times can be minimised. This ensures that EVs can be used in the same way as conventional vehicles without compromising the effectiveness of the system.

The methodology was mainly based on the critical review approach. Initially, the state of the art of power delivery/charging of EVs was discussed, with the aim of identifying ways of overcoming the challenges and unlock a widespread electrification of road transportation. For each explored case, a framework was proposed that allows the exploitation of current and potential future electrification technologies to enable shifting towards EVs. Based on that, simulation tools and methods were developed to calculate the power requirements of EVs travelling on specified driving cycles and set the performance requirements for a practical system. Appropriate charging infrastructures were proposed for each investigated operation. The additional power demand and electric load were calculated and any implications for the electricity supply network were explored. The total expenditure needed for each operation and the impact on CO₂ emission savings were also calculated.
The chapter of ‘Literature Review’ discussed the state of the art of power delivery/charging of EVs with the aim of identifying ways of overcoming the challenges and enabling the shift towards electric road transportation. The technologies of Inductive Power Transfer (IPT), Overhead Catenary Systems (OhC) and In-road conductive charging were discussed. It was shown that the technologies of IPT and OhC have advanced significantly the last few years but research into the characteristics of charging systems at national scale is need of more comprehensive consideration.

Chapter 3, ‘Prospects for Electrification of Road Freight’, showed that deep decarbonisation of the national road freight system by electrification is feasible.

(i) It would require installation of a backbone charge-on-the-move (CoM) network on the nation’s motorways. This could be achieved with either IPT or OhC systems.

(ii) A logistics concept was proposed that, in conjunction with current and likely future electrification technologies, could provide a framework for the electrification of most road freight operations. The proposed logistics concept is divided into four operations which are the ‘long-haul trunking’, ‘urban delivery’, ‘home delivery’, and other ‘auxiliary services’ such as refuse collection functions within the area of municipalities. Different electric freight vehicles and charging mechanisms were suggested for each of these operations.

(iii) The power requirement of each vehicle model was calculated over appropriate driving cycles using the Advanced Vehicle Simulator (Advisor). The outputs were then combined with GB traffic data in order to set the baseline of the required power demand across GB. It was shown that an additional electrical load of 9.4 GW would be added on the power demand during the peak hours of commuting due to the electrification of road freight transportation.

(iv) A charging simulation tool was also developed to investigate the application of dynamic charging and the effects of system design variables on important performance parameters, such as the mileage range and the SOC.

(v) Four case studies were developed for assessing the feasibility of electrification of road freight. It was shown that the shift towards electric freight vehicles appears to be technically and financially feasible since large and expensive on-board batteries are not required. Significant reduction of 75% CO₂ emissions when compared with
conventional freight vehicles could be achieved by 2030 for all case studies examined.

Even higher reduction of 90% CO\textsubscript{2} emissions by 2050 is feasible provided the current projections for decarbonisation of the electricity grid are achieved.

Chapter 4, ‘An Urban Charging Network: A case study for Cambridge UK’ explored a potential charging infrastructure for electric road freight operations within the boundaries of the city, including the auxiliary services of buses and refuse collection functions. The results were also combined with estimated performance requirements for electrified urban freight deliveries and urban travel by passenger cars at Cambridge to explore a complete urban charging network in the long-term.

(i) Real data about existing operations were collected for this study to define accurate drive cycles. The five Park and Ride bus routes, the refuse collection operations and two home delivery operations at Cambridge were investigated.

(ii) Different vehicles were modelled for each operation and their performance was evaluated over the defined drive cycles. Different charging infrastructures were proposed for each operation. The additional power demand, additional load, capital cost needed and the CO\textsubscript{2} emissions savings for each case were calculated. In the end, the results were scaled up for the entire city and any implications for the electricity supply network were explored.

(iii) It was shown that the charge-on-the-stop (CoS) approach appears to be the best solution for electrifying the Park and Ride bus routes of the city. Such a system requires an on-board battery of practical size, charging points at either end of each route and less powerful chargers at the depot to fully recharge the vehicles overnight. The size of batteries, around 135 kWh on average for all Park and Ride bus routes, would have minimal impact on the passenger capacity of the vehicle and on some cases (e.g. Trumpington Park and Ride) the electric bus would be lighter than the conventional vehicle. The additional peak power demand for such a system was calculated at 1,300 kW and the additional consumption of electricity at 3,141 MWh per year. This system would cost £9.1 million and would result to an accumulated CO\textsubscript{2} emission savings of 38 ktCO\textsubscript{2} by 2050.

(iv) Combination of the CoS and the overnight charging (OnC) approach was considered as the most appropriate solution for electrifying the refuse collection operations of
Cambridge. In such a system, the 110 kWh on-board battery of vehicle is adequately big to provide all the energy needed for the entire day. Yet, it has a practical size which does not compromise the system. For some routes, it would be necessary to recharge the vehicles during unloading at the depot before performing the second part of the shift. It was shown that three 165 kW charging points installed at the depot (one charger for each of the Domestic, Dry Recycling and Trade vehicles) combined occasionally with an additional 5-10 min stop during unloading would deliver sufficient charging boost to the vehicles. Low power chargers are needed at the depot to fully recharge the vehicles overnight. The additional peak power demand for the city and the additional load per year were calculated as 200 kW and 334 MWh respectively. A total capital cost of £9.3 million was computed for this system and 13 ktCO$_2$ emissions savings are possible by 2050.

(v) For the case of home deliveries, it was shown that a 45 kWh on-board battery would provide the needed energy for the entire day. If needed, a charging point can be installed at the depot and recharge the batteries of the vehicles during re-loading. The peak power demand was computed as 76 kW for two of the city’s supermarket chains and the additional electricity consumption for both operations was calculated at 20.7 MWh per year. The combined system would cost £0.53 million and would save up to 0.25 ktCO$_2$ by 2050.

(vi) The results were then scaled up for the entire city of Cambridge. It was shown that a total shift towards electric bus routes, refuse collection operations and home deliveries would increase the peak power demand of the city by 6.7 MW and the electricity consumption by 16.1 GWh per year. This increase of 6.3% and 2.0% respectively based on today’s figures, is considerably lower than the expected increase due to the growth of population and shifting to electric heating. The total cost to be shared by the Cambridge City Council, bus operators and grocery suppliers is £57.5 million which is substantially lower than other infrastructure projects of the city. Such a system would save up to 205 ktCO$_2$ emissions by 2050.

(vii) It was also shown that OnC for electrifying the bus routes of the city eliminates any bad implications for the electricity supply network. The additional power demand of such a system could be limited to only 0.19 MW which corresponds to 0.18% of current demand. However, OnC for the bus routes of Cambridge is not a viable option.
Massive batteries would be needed on-board which significantly increases the capital costs of the system. OnC is financially less attractive than the CoS approach even if zero electricity cost is considered for OnC. Besides, OnC buses have restricted passenger capacity due to their very heavy batteries and would require twice as many buses to maintain the same passenger capacity. This means that the system would require twice as much energy and would introduce considerable additional capital cost. Adoption of the OnC approach, which may be advantageous for the electricity grid, is dependent on overcoming these problems. Combinations of government incentives such as tax relief, lower operating costs and capital cost support, need to be considered to make OnC a more attractive solution.

(viii) An electrified system for urban deliveries at Cambridge was then explored. It was shown that the peak power demand of the city would increase by 14 MW (13.2% of the current peak) and the consumption of electricity by 34.5 GWh (4.3% of current consumption). This means that a small adoption of electrified urban deliveries is possible in the short-term. A complete electrification of urban deliveries at Cambridge would require an upgrade to the electricity supply network to meet the additional power demand. The cost needed for this system was estimated at £91 million. The impact would be an accumulated saving of 430 ktCO₂ by 2050.

(ix) The implications from an electrified system for passenger cars were also explored. It was shown that such a system would require significant upgrade to the electricity supply network at national scale. The cost to install the required home chargers was calculated at £73.5 million and the impact would be an aggregated saving of 870 ktCO₂ by 2050.

(x) Overall, the impact of total shift towards EVs at Cambridge, which includes electrification of all bus routes, refuse collection vehicles, home deliveries, urban deliveries and urban travel by passenger cars, would increase the power demand of the city by 20.6 MW (19.5% of the current peak) and the energy consumption by 117 GWh per year (14.6% of current consumption). Nevertheless, the anticipated installed generating capacity and generation of electricity in GB is estimated to increase by 145% and 200% respectively. This allows a considerable margin for the electrification of transportation.
(xi) The total capital cost needed for such a project was calculated at £222 million which is similar to the cost of other city’s projects like the Cambridge Guided Busway. The impact would be a significant aggregate saving of 1.5 MtCO₂ by 2050.

‘An autonomous taxi service for future cities’, was explored in Chapter 5. Such a system could be considered as part of an integrated sustainable urban transport system for successful mobility management in cities. A taxi service of this type offers a complimentary service to mass transit systems by providing an affordable solution for any first/last mile transport requirements. It is also an alternative solution for random intra-site movements within an existing urban context.

(i) A critical review of the system showed that it could deliver environmental benefits and improve the experience of personal mobility in closed urban environments. The impact on environment, social sustainability and required infrastructure were explored.

(ii) A methodology was then proposed to estimate the levels of demand of such a system and set the performance requirements. The methodology was presented through a case study of the Biomedical Campus, which is a medical and research campus at the University of Cambridge.

(iii) It was shown that a fleet of 57 vehicles would be needed to serve 2,778 people per day. The capacity of the on-board battery was found to be 11 kWh and a charging infrastructure of 5 chargers at 11 kW was suggested to deliver the energy requirements of the system. The additional power load was calculated at 150 MWh per year which corresponds approximately to 0.17% of the current energy consumption at the Biomedical Campus. The peak power demand of the site would be unaltered, provided charging of the vehicles is performed between the evening and morning hours.

(iv) A financial analysis showed that such a system is financially viable with positive net profit even from the first year of operation, assuming a ticket price as low as £1-2 per person.

(v) Similar analyses were performed for the West Cambridge and the North-West Cambridge campuses of the university and similar results were obtained.
The rest of the thesis is focused on the charge-on-the-move (CoM) technology. CoM is considered to be a key enabling factor in moving towards the widespread use of EVs for long distance travel. It would be impractical, and too expensive, to carry batteries on-board for long distance journeys by passenger cars and long-haul operations by HGVs. The development of IPT charging devices and OhC systems for implementing a CoM infrastructure has advanced significantly over the last few years but their integration with the road infrastructure on a national scale needs more comprehensive consideration. Chapter 6, ‘A National Infrastructure for Charge-on-the-move’, presented an overview of the performance requirements for implementing a national CoM infrastructure.

(i) A medium-sized passenger vehicle was modelled and its energy requirements were calculated over a variety of drive cycles. The results were combined with the number of vehicles on roads, in order to estimate the total power demand needed from the power infrastructure. The results indicate a need for an additional 3.7 MW per km of motorway and 1.3 MW per km of rural section of road, assuming an electrified CoM system for both passenger cars and freight vehicles. For GB, an additional demand of 16.3 GW is needed for CoM, of which 7.6 GW is due to passenger cars. The remaining load is due to road freight vehicles. Furthermore, a charging simulation tool was proposed to investigate the application of dynamic charging. It was shown that a charging infrastructure capable of transferring 0.22 kWh/km would preserve 100% SOC of the on-board battery for EVs travelling on motorways while 0.18 kWh/km would be needed for rural sections of ‘A’ roads.

(ii) A possible CoM layout based on the IPT technology was proposed. Such a charging layout includes (i) charging segment length at 3 m, (ii) power rating at 30 kW and (iii) distance between consecutive chargers at 4.2 m (1.2 m gap between chargers) for motorways and 8.6 m (5.6 m gap between chargers) for rural sections of road. This configuration offers minimum power demand variance per km of road for three examined scenarios about the density of EVs per km of motorway. Long-haul vehicles with multiple pick-up systems could exploit the same charging infrastructure on motorways for achieving the needed 2.5 kWh/km.

(iii) A strategic overview for the CoM proposal for GB showed that a nationwide infrastructure of this type could be financially viable. The development of potential
power distribution configurations was combined with an economic appraisal to calculate the cost needed for implementing CoM. The installation of IPT charging devices on motorways would require £3.6 million per km on average according to the three power distribution configurations investigated in this study. The cost needed for the rural sections of roads was calculated at £1.9 million per km. These figures include also the cost to reinforce the distribution network for meeting the additional power demand. The cost of an OhC system is £1.2 million per km of motorway.

(iv) Installation of IPT charging devices on motorways would cover 60% of all car-miles in GB (excluding car-miles driven on urban roads). CoM on motorways and trunk rural sections of ‘A’ roads would cover 70% of car-miles. Installation of chargers additionally on principal rural sections of ‘A’ roads would enable 86% electrification of car-miles. Long-haul operations could take advantage of the installed CoM infrastructure on motorways. As an alternative, OhC technology could be adopted for implementing CoM for freight vehicles.

(v) Cash flow figures were produced for an electrified CoM system suitable for passenger cars, for freight vehicles and for both type of vehicles. A CoM infrastructure for passenger cars would involve installation of IPT charging devices. It was concluded that such a system could be financially viable when CoM devices are installed on GB’s motorways and rural sections of ‘A’ roads, which covers up to 86% of all car-miles in GB as long as drivers are prepared to buy electricity based on today’s prices of diesel. The system is still financially viable even if 20% of revenue is deducted for fuel duty. Negative profit margin is realised if CoM devices are introduced additionally on rural sections of minor roads or fuel is sold to drivers based on today’s prices of electricity.

(vi) A CoM infrastructure for freight vehicles could involve IPT devices or OhC systems on GB’s motorways. A CoM system based on the IPT technology is financially viable when drivers buy fuel at today’s prices of diesel whereas diesel or electricity prices can be adopted when the OhC technology is used.

(vii) A CoM network for both passenger cars and freight vehicles could be implemented either by an IPT infrastructure (suitable for EVs and HGVs) or a combination of an IPT (for EVs) and OhC (for HGVs) infrastructure. Both systems would ultimately require two charging lanes on motorways to have sufficient capacity for all motorway traffic with passenger cars and freight vehicles using separate charging lanes. Although
higher capital costs are required, revenue is returned from both EVs and HGVs. Such a system could be privately funded or be paid by the government. The capital cost which was calculated at £114-128 billion, depending on the chosen infrastructure, is similar to the cost of other national large infrastructure projects in GB. The cost per vehicle of implementing CoM was calculated at £4,100 which is the same with cost of an 8.5 kWh battery. A nationwide CoM infrastructure would offer wider economic benefits if the capacity of the on-board batteries is reduced by 8.5 kWh in average per vehicle.

(viii) The impact of this system would be to reduce the combined GB passenger vehicle and freight emissions by 24 MtCO₂ per year at today’s emission rates and by 56 MtCO₂ per year by 2050. Overall, an aggregated saving of 1,230 MtCO₂ by 2050 is possible.

This dissertation has presented innovative and interesting results for academia, government and industry. Electrification is a viable strategy for more sustainable transportation that could make a big difference in the future. An almost complete decarbonisation of the road transport sector is possible in the long-term (provided the current projections for decarbonisation of the electricity grid are achieved). Various operations and type of vehicles were investigated in this study, including long-haul operations, urban road freight operations, bus routes, refuse collection vehicles and long-distance journeys of private cars and freight vehicles. Aspects of autonomous systems for public transportation were investigated as well. Overall, it was shown that electrification is a feasible method for supporting growth in transport in an environmentally-responsible way.

Previously it was thought that electrification might not be a practical approach for achieving the deep levels of decarbonisation needed in the long-term. Mainly because of the high energy demands of the vehicles, the implications for the electricity supply network and the cost required for deploying the necessary charging infrastructure. This dissertation has now shown that this view is incorrect. Large and expensive on-board batteries are not required for operation within the proposed frameworks and recharging times are limited to minimum without compromising the effectiveness of the system. However, a significant investment is needed in charging infrastructure – both in cities for buses, freight vehicles, passenger cars, etc. and in the form of CoM technologies along the road infrastructure. Nevertheless, it was
shown that these costs are similar to the cost of other national large infrastructure projects of GB.

An overview of all electrification strategies explored in this study is provided in TABLE 7-1. Each column of the table refers to the research questions that were posed in section 2.3. These are the following:

(i) Is electrification a feasible approach for various road transport sectors and type of journeys, with particular focus on passenger cars, light good vehicles, heavy good vehicles and buses which are responsible for 95% of total road transport CO₂ emissions in GB?

(ii) What are the environmental benefits of an electrified transport sector?

(iii) How can novel power charging/electricity distribution technologies be used to unlock widespread electrification of road transportation?

(iv) What charging systems are feasible in the short/long term and for urban/inter-urban mobility?

(v) What would be the performance requirements and charging infrastructure for a practical system and what are the implications on the electricity supply network?

(vi) What financial resources are required for each system?

(vii) It is noticed in TABLE 7-1 that electrification strategies can be categorised into short-term and long-term solutions. Transitional strategies include the electrification of bus routes, refuse collection functions, home deliveries and aspects of autonomous operations for public transportation within the boundaries of the cities. They require some civil work to be done, mainly for installing the chargers and connecting them to the electricity supply network but not much else. The additional power demand and electric load is relatively low and can be met by the current electricity supply network. Such systems are easily funded and are capable of delivering substantial environmental benefits in the short-term.

(viii) In the long-term, focus is given on passenger cars and freight vehicles for both urban and inter-urban journeys. This would require deployment of urban charging networks to allow charging at home and delivery points, such as convenience stores, and a nationwide CoM infrastructure to enable widespread penetration of EVs for long-distance journeys. Substantial upgrade to the electricity supply network is
needed to accommodate the new power demand but significant CO$_2$ emission savings by 2050 could be achieved.

Figure 7-1 compares the proposed solutions in terms of i) additional power demand, ii) additional electric load, iii) capital cost needed and iv) CO$_2$ emission savings by 2050.

### TABLE 7-1: Overview of Road Transport Electrification

<table>
<thead>
<tr>
<th>Electrification Strategy</th>
<th>Q. i</th>
<th>Q. ii</th>
<th>Q. iii Recommended charging infrastructure</th>
<th>Q. iv Power demand</th>
<th>Q. v Energy demand</th>
<th>Q. vi Capital Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buses</td>
<td>City: 190 ktCO$_2$ GB: 95 MtCO$_2$</td>
<td>135 kWh on-board batteries; chargers at either end of route;</td>
<td>Short</td>
<td>City: 7 MW GB: 3.5 GW 6.6%</td>
<td>City: 15.7 GWh GB: 7.9 TWh 2.0%</td>
<td>City: £45.5 m GB: £22.8 b</td>
</tr>
<tr>
<td>Refuse Collection</td>
<td>City: 13 ktCO$_2$ GB: 6.5 MtCO$_2$</td>
<td>110 kWh on-board batteries; charging during unloading</td>
<td>Short</td>
<td>City: 0.2 MW GB: 0.1 GW 0.2%</td>
<td>City: 0.3 GWh GB: 0.2 TWh 0.1%</td>
<td>City: £9.3 m GB: £4.7 b</td>
</tr>
<tr>
<td>Home Deliveries</td>
<td>City: 1.3 ktCO$_2$ GB: 0.7 MtCO$_2$</td>
<td>45 kWh on-board batteries; charging during loading</td>
<td>Short</td>
<td>City: 0.4 MW GB: 0.2 GW 0.2%</td>
<td>City: 0.1 GWh GB: 0.1 TWh 0.1%</td>
<td>City: £2.7 m GB: £1.4 b</td>
</tr>
<tr>
<td>Urban Deliveries</td>
<td>City: 430 ktCO$_2$ GB: 215 MtCO$_2$</td>
<td>No Data</td>
<td>Long</td>
<td>City: 14 MW GB: 7 GW 13.2%</td>
<td>City: 34.5 GWh GB: 17.3 TWh 4.3%</td>
<td>City: £91 m GB: £45.5 b</td>
</tr>
<tr>
<td>Cars in Cities</td>
<td>City: 870 ktCO$_2$ GB: 435 MtCO$_2$</td>
<td>Charging overnight using home chargers</td>
<td>Long</td>
<td>City: 22 MW GB: 11 GW 20.7%</td>
<td>City: 66 GWh GB: 33 TWh 8.3%</td>
<td>City: £73.5 m GB: £36.8 b</td>
</tr>
<tr>
<td>Autonomous Pods</td>
<td>Not applied (NA)</td>
<td>Charging overnight</td>
<td>Short</td>
<td>City: 0.1 MW GB: 0.1 GW 0.1%</td>
<td>City: 0.4 GWh GB: 0.2 TWh 0.1%</td>
<td>City: £0.8 m GB: £0.4 b</td>
</tr>
<tr>
<td>Cars long-distance</td>
<td>City: NA GB: 710 MtCO$_2$</td>
<td>CoM on motorways and rural sections of ‘A’ roads</td>
<td>Long</td>
<td>City: NA GB: 7.6 GW 14.3%</td>
<td>City: NA GB: 48 TWh 12.0%</td>
<td>City: NA GB: £105 b</td>
</tr>
<tr>
<td>Freight long-distance</td>
<td>City: NA GB: 520 MtCO$_2$</td>
<td>CoM on motorways</td>
<td>Long</td>
<td>City: NA GB: 8.7 GW 16.4%</td>
<td>City: NA GB: 72 TWh 18.0%</td>
<td>City: NA GB: £8.6 b</td>
</tr>
<tr>
<td>Nationwide adoption of electrification strategies</td>
<td>GB: 1,982 MtCO$_2$</td>
<td>Various charging infrastructures</td>
<td>Long</td>
<td>GB: 38.2 GW 72.1%</td>
<td>GB: 178.7 TWh 44.7%</td>
<td>GB: £225.2 b</td>
</tr>
</tbody>
</table>
Conclusions and Future work

A nationwide adoption of all electrification strategies proposed in this thesis would increase the peak power demand of the country by approximately 38 GW and the electricity consumption by 180 TWh per year. This corresponds to an additional power demand of 72% based on the current peak [106] and an additional electricity load of 45% based on current consumption [108]. A significant upgrade to the electricity supply network is required to meet the additional demand. Nevertheless, various authorities have already embarked on plans to upgrade the electricity supply network, mainly due to the shift to EVs and electric heating [91]–[94]. The anticipated installed generating capacity in GB is estimated to increase by 145% (from approximately 53 GW to 130 GB) and the generation of electricity by 100% (from 400 TWh to 800 TWh per year). This would allow a considerable margin for the electrification of road transport.

The total capital cost required for a complete charging network at national scale, which includes solutions for urban and inter-urban travel, was calculated at £225 billion. This is similar to the cost of other large infrastructure projects of GB. The impact would be a significant aggregate saving of approximately 2,000 MtCO2 between the numbers calculated for today’s norms (2018) and those calculated for 2050.

Figure 7-1: Comparison between electrification solutions for road transportation

Additional power demand (GW) b) Additional load (TWh) c) Capital cost (£ billion) d) Accumulated savings by 2050 (MtCO2)
Simply because road-vehicle related emissions are such a large fraction of the emissions footprint of GB, the potential for national and global impact is unquestionably large. Electrified road transportation systems could deliver significant CO$_2$ emission savings which are up to 1,000 orders of magnitude more than the anticipated savings from other similar size projects like the High Speed 2 project in GB.

Indeed, the transport sector in GB was responsible for 108 MtCO$_2$ in 1990 and 111 MtCO$_2$ in 2015 as shown in Figure 7-2 [153]. The average CO$_2$ emissions per km from all registered cars in GB is anticipated to decrease from 145 gCO$_2$\textsuperscript{1} to 115 gCO$_2$\textsuperscript{2} between 2015 and 2020. This, combined with 253 billion car-miles travelled in GB in 2016 [115] result in an estimated saving of 14 MtCO$_2$ per year. In the long-term, the expected average emission per km is 95 gCO$_2$\textsuperscript{3}. This would result in 22 MtCO$_2$ saving per year by 2050 which corresponds to 20% reduction based on the 1990’s figure.

For CO$_2$ emission reductions beyond that level, alternative strategies need to be adopted. Electrification was shown as a beneficial approach to achieve the deep levels of decarbonisation needed in the long-term. Indeed, electrification of buses, refuse collection functions and home deliveries would reduce the carbon footprint of the transport sector by 2.3 MtCO$_2$ per year in the short-term and 4.5 MtCO$_2$ per year in the long-term as described in TABLE 7-2. Electrification of urban deliveries in cities and a widespread penetration of EVs (both passenger cars and HGVs) for long distance travel, as a result of a CoM system, would result in a total saving of 80 MtCO$_2$ per year. This means that the carbon account of the transport sector would be as low as 4.4 MtCO$_2$ per year in the long-term which corresponds to more than 90% reduction based on the 1990’s figure.

---

\textsuperscript{1} The average CO$_2$ emissions from all registered cars in GB in 2015 was 145 gCO$_2$ per km which was 20% higher than the average rate for a new car at 121 gCO$_2$ per km [8].

\textsuperscript{2} The UK target for the new car average CO$_2$ emissions by 2020 is 95 gCO$_2$ per km. This means that the estimated CO$_2$ per km for the entire fleet would be 115 gCO$_2$ by 2020 (20% higher than the target figure).

\textsuperscript{3} In the long term (by 2050), the expected average CO$_2$ per km across the entire fleet is 95 gCO$_2$ which is the UK target for new cars for 2020.
Figure 7-2: Transport sector carbon footprint

<table>
<thead>
<tr>
<th>Option</th>
<th>Short-term (kg CO₂)</th>
<th>Long-term (Mt CO₂)</th>
<th>From</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buses</td>
<td>City: 4 kg CO₂</td>
<td>City: 8.1 kg CO₂</td>
<td>Section: 4.3.5</td>
</tr>
<tr>
<td></td>
<td>GB: 2.0 Mt CO₂</td>
<td>GB: 4.1 Mt CO₂</td>
<td></td>
</tr>
<tr>
<td>Refuse Collection</td>
<td>City: 0.4 kg CO₂</td>
<td>City: 0.5 kg CO₂</td>
<td>Section: 4.4.2</td>
</tr>
<tr>
<td></td>
<td>GB: 0.2 Mt CO₂</td>
<td>GB: 0.3 Mt CO₂</td>
<td></td>
</tr>
<tr>
<td>Home Deliveries</td>
<td>City: 0.1 kg CO₂</td>
<td>City: 0.1 kg CO₂</td>
<td>Section: 4.5</td>
</tr>
<tr>
<td></td>
<td>GB: 0.1 Mt CO₂</td>
<td>GB: 0.1 Mt CO₂</td>
<td></td>
</tr>
<tr>
<td>Urban Deliveries</td>
<td>Not applicable</td>
<td>City: 18 kg CO₂</td>
<td>Section: 4.6.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GB: 9 Mt CO₂</td>
<td></td>
</tr>
<tr>
<td>Cars in Cities</td>
<td>Not applicable</td>
<td>City: 31 kg CO₂</td>
<td>Section: 4.6.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GB: 16 Mt CO₂</td>
<td></td>
</tr>
<tr>
<td>Cars CoM</td>
<td>Not applicable</td>
<td>City: Not applicable</td>
<td>Section: 6.5.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GB: 28 Mt CO₂</td>
<td></td>
</tr>
<tr>
<td>Freight CoM</td>
<td>Not applicable</td>
<td>City: Not applicable</td>
<td>Section: 6.5.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GB: 27 Mt CO₂</td>
<td></td>
</tr>
</tbody>
</table>

7.2 Future Work

This PhD thesis has raised some questions for further investigation in the future. Chapter 2 shows that the development of individual charging devices for EVs has been rapid but an industry-wide specification guideline that defines criteria for interoperability, electromagnetic compatibility, etc. is still needed to facilitate a widespread roll-out of EVs charging infrastructure. Some bodies were established for this purpose but issues of interoperability between static and dynamic systems, compatibility of EVs with both wireless
and conductive chargers, operating frequency, power transfer rate, etc. still need to be addressed. However, standardisation must not limit the potential for future innovations.

Chapter 3 explores the prospects for electrification of road freight and Chapter 4 refines the analysis to present results based on more detailed data for the city of Cambridge UK. Some assumptions were made to estimate the performance requirements of an electrified system for urban freight deliveries and urban travel by passenger cars. Future research aims to analyse data about existing operations to determine an accurate charging infrastructure and allow any potential limitations to be ascertained. In addition, the available capacity of the grid and the required upgrade to accommodate the new power demand need to be investigated more comprehensively particularly at locations proposed for charging points. Based on that, the methodology for selecting en-route charging points needs to be adjusted to consider the impacts for the grid specifically at the point of use.

Chapter 5 proposes an autonomous taxi service as a sustainable urban transport system for future cities. The cases of Biomedical campus, West Cambridge and North-West Cambridge at the city of Cambridge were developed to demonstrate the concept. Future work aims to explore the potential for autonomous operations in other parts of the city. It is anticipated that the existing Guided Busway could provide a good opportunity to run autonomous pods trials. Such a system could serve people travelling to research institutions and residences in the area. The possibility of a shuttle service using autonomous pods between the Cambridge Railway station and Trumpington Park and Ride, which are connected by the Guided Busway, also need to be investigated as an alternative solution.

Chapter 6 outlines the performance requirements of a national power infrastructure suitable for implementing CoM. Future work aims to refine the section of ‘assessment of the national infrastructure’. In particular, the financial viability of a CoM system at national scale needs to be explored considering gradual uptake of EVs and different charging methods for the users of the system. For example, this might include fixed or dynamic prices throughout the day, customers pay a fixed amount regardless the amount of electricity consumption and combined costs with road use pricing (direct chargers levied for the use of road including road tolls, distance or time-based fees, congestion chargers etc.).
It is therefore expected that industry, academia and government should consider electrification of road transportation as a viable route for more sustainable transportation. Governments and funding bodies are also urged to acknowledge the potential benefits of an electrified road transport system and support this endeavour.
Appendix I  The potential for supplying coils by capacitive coupling

This appendix explores the potential for adopting capacitive coupling to supply road charging coils for the charge-on-the-move transport application. Both unipolar and bipolar approaches are investigated and additionally, various designs are developed for vertical and lateral power transfer applications. According to the vertical design, energy is transferred from a lower layer to an upper layer of the road pavement across a 250 mm gap; whereas for the lateral design, the charging coils are supplied wirelessly from the hard-shoulder across a 1.8 m gap. Potential capacitor modules are modelled and evaluated based on their circuit performance and electromagnetic pollution using finite element software. For the vertical design, it is shown that efficiencies between 80-86% could be obtained at 1 MHz and 85 kHz respectively. Power factor of 1.00 was achieved for both operating frequencies. Similarly, 75-79% efficiencies and 1.00 power factor could be obtained for the lateral design at 1 MHz and 85 kHz respectively. The work explores various requirements of such a system including natural decay of the electric field, control of electromagnetic interference and inclusion of a car in the model which restricts driver’s exposure to electromagnetic field. A technique to control the stray field on the hard-shoulder is also proposed. Finally, the performance of the system is appraised for operation under wet conditions. The bipolar vertical design is the more promising configuration but the bipolar lateral approach should be also investigated further. The option to supply energy wirelessly from the hard-shoulder is an attractive feature for minimising excavation of road.

I.1 Introduction

Installation of Inductive Power Transfer (IPT) charging devices for implementing charge-on-the-move (CoM) would require digging-up much of the existing road network. Fragile and expensive materials are used in IPT devices, such as ferrite, and their integration with the hostile environment of road pavement would be challenging. The installation would have to ensure that the embedded chargers adapt to the continuous loading from traffic, any induced thermal contraction and expansion inside the pavement and any seasonal environmental stresses [96]. In addition, the installation should consider any problems from occasional maintenance of road pavement.
Moreover, the effective and practical supply of thousands of charging coils installed along the road infrastructure of a country is a significant consideration that has to be addressed by researchers and practitioners. The adoption of physical connections between individual road charging coils and feeder cables present both civil engineering issues and financial concerns. In particular, this direct approach for supplying the road chargers involves installations with high electrical demand and novel maintenance procedures but also it could compromise the stability and integrity of the road pavement due to the wiring requirements.

Heavy duty road pavement in GB consists of multiple layers of various materials and characterised by different thicknesses [154]. A typical structure is illustrated in Figure I-2a where the reader may notice the five main layers of the road pavement – the top layer or ‘wearing course’ (asphalt), the ‘base course’ (asphalt), the ‘road base’ (compacted aggregate usually stabilised with some cement called lean concrete or cement bound material), the ‘sub-base’ (similar material with the road base or hard-rock) and the ‘subgrade’ layer (usually hard-rock or soil). Although each layer has a specific purpose, such as smooth ride, skid resistance, load spreading, drainage, etc., a simplified diagram of road pavement is used in this study as shown in Figure I-2b. Some layers are merged together because they involve similar type materials. These are the ‘top layer’, ‘base layer’ and ‘subgrade layer’.

Three construction methods were suggested by TRL to install IPT charging coils for implementing CoM [60]. These are the i) trench-based construction ii) full-lane reconstruction and iii) full-lane prefabricated construction. For the former approach, a trench is excavated in the existing road pavement to install the IPT charging coils. This means that the ‘top layer’ is excavated to install the IPT charging coils without removing the other layers of road. Power supply would be taken in from roadside cabinets using wires embedded in the ‘top layer’. A
possible configuration of a CoM system embedded in the road pavement is shown in Figure I-2. This method was identified as the quickest and cheapest option among the three options but cracking issues are expected to occur at the surface around the embedded device and the supplying wires [60]. This may compromise smooth ride and safety.

Figure I-2: Trench based method – supplying wires through the ‘top layer’ not to scale

The full-lane reconstruction method involves removing all layers of the road pavement, installing the charging coils and then resurfacing the whole lane. This process occurs either on-site or off-site according to the full-lane prefabricated method. For the latter method, a full lane width prefabricated section is prepared at a depot near the construction area (including the IPT charging devices) and then delivered to site. All layers of road are reconstructed for both options and therefore supplying wires could be positioned through the ‘base layer’ (see Figure I-3) – in comparison with the trench-based method which requires supplying wires to be installed in the ‘top layer’ (Figure I-2). This, would avoid cracking at the surface of the road pavement which is a possible issue of the trench-based method. However, positioning supplying wires through the ‘base layer’ might compromise the physical strength and life span of the road because ‘base’ is regarded as the main load spreading layer in the road structure [154].

Figure I-3: Full lane method - supplying wires through the ‘base’ layer - not to scale
This chapter explores the potential for adopting wireless connections to supply the vehicle charging coils installed in the ‘top layer’ without the need to lay wires through the ‘top’ or ‘base’ layers of road pavement. This would minimise cracking at the surface of the lane and avoid compromising the physical strength and life span of the road. Two configurations were studied which are the vertical and lateral designs.

The vertical design is illustrated in Figure I-4a whereby power is transferred to the road chargers across a 250 mm distance through the ‘base layer’. This design was developed to facilitate the installation of CoM according to the full-lane reconstruction and full-lane prefabricated construction methods suggested by TRL. The well-practised methods of road construction are followed without the need to lay any wires through the ‘base’ or the ‘top’ layer of road. The transmitting and receiving system would be installed just before and after the formation of the ‘base layer’ as shown by the heavy black bodies in Figure I-4a. The feeder cables are buried in the ‘subgrade layer’ of the road pavement but this is not a problem as these two construction methods (full-lane reconstruction and full-lane prefabricated construction) involve removing all layers of the road pavement.

The lateral approach is shown in Figure I-4b with the feeder cables located in the hard-shoulder. Power is supplied to the chargers laterally across a 1.8 m gap, which is the half width of a typical motorway lane in GB. It is expected that the lateral configuration would enable the most advantageous trench-based construction method which would involve installing IPT charging devices without removing all layers of road or installing any supplying wires. It could be a retrofit construction method to the existing road network.

![Figure I-4: Wireless connections to supply road charging coils -not to scale-](image)

(a) vertical design (b) lateral design. The transmitting and receiving systems are represented by the heavy black bodies. Charging coils are embedded in the middle of the driving lane and the dotted vertical line separates the hard-shoulder with the driving lane.
The two main methods for transferring energy wirelessly over short distances are inductive and capacitive coupling techniques. For the former method, energy is transferred between coils in the form of a magnetic field. An alternating current energises the transmitting coil of the system and the resulting magnetic field induces an alternating voltage in the receiver coil [155]. By contrast, capacitive coupling transmits the energy between electrodes, i.e. metal plates, using an electric field [156], [157]. In particular, when an oscillating voltage is applied to the transmitting plate a displacement current travels through the intervening dielectric material and as a result, current flows to the receiving plate [158]. Notably, two metal plates coupled with a dielectric material comprise a capacitor that allows electric current to flow between two circuits that are not physically connected.

To date the predominant method of transferring energy wirelessly over short distances is inductive. The use of the capacitive coupling technique has been limited to low power applications because the capacitance of the system is constrained due to the available area; thus implying the employment of a high magnitude voltage source to achieve higher power ratings [159]. However, capacitive coupling has recently become an active topic of research within academia and industry since it offers advantages over the inductive technique. The electric field of a capacitor is constrained ideally between its two metal plates and for that reason, capacitive coupling technique does not entail bulky and expensive components for flux guiding and shielding [160]. In particular, being able to avoid installing fragile components in a harsh environment like the core of road pavement could increase the reliability of the system and make the adoption of capacitive coupling a preferable option. Furthermore, the ‘road base’ layer of the road pavement has better electric than magnetic properties which allows us to surmise that superior performance may be obtained by adopting the capacitive coupling technique instead of inductive. Besides, misalignment between the metal plates of a capacitive coupling system is a less critical concern [161]; whereas the efficiency of inductive power transfer is strongly degraded by small misalignment between the transmitting and receiving parts of the system.

Capacitive coupling technology has been explored by the automotive industry where it offers attractive solutions for electric vehicle (EV) charging applications. Significant operational benefits, coupled with the limited demands on the driver, due the avoidance of plug-in cables and simple systems are attractive futures. For example, researchers have proposed an EV
charging system which takes advantage of capacitive coupling between the charging station and the bumper of vehicle. The proposed system has around 90% efficiency for 1 kW power transfer [162] across a gap of tens of millimetres. Similar performances between 78-94% have been reported in literature for other EV charging systems operating at frequencies up to 6.78 MHz [163]–[166]. Nevertheless, capacitive coupling for EV charging applications is still in early stages of research. It is therefore expected that higher efficiencies could be achieved in the future as technology becomes more mature.

Two categories of circuits have been used to implement capacitive coupling namely the unipolar and bipolar approach (Figure I-5). For the former method, one set of transmitting and receiving plates is exploited, coupled with two large passive plates in order to provide the path for the return current. The load is connected between an active and a passive electrode and low power applications are typically based on this technique [156], [157]. By contrast, the bipolar technique exploits two sets of plates so large passive plates are not needed. Voltages with 180° degrees phase difference are applied to the transmitting plates and the load is connected between the two receiving plates. Higher power applications (1-2 kW) have been reported based on this approach [163] - [166].

Overall, this chapter explores the potential for developing capacitive connections to supply vehicle charging coils installed in the ‘top layer’. Both the unipolar and bipolar approach were investigated but more emphasis was placed on the bipolar approach. According to the vertical design, energy is transferred from a lower layer to an upper layer of the road pavement across a 250 mm gap; whereas for the lateral design, the charging coils are supplied wirelessly from the hard-shoulder across a 1.8 m gap. Potential capacitor modules are modelled and evaluated based on their circuit performance and electromagnetic pollution using finite element software.
The potential for supplying coils by capacitive coupling

I.2 Assumptions

The assumptions to enable adoption of capacitive connections are presented in this section. The assumptions are categorised under the headings of road pavement electric properties, power density, and electromagnetic field exposure limits.

I.2.1 Road pavement electric properties

The analysis begins by assuming that the road pavement consists of three main layers, as described earlier, which are the ‘top’, ‘base’, and ‘subgrade’ layer. Typical thickness figures for these layers suggest 100 mm, 250 mm, and around 100 mm respectively but our analysis considers a 600 mm ‘subgrade’ thickness in order to include any fringing field implications.

The next step was to determine the electric properties of the materials and in particular, their permittivity $\varepsilon_r$ and conductivity $\sigma$. The effective relative dielectric constant and loss tangent for ‘base’ materials are discussed in [167] for both dry and wet conditions for various frequencies. The base data, dielectric constant $\varepsilon_r$ and loss tangent $\tan \theta$, is shown in TABLE I-1. These figures were extrapolated according to the trendlines shown in Figure I-6 to determine the electric properties at the preferred operating frequencies, which are the 85 kHz, 1 MHz, and 10 MHz. The former is emerging as a standard operating frequency of IPT charging devices and the latter two are typical figures of capacitive coupling power applications [163]–[166].

<table>
<thead>
<tr>
<th>Freq. (MHz)</th>
<th>Dry Conditions</th>
<th>Wet Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>470 kHz</td>
<td>$\varepsilon_r$</td>
<td>$\tan \theta$</td>
</tr>
<tr>
<td>8.5</td>
<td>0.08</td>
<td>27.5</td>
</tr>
<tr>
<td>6.5</td>
<td>0.11</td>
<td>19.0</td>
</tr>
<tr>
<td>5.8</td>
<td>0.15</td>
<td>13.5</td>
</tr>
</tbody>
</table>

TABLE I-1: Electric properties for ‘base’ materials obtained from [167]

![Figure I-6: Electric properties for ‘base’ materials obtained from [167]](image-url)
The electric conductivity \( \sigma \) was calculated from the loss tangent, \( \tan \theta \), of the base layer material using

\[
\sigma = \omega \varepsilon_r \tan \theta
\]

where \( \omega \) is the angular operating frequency, \( \varepsilon_r \) the dielectric constant. The results are summarised in TABLE I-2.

The electric permittivity for the ‘top layer’ (asphalt) of road pavements is explored in [168] where forty-three asphalt samples were measured over the frequency domain of 100 kHz – 1.5 GHz. The average dielectric constant was 6 for dry specimens and 6.5 for wet samples. The same figures were assumed for the 85 kHz, 1 MHz and 10 MHz frequencies that used in this study. The electric conductivity, \( \sigma \), of ‘top layer’ materials (asphalt) for dry and wet conditions was obtained from the IEEE Guide for safety in AC substation grounding [169].

Dielectric constant and electrical conductivity figures were also determined for the ‘subgrade layer’ (hard-core/ soil). Data about the permittivity and loss tangent figures of the subgrade material is available in [170] for various frequencies including the three frequencies of interest – 85 kHz, 1 MHz and 10 MHz. Equation (I-1) was used to calculate the electric conductivity, \( \sigma \), according to the obtained loss tangent figures.

Overall, the estimated electric properties for the three layers of the road pavement are summarised in TABLE I-2.

<table>
<thead>
<tr>
<th>Freq.</th>
<th>Dry conditions</th>
<th>Subgrade</th>
<th>Wet conditions</th>
<th>Subgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top layer</td>
<td>Base layer</td>
<td>Subgrade</td>
<td>Top layer</td>
</tr>
<tr>
<td>85kHz</td>
<td>6</td>
<td>5e-7</td>
<td>28.7</td>
<td>1e-4</td>
</tr>
<tr>
<td>10MHz</td>
<td>7</td>
<td>1e-4</td>
<td>13.8</td>
<td>1e-3</td>
</tr>
</tbody>
</table>

It should be kept in mind that the stated figures may not be necessarily the representative electric properties of the materials involved. For the case of wet conditions especially, the literature highlights that the figures should be only used as practical engineering assumptions
because factors such as mineral content of the water and degree of water penetration were not considered in the study [167], [168]. Furthermore, various construction procedures and types of material could be selected based on local availability and requirements. The precise nature of aggregates could then, not be assumed fixed and the electrical properties of road pavement might be rather dissimilar across regions.

I.2.2 Power density

In this section, the required power density to be transferred wirelessly is discussed based on information derived from literature. The Mean Effective Charging Rate (MECR) is the average energy delivered by the CoM infrastructure to road vehicles per km along the road. It was shown in Chapter 6 that a 0.22 kWh/km MECR is needed to balance out the energy consumption by an average EV driving on motorways. As it was explained, various combinations of charger length, power rating, and distance between chargers could be adopted to meet the specified targets. Although a charging layout was recommended in the previous chapters, a standard power density requirement has not been determined to date.

Nevertheless, two specific charging layouts were proposed by TRL in [60] and our analysis is based on this piece of work. For one layout, 20 kW of power has to be supplied along a 1.8 m charging segment whereas for another layout 20 kW has to be supplied along 5.7 m of charging segment (or similarly, 6.32 kW along 1.8 m). Furthermore, the same source advocates that chargers should have 1 m width to eliminate any lateral misalignments between the road pad and the receiving unit mounted underneath the vehicle. Consequently, our proposed capacitor modules should have maximum dimensions of 1x1.8 m and should be evaluated separately for 20 kW and 6.32 kW power transfer capabilities based on the two proposed layouts.

I.2.3 Electromagnetic field exposure limits

Electromagnetic field (EMF) exposure limits state reference levels to limit human exposure to any kind of electromagnetic field. So far, no scientific consensus has been agreed regarding the exposure levels and different standards have been introduced to provide practical guide. The most common electromagnetic field standards are the i) IEEE Standard for safety levels with respect to human exposure to radio frequency electromagnetic fields (3 kHz to 3 GHz) [171] and the ii) ICNIRP Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (0 Hz – 300 GHz) [172]. The reference levels for general public
exposure to time-varying electric fields are reproduced in TABLE I-3. The study was based on these EMF exposure limits.

<table>
<thead>
<tr>
<th>Freq. (MHz)</th>
<th>IEEE (V/m)</th>
<th>ICNIRP (V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.003 – 1.34</td>
<td>614</td>
<td>87</td>
</tr>
<tr>
<td>1.34 - 10</td>
<td>823.8/f</td>
<td>87/vf</td>
</tr>
<tr>
<td>10 - 30</td>
<td>823.8/f</td>
<td>28</td>
</tr>
<tr>
<td>30 – 100</td>
<td>27.5</td>
<td>28</td>
</tr>
</tbody>
</table>

I.3 Road capacitive coupling

Potential capacitor modules to enable the supply of vehicle road chargers wirelessly were studied using the COMSOL Multiphysics version 5.0 software for modelling and simulation. The designs are distinguished by the unipolar and bipolar capacitive approach and by the vertical and lateral configurations. The circuit components and efficiency were calculated for the two charging layouts (20 kW/6.32 kW) and moreover, each example was evaluated based on the EMF exposure reference levels. AC circuit theory was exploited for the following analysis and all variables are expressed in RMS values.

I.3.1 Unipolar Approach

The equivalent unipolar capacitive coupling circuit may be envisaged as in Figure I-7. There is one transmitting and one receiving plate according to the unipolar method shown in Figure I-5a. The supplied charging coil, represented as $R_{Load}$, could be assumed as purely resistive because suitable power factor correction and compensation topologies can be employed to set the power factor of the device at unity [43], [99], [100].

![Figure I-7: Unipolar capacitive coupling equivalent circuit](image)

The capacitor $C$ represents the capacitance between the transmitting and receiving electrodes whereas the dielectric losses of the intervening material is denoted by the series
resistance $R_c$. The inductor $L$, coupled with its Ohmic series resistance $R_L$, is added for compensating the capacitive reactance of the circuit.

The current in the circuit $i_{\text{Load}}$ is given by

$$i_{\text{LOAD}} = \frac{V_s}{(j\omega L + R_L + \frac{1}{j\omega C} + R_c + R_{\text{Load}})}$$  \hspace{1cm} (I-2)

where $V_s$ is the voltage applied to the circuit and $\omega$ the angular operating frequency (in radians) which is expressed as

$$\omega = 2\pi f.$$ \hspace{1cm} (I-3)

$f$ is the operating frequency of the circuit measured in Hz. When the circuit is tuned at the resonant frequency $f_0$, which is given by

$$\omega_0 = 2\pi f_0 = \frac{1}{\sqrt{LC}} \rightarrow f_0 = \frac{1}{2\pi \sqrt{LC}},$$ \hspace{1cm} (I-4)

the capacitive reactance of the circuit is counter-balanced by the reactance of the added inductor. Hence, the load current $i_{\text{Load}}$ given by (I-2) gets its maximum value as follows

$$i_{\text{LOAD}} = \frac{V}{(R_L + R_c + R_{\text{Load}})}.$$ \hspace{1cm} (I-5)

For a specific capacitance, $C$, between the transmitting and receiving electrodes which is influenced by the geometry of the module, the value of the compensating inductor is calculated by

$$L = \frac{1}{4\pi^2 f_0^2 C}.$$ \hspace{1cm} (I-6)

The vertical design was firstly studied and the simulation model is shown Figure I-8. The geometry includes the three main layers of road pavement, which are the ‘subgrade’, ‘base’ and ‘top’ layers, which are shown in Figure I-1b. The ‘y’ direction of the model refers to the direction of vehicles’ travelling whereas the ‘x’ direction is the lateral dimension of the driving lane. The ‘x’ dimension of layers in the simulation model was set as 3.6 m which is the typical width of a motorway lane in GB whereas the ‘y’ dimension was set as 4 m. The ‘z’ dimension
of each layer was based on the typical width figures of road pavement shown in Figure I-1b. It should be noted that the ‘subgrade layer’ was extended from 100 mm to 600 mm and 1 m of air layer was included on top of the model for investigating the electric fringing effect. This geometry of road pavement is big enough for investigating a capacitor module with 1x1.8 m maximum dimensions (in the ‘x’ and ‘y’ dimension respectively) as described in section I.2.2. The estimated electric properties of road pavement, summarised in TABLE I-2, were used to determine the properties of each material in the model.

Figure I-8: Unipolar vertical design simulation model
The model includes the three layers of road (subgrade, base and top layers) and a layer of air on top to investigate the electric fringing effect. The transmitting and receiving plates are shown in the centre of the model.

The investigated capacitor module consists of two metal plates (according to the unipolar approach shown in Figure I-5a): transmitting and receiving plate. The two plates are shown in the simulation model of Figure I-8 with the heavy black rectangles in the centre of the model. It was assumed that they are made of aluminium, which is a highly conductive material. The receiving plate (load side) is located between the ‘top’ and ‘base’ layer of the road pavement. It covers the entire area of the capacitor module, i.e. 1x1.8 m in the ‘x’ and ‘y’ dimension respectively. The transmitting plate is located between the ‘base’ and ‘subgrade layer’. The size of the place was set as 0.5x0.9 m in the ‘x’ and ‘y’ dimension respectively which is half the size of the receiving plate. This configuration was chosen among other options because it was shown that it minimises the fringing effect.

The finite element software used in this study provides a number of ‘Physics interfaces’ which involve settings that set up the underlying equations, material properties and boundary conditions for a given problem. Some examples are the AC/DC currents, Fluid flow, Heat
transfer, etc. For this particular study, the AC/DC currents interface was assigned to the simulation. Meshing the geometry is performed automatically by the software which creates a mesh adapted to the physics interface in the model. For example, a finer mesh than the default is created close to boundaries, terminals, electric contacts, etc. This feature assures appropriate meshing which does not undermine the credibility of computed results.

Firstly, the circuit components of the equivalent circuit shown in Figure I-7 need to be determined. A first simulation of the model was executed to compute the admittance $Y$ between the two plates. Admittance is a measure of how easily the current can flow between the plates and it is defined as the reciprocal of impedance $Z$ as follows:

$$Y = \frac{1}{Z}. \quad (I-7)$$

For a capacitor, the impedance $Z$ is given by

$$Z_c = R_c + jX_c = R_c + \frac{j}{\omega C}. \quad (I-8)$$

where $R_c$ is the series component of the device, $\omega$ the angular frequency of excitation and $C$ the capacitance of the device. Combining $(I-7)$ and $(I-8)$ results in the following expression

$$Y = \frac{1}{R_c + \frac{j}{\omega C}} \rightarrow \frac{1}{Y} = R_c + \frac{j}{\omega C}. \quad (I-9)$$

The capacitance $C$ and series resistance $R_c$ of the capacitor module can be calculated using $(I-9)$. In particular, $R_c$ is the real part of the complex number of the left-hand side of $(I-9)$ as given by

$$R_c = \text{Real} \left\{ \frac{1}{Y} \right\} \quad (I-10)$$

and capacitance $C$ is computed as

$$C = \frac{1}{\text{Imag} \left\{ \frac{1}{Y} \right\} \cdot \omega}, \quad (I-11)$$

where $Y$ is the admittance of the module as computed by the simulation software and $\omega$ the angular operating frequency.
The value of capacitor $C$ and series resistance $R_C$ of the unipolar vertical model are shown in TABLE I-4 for an operating frequency of 85 kHz, 1 MHz and 10 MHz. Based on these figures, the value of inductor $L$ was selected appropriately for compensation purposes using (I-6). The series resistance of inductor, $R_L$, was computed using

$$R_L = \frac{\omega L}{Q} \quad \text{(I-12)}$$

to give quality factor $Q$ of 50.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>85 kHz</th>
<th>1 MHz</th>
<th>10 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$ (pF)</td>
<td>320</td>
<td>260</td>
<td>213</td>
</tr>
<tr>
<td>$R_C$ (Ohms)</td>
<td>335</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>$L$ (mH)</td>
<td>11</td>
<td>0.1</td>
<td>1.2e-3</td>
</tr>
<tr>
<td>$R_L$ (Ω)</td>
<td>118</td>
<td>12</td>
<td>2</td>
</tr>
</tbody>
</table>

A second simulation of the model was conducted after adding the inductor $L$ and its series resistance $R_L$ in the model. The results of the analysis are shown in Figure I-9 for an 85 kHz operating frequency. The transmitting and receiving plates are represented by the heavy black bodies in the figure. The shaded part of the geometry represents the three main layers of road. It is noticed that the electric field is directly perpendicular between the two plates and it curves around the corners.

Figure I-9: Unipolar vertical design simulation results at 85 kHz
The shaded parts of the geometry represent the road pavement which includes three layers – ‘subgrade’, ‘base’ and ‘top’. The transmitting plate was installed between the ‘subgrade’ and ‘base’ layer. The receiving plate was installed between the ‘base’ and ‘top’ layer. The arrows indicate the intensity and direction of electric field lines.
The potential for supplying coils by capacitive coupling

The large gap between the transmitting and receiving plates (250 mm – width of ‘base layer’) creates stray fields to the surrounding environment. The intensity is measured at an imaginary ‘xy’ plane 25 cm above the road surface, which is a typical gap between the road surface and base of a car. The results are shown in Figure I-10. The maximum stray electric field was measured at 87 V/m around the corners of the capacitor module.

![Stray field of the Unipolar vertical design at 85 kHz](image)

Figure I-10: Stray field of the Unipolar vertical design at 85 kHz measured at an imaginary ‘xy’ plane 25 cm above the road surface. The figure also shows the road pavement with the three layers and the two plates of the system.

The accuracy of the mesh density in the model was then explored – mesh convergence. This refers to the smallness of the elements required in the model to ensure that the results of the analysis are not affected by changing the size of the mesh. The intensity of stray fields was measured 25 cm above the road surface for different levels of mesh density (different size of finite elements). The results are shown Figure I-11 and it is shown that mesh convergence was achieved when the mesh of the model consists of at least 540,000 finite elements. This corresponds to tetrahedral elements of 15 mm maximum size. Mesh convergence was investigated for each model to ensure that meshing does not affect the simulation results.

![Mesh convergence of the unipolar vertical design](image)

Figure I-11: Mesh convergence of the unipolar vertical design
It was shown that the intensity of the stray electric field 25 cm above the road surface is within the reference levels for human exposure to EMF (87 V/m according to ICNIRP) when a maximum load current, $i_{\text{Load}}$, of 0.15 A is allowed in the circuit at an operating frequency of 85 kHz. A maximum load current of 1.2 A and 2.7 A is allowed at an operating frequency of 1 MHz and 10 MHz respectively. To this end, high magnitude voltage source, $V_s$, is required to deliver 20 kW and 6.32 kW according to the two charging layouts. It is noticed in TABLE I-5 that abnormally high voltage sources are required at 85 kHz in particular.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>85 kHz</th>
<th>1 MHz</th>
<th>10 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i_{\text{Load}}$ (A) - max</td>
<td>0.15</td>
<td>1.2</td>
<td>2.7</td>
</tr>
<tr>
<td>$V_s$ (kV) for 20 kW</td>
<td>133</td>
<td>17</td>
<td>7.4</td>
</tr>
<tr>
<td>$V_s$ (kV) for 6.32 kW</td>
<td>42</td>
<td>5</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Similar analysis was conducted for the lateral design whereby the charging coils are supplied wirelessly from the hard-shoulder across a 1.8 m gap. The simulation model is shown in Figure I-12. The model includes the three main layers of road, which are the ‘subgrade’, ‘base’ and ‘top’ layers, and a section of air on the top to account the electric fringing effect.

The figure shows the three layers of road pavement (‘subgrade’, ‘base’ and ‘top’) and a layer of air on top of road to investigate stray electric fields. The transmitting plate was installed in the hard-shoulder area, half a meter from the beginning of the driving lane which is the origin of the ‘x’ axis. The receiving plate was installed in the driving lane at the 1.3 m position. The ‘y’ dimension of plates was set as 1.8 m based on the available area of a single capacitor module.

The two metal plates of the capacitor are represented by the two heavy black strips. Again, it was assumed that the plates are made of highly conductive material. They were embedded in the ‘top layer’ of road as shown in Figure I-4 and they were 1.8 m in length which is the available area of a single capacitor module. The origin of the ‘x’ axis in the figure separates
The potential for supplying coils by capacitive coupling

the hard shoulder and the driving lane of road. The transmitting plate was installed half a meter in the negative direction of ‘x’ axis and the receiving plate at the 1.3 m position (as shown in Figure I-4). The distance between the two plates was 1.8 m.

A first simulation was run to compute the admittance, \( Y \), of the capacitor module in order to determine the capacitance, \( C \), and series resistance, \( R_c \), of the model as given by (I-10) and (I-11). The inductor, \( L \), was calculated using (I-6) for compensation purposes and its series resistance, \( R_L \), was calculated using (I-12) to give a quality factor of 50. The results are shown in TABLE I-6 for 85 kHz, 1 MHz and 10 MHz frequencies. The maximum load current, \( i_{Load} \), to maintain stray fields within the reference levels of ICNIRP is 0.01 A at 85 kHz, 0.1 A at 1 MHz and 0.25 A at 10 MHz. Abnormally high voltage sources are needed for both 20 kW and 6.32 kW power transfer rates as shown in TABLE I-6.

<table>
<thead>
<tr>
<th>TABLE I-6: Circuit components of the unipolar lateral design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>C (pF)</td>
</tr>
<tr>
<td>( R_c ) (Ohms)</td>
</tr>
<tr>
<td>L (mH)</td>
</tr>
<tr>
<td>( R_L ) (Ω)</td>
</tr>
<tr>
<td>( i_{Load} ) (A) - max</td>
</tr>
<tr>
<td>Vs (kV) for 20 kW</td>
</tr>
<tr>
<td>Vs (kV) for 6.32 kW</td>
</tr>
</tbody>
</table>

Overall, the analysis suggests that the adoption of the unipolar approach is not a feasible approach to supply wirelessly the charging coils. It was shown that low load currents, \( i_{Load} \), are necessary to meet the reference levels of human exposure to EMF. This requires the employment of abnormally high voltage sources to deliver 20 kW or 6.32 kW power according to the two charging layouts. As a result, the rest of this chapter focuses on the development of capacitive connections based on the bipolar approach.

I.3.2 Bipolar Approach

The first model to be investigated for the bipolar capacitive coupling approach is the vertical design with a car included in the model as shown in Figure I-13. The model includes the three layers of the road pavement and a layer of air at the top to investigate stray electric fields. The capacitor module includes two sets of capacitors according to the bipolar approach shown in Figure I-5. Nevertheless, the system conforms to the 1x1.8 m target area in the ‘x’ and ‘y’ direction respectively. The two transmitting and receiving electrodes were installed
just below and above the ‘base layer’ respectively with 250 mm separation distance as described in Figure I-4. The ‘y’ direction of the model refers to the direction of vehicles’ travelling whereas the ‘x’ direction is the lateral dimension of the driving lane. The geometry of the car was obtained from COMSOL’s database. It was assumed that the highlighted parts of the car (see Figure I-13) are made of conductive materials. Glass material properties were assigned for the windows, rubber properties for the tyres and alloy-steel properties for the wheels of the car.

![Figure I-13: Bipolar vertical design with car included in the model](image)

The two transmitting plates of the capacitor module are represented by electrodes 1-2 in the model. The two receiving plates are represented by 3-4 and the conductive body of the car by electrode number 5.

The work on the bipolar technique starts with the identification of the mutual capacitances due to the existence of multiple electrodes in the system. The equivalent circuit of the road diagram (illustrated in Figure I-13) is shown in Figure I-14. Electrodes with numbering 1-4 refer to the four active transmitting and receiving plates of the capacitor module while number 5 stands for the floating electrode due to the metallic parts of the vehicle.

![Figure I-14: Mutual capacitance between electrodes](image)

The heavy black vertical lines 1-5 represent the electrodes of the system. The solid lines, $C_{13}$ and $C_{14}$, indicate intentional capacitance. The dotted lines indicate unintentional mutual capacitance that occurs between any two electrodes.
The potential for supplying coils by capacitive coupling

The relation between voltages and charges on the electrodes of the system is provided by the Maxwell capacitance matrix which is explained in [17]. For a set of conductors, the following relation is valid

\[ Q = C \cdot V \]  \hspace{1cm} (I-13)

where \( C \) is the Maxwell capacitance matrix, and \( V \) and \( Q \) are voltage and charge vectors respectively. For the model under investigation, relation (I-13) takes the form of

\[
\begin{bmatrix}
Q_1 \\
Q_2 \\
Q_3 \\
Q_4 \\
Q_5
\end{bmatrix} =
\begin{bmatrix}
\sum_{j=1}^{5} C_{1j} & -C_{12} & -C_{13} & -C_{14} & -C_{15} \\
-C_{21} & \sum_{j=1}^{5} C_{2j} & -C_{23} & -C_{24} & -C_{25} \\
-C_{31} & -C_{32} & \sum_{j=1}^{5} C_{3j} & -C_{34} & -C_{35} \\
-C_{41} & -C_{42} & -C_{43} & \sum_{j=1}^{5} C_{4j} & -C_{45} \\
-C_{51} & -C_{52} & -C_{53} & -C_{54} & \sum_{j=1}^{5} C_{5j}
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2 \\
V_3 \\
V_4 \\
V_5
\end{bmatrix}
\]  \hspace{1cm} (I-14)

where \( Q_i \) and \( V_i \) is the charge and voltage on the \( i_{th} \) electrode. \( C_{ij} \) is the capacitance between the \( i_{th} \) and \( j_{th} \) electrode of the system. Assuming

\[
V = \begin{bmatrix}
V_1 \\
V_2 \\
V_3 \\
V_4 \\
V_5
\end{bmatrix} = \begin{bmatrix}
1 \\
0 \\
0 \\
0 \\
0
\end{bmatrix},
\]  \hspace{1cm} (I-15)

expression (I-14) takes the form of

\[
\begin{bmatrix}
Q_1 \\
Q_2 \\
Q_3 \\
Q_4 \\
Q_5
\end{bmatrix} =
\begin{bmatrix}
C_{11} + C_{12} + C_{13} + C_{14} + C_{15} \\
-C_{12} \\
-C_{13} \\
-C_{14} \\
-C_{15}
\end{bmatrix}
\]  \hspace{1cm} (I-16)

The charge \( Q \) on each electrode was computed by the software and hence, the following capacitances can be calculated as follows:
\[
\begin{bmatrix}
C_{12} \\
C_{13} \\
C_{14} \\
C_{15}
\end{bmatrix} = 
\begin{bmatrix}
-Q_2 \\
-Q_3 \\
-Q_4 \\
-Q_5
\end{bmatrix}.
\]

(I-17)

The process was repeated four more times to calculate all capacitances of the system between the \(i_{th}\) and \(j_{th}\) electrodes, \(C_{ij}\). For each simulation denoted \(k\), the following voltages were applied

\[
V = \begin{cases}
V_k = 1 \\
V_{\text{other}} = 0
\end{cases}.
\]

(I-18)

Similarly, the series resistance \(R_{ij}\) for each section of the circuit (dielectric losses) was calculated according to the methodology described in I.3.1. The equivalent circuit of the model, including the mutual capacitance between electrodes their series resistance, is depicted in Figure I-15.

![Figure I-15: Bipolar capacitive coupling equivalent circuit](image)

The series capacitor-resistance networks in the circuit were altered to their equivalent parallel components using

\[
C'_{ij} = C_{ij}
\]

(I-19)

\[
R'_{ij} = \frac{1}{\omega^2 C^2 R_{ij}}
\]

(I-20)

where \(C_{ij}, R_{ij}\) and \(C'_{ij}, R'_{ij}\) are the series and parallel components respectively. For example, the series network between electrodes 1 and 4 \((C_{14}, R_{14})\) in Figure I-15 was converted to the parallel network \((C'_{14}, R'_{14})\) as it is shown in Figure I-16.
The potential for supplying coils by capacitive coupling

Then, some components of the circuit in Figure I-15 were re-arranged for simplification. Capacitors $C_{15}$ and $C_{25}$ can be considered as a series network since they have a common node. The equivalent shunt capacitance between electrodes 1-2, $C_{p1}$, is determined by

$$C_{p1} = C_{12} + \frac{C_{15} \times C_{25}}{C_{15} + C_{25}}$$

(I-21)

and the equivalent shunt resistance, $R_{p1}$, is given by

$$R_{p1} = \frac{1}{\left(\frac{1}{R'_{12}} + \frac{1}{R'_{15} + R'_{25}}\right)}$$

(I-22)

where $R'_{12}$, $R'_{15}$ and $R'_{25}$ are the series resistance of capacitors $C_{12}$, $C_{15}$ and $C_{25}$ respectively after the conversion into the equivalent parallel network using (I-20).

The same approach was followed for the receiving side of the circuit. The equivalent shunt capacitance and resistance between electrodes 3-4, $C_{p2}$, $R_{p2}$, were calculated using

$$C_{p2} = C_{34} + \frac{C_{35} \times C_{45}}{C_{35} + C_{45}}$$

(I-23)

$$R_{p2} = \frac{1}{\left(\frac{1}{R'_{34}} + \frac{1}{R'_{35} + R'_{45}}\right)}$$

(I-24)

The reduced circuit is shown in Figure I-16.

Then, we introduced inductors $L_{13}, L_{24}, L_{p1}$, and $L_{p2}$ to compensate the capacitive reactance of capacitors $C_{13}, C_{24}, C_{p1}$, and $C_{p2}$ respectively as it shown in Figure I-17. Their values were determined using (I-6) and their series resistance, $R_L$, was calculated using (I-12) to give a quality factor of 50.
The capacitive reactance of the circuit is counter-balanced by the reactance of the added inductors and therefore, the equivalent circuit with only resistive components was obtained as shown in Figure I-18. The cross-coupling capacitances of the system, \( C_{14}, C_{32} \), was temporarily ignored.

The ‘Delta to Y’ transformation technique was exploited to make the analysis of the circuit a more straightforward task. In particular, the ‘Delta’ network 1-3-4 was identified and converted into the equivalent ‘\( \gamma \)’ network as shown in Figure I-19.

The components of the circuit are described by

\[
R_1 = \frac{R_{13} \times R_{14}'}{R_{13} + R_{14}' + \frac{R_{P2} \times R_{LOAD}}{R_{P2} + R_{LOAD}}} \quad \text{(I-25)}
\]
The potential for supplying coils by capacitive coupling

\[ R_2 = \frac{R_p X R_{LOAD} X R'_{14}}{R_1 + R'_{14} + \frac{R_p X R_{LOAD}}{R_2 + R_{LOAD}}} \]  
\[ R_3 = \frac{R_p X R_{LOAD} X R_{13}}{R_1 + R'_{14} + \frac{R_p X R_{LOAD}}{R_2 + R_{LOAD}}} \]

The resulting circuit is shown in Figure I-20.

The shunt impedance across nodes 1 and 2, \( Z_{12} \), (parallel to \( R_p \)) can be calculated as

\[ Z_{12} = R_1 + \frac{(R_2 + R_{13})(R_3 + R'_{32})}{R_2 + R_{13} + R_3 + R'_{32}}. \]  

The total impedance of the circuit \( Z_{total} \) is therefore given by

\[ Z_{total} = R_{L13} + R_{L24} + \frac{R_p X z_{12}}{R_p + z_{12}} \]  

and the current source \( i_s \) is defined by

\[ i_s = \frac{2V_s}{Z_{total}}. \]  

The current in other paths of the circuit was calculated as follows:

\[ i_1 = \frac{i_s R_p}{R_p + z_{12}} \]  
\[ i_2 = \frac{i_1(R_2 + R_{13})}{(R_2 + R_{13} + R_3 + R'_{32})} \]  
\[ i_3 = \frac{i_1(R_3 + R'_{32})}{R_2 + R_{13} + R_3 + R'_{32}}. \]
Keeping in mind that the load is connected between nodes 3 and 4 of Figure I-20, the power supplied to the load was calculated using

\[ P_{LOAD} = \frac{V_{LOAD}^2}{R_{LOAD}} = \frac{V_{34}^2}{R_{LOAD}} \]  

where the voltage difference between nodes 3 and 4, \( V_{34} \), is given by

\[ V_{34} = V_{32} - V_{42} = i_2 R_{32}' - i_3 R_{13}. \]  

Combining together (I-20) - (I-35) shows that the power supplied to load, \( P_{Load} \), is a function of the voltage source \( V_s \), the equivalent load resistance \( R_{Load} \), the series resistances of various capacitors \( R_{ij} \) between the \( i_{th} \) and \( j_{th} \) electrode in the circuit and the series resistance \( R_L \) of the added inductors,

\[ P_{Load} = f(V_s, R_{Load}, R_{ij}, R_L). \]  

The effect of the cross-coupling parasitic capacitances was then considered. The inductors \( L_5 \) - \( L_8 \) were added to the circuit of Figure I-17 to counter-balance the capacitive reactance of \( C_{14} \) and \( C_{34} \). The resulting circuit is shown in Figure I-21.

\[ i c_{14} = \frac{j \omega C_{14}(V_1 - V_4)}{1 + j \omega R_{14} C_{14}} \]  

where \( V_4 \) equals \( V_s \) and \( V_1 \) is given by

\[ V_1 = V_s - i_s (R_{L13} + j \omega L_{13}). \]
The potential for supplying coils by capacitive coupling

The magnitude of $i_{c14}$ is the same with the current flowing through the cross-coupling parasitic capacitance $C_{32}$ because $V_1$ equals $-V_2$ and $V_3$ equals $-V_4$. Capacitors $C_{14}$ and $C_{32}$ have also the same magnitude.

Assuming that the same amount of current should pass through the added inductors, $L_5 - L_8$, for balancing out the reactive power of cross-coupling reactance, we can determine their inductance as follows

$$L_5 = L_6 = \frac{-V_1}{j\omega i_{c14}} \quad (I-39)$$

$$L_7 = L_8 = \frac{-V_5}{j\omega i_{c14}}. \quad (I-40)$$

Inductors $L_5$ and $L_6$ are connected in series and this combination is in parallel with the $L_{p1}$ inductor. To this end, a single inductor $L_{p\,tra}$ can be inserted to replace the three individual inductors on the transmitting side. Its value is given by

$$L_{p\,tra} = \frac{L_{p1}X (L_5 + L_6)}{L_{p1} + L_5 + L_6}. \quad (I-41)$$

In a similar way, the $L_{p\,rec}$ inductor on the receiving side was calculated by

$$L_{p\,rec} = \frac{L_{p2}X (L_7 + L_8)}{L_{p2} + L_7 + L_8}. \quad (I-42)$$

The final bipolar capacitive coupling equivalent circuit is shown in Figure I-22.

\[\text{Figure I-22: Bipolar capacitive coupling circuit}\]

**Bipolar vertical design**

The first model to be investigated for the bipolar capacitive coupling approach is the vertical design with a car included in the model which was presented earlier in Figure I-13. At the
beginning, the circuit components of Figure I-22 were determined and after that, the performance of the system was evaluated using the finite element software. The AC/DC currents interface was assigned to the simulation model and meshing the geometry was performed automatically by the software as described in section I.3.1.

Choosing the circuit components of Figure I-22 depends on the geometry of the model and in particular, the capacitances and series resistance between the various electrodes of the system. To this end, a first simulation was conducted to compute these parameters based on the analysis presented above. A variety of design models were investigated with the intention of minimising parasitic capacitances and maximising the effective capacitance between electrodes 1 to 3, \( C_{13} \) (or \( C_{24} \)). The available area of 1x1.8 m for a single capacitor module was considered as shown in Figure I-23. Different sizes of plates in the ‘x’ and ‘y’ dimensions were investigated. The distance between plates in the ‘y’ direction was also explored whereas the ‘z’ separation distance remained fixed at 250 mm (width of ‘base layer’).

![Figure I-23: Minimising parasitic capacitance for the bipolar vertical design](image)

The results of the analysis are shown in TABLE I-7. Electrodes 1-2 refer to the transmitting plates and 3-4 to the receiving plates of the capacitor module. Electrode 5 refers to the conductive parts of the car in the model. The capacitances \( C_{12}, C_{14}, C_{15}, C_{34} \) and \( C_{35} \) were computed and after that, the normalised capacitances were calculated over the effective capacitance \( C_{13} \). The total normalised capacitance of the model for each configuration is shown in Figure I-24.

It is noticed that minimum parasitic capacitance is possible when both the transmitter and receiver plates have dimensions of 1x0.6 m in the ‘x’ and ‘y’ direction respectively separated
The potential for supplying coils by capacitive coupling

by 0.3 m in the ‘y’ direction. It should be mentioned that installation of multiple capacitor modules adjacent to each other does not affect the characteristics of the system because the gap between each electrode remains constant.

**TABLE I-7: Minimising parasitic capacitance for the bipolar vertical design**

<table>
<thead>
<tr>
<th>Configuration number</th>
<th>Dimensions (m)</th>
<th>Capacitance (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$X_{tra}$</td>
<td>$X_{rec}$</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure I-24: Normalised parasitic capacitance for various model designs

After choosing the geometry of the system for minimising parasitic capacitance, the compensating components of the circuit were determined to counter-balance the reactive capacitance of the system. The value of inductors $L_{13}$, $L_{14}$, $L_{ptra}$, $L_{prec}$ coupled with the series resistance $R_{L13}$, $R_{L14}$, $R_{ptra}$, $R_{prec}$ were calculated as described above. The series resistances were computed to give a quality factor $Q$ of 50.

The load resistance, $R_{LOAD}$, was then chosen appropriately to maximise the efficiency of the system. A relatively small load resistance, generates high magnitude of current. Dielectric losses are dependent on the square value of current and therefore, a great proportion of the input power is lost as heat. By contrast, a relatively big $R_{Load}$ creates a not favoured path for the current in the circuit which predominantly flows in other lower resistive paths. Under this condition, a small proportion of the input power is supplied to the load which compromises
efficiency. Overall, the efficiency of the system as function of the load resistance is shown in Figure I-25.

![Figure I-25: Efficiency of the bipolar capacitive coupling system as function of the load resistance, $R_{LOAD}$ (equivalent resistance of charging coil) at 85kHz](image)

The magnitude of voltage source $V_s$ was determined to achieve the required output power and complete the circuit of Figure I-22. This was achieved by solving (I-36) for $V_s$. The calculated circuit components are summarised in TABLE I-8 for 85 kHz and 1 MHz.

<table>
<thead>
<tr>
<th>TABLE I-8: Circuit components and simulation results - bipolar vertical design with car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>$[C_{12}, C_{150}, C_{153}]$ (pF)</td>
</tr>
<tr>
<td>$[C_{34}, C_{35}]$ (pF)</td>
</tr>
<tr>
<td>$[R_{12}, R_{153}, R_{34}, R_{153}]$ (Ohms)</td>
</tr>
<tr>
<td>$[R_{34}, R_{453}]$ (Ohms)</td>
</tr>
<tr>
<td>$L_{13}-L_{24}$ (mH)</td>
</tr>
<tr>
<td>$R_{13}-R_{24}$ (Ohms)</td>
</tr>
<tr>
<td>$[L_{Ptra}, L_{Prec}]$ (mH)</td>
</tr>
<tr>
<td>$[R_{LPtra}, R_{LPrec}]$ (Ohms)</td>
</tr>
<tr>
<td>$R_{LOAD}$ (kOhms)</td>
</tr>
<tr>
<td>$V_s$ (kV) for 20 kW</td>
</tr>
<tr>
<td>$V_s$ (kV) for 6.32 kW</td>
</tr>
<tr>
<td>EMF to drivers (V/m) for 20 kW</td>
</tr>
<tr>
<td>EMF to drivers (V/m) for 6.32 kW</td>
</tr>
<tr>
<td>COMSOL efficiency (%)</td>
</tr>
<tr>
<td>COMSOL power factor</td>
</tr>
</tbody>
</table>

After choosing the circuit components of Figure I-22, the proper functionality of the model was verified using the selected finite element software. Two models were examined based on the two possible charging layouts (20 kW and 6.32 kW) for an operating frequency of...
85 kHz. The efficiency of the system and the power factor were calculated based on the simulation software. The results are shown in the lower part of TABLE 1-8.

It should be noted that efficiency is defined as the power delivered to load over the power supplied to the capacitive coupling circuit presented in Figure 1-22. Dielectric losses in the materials involved and power losses in inductors windings were taken into consideration. Any losses within the power converters before the capacitive coupling system were not considered in the study.

From TABLE 1-8 it can be seen that the calculated efficiency is 86% at 85 kHz which is a comparable figure with the 78-94% efficiency reported in the literature. For comparison, 90% efficiency has been reported in [162] but the gap between the transmitting and receiving plates was limited to 120 mm instead of 250 mm. Furthermore, the intervening material between the transmitting and receiving plates in [162] was selected to provide enhanced relative permittivity; a technique which is not possible for the proposed system. Efficiencies around 90-94% have been also reported in [163] and [166] but the separation distance was once again smaller at 150 mm.

Figure 1-26 shows the power delivered to the load, $P_{\text{Load}}$, and the efficiency relative to the level of mesh density. It is shown that mesh convergence is possible when the mesh of the model consists of at least 1,000,000 tetrahedral finite elements of 25 mm maximum size.

![Figure 1-26: Mesh convergence of the bipolar vertical design](image)

The area with electric fields above the reference level of 614 V/m by IEEE (TABLE 1-3), is shaded in Figure 1-27. The electric field inside the car is well below the reference levels; and as low as 24 V/m for 20 kW power transfer and 13 V/m for 6.32 kW power transfer. This is
due to the fact that the car acts like a Faraday cage and prevents the penetration of electric field into the interior.

![Diagram of a car](image)

**Figure I-27:** Electric field above 614 V/m at 85 kHz for the 6.32 kW power transfer

Notably, steel and carbon fibre are mostly used by the automotive industry for manufacturing car bodies and both are conductive materials. It was described earlier that the highlighted parts of the car in Figure I-13 are assumed to be made of conductive materials. The electric field inside the vehicle is kept to a minimum even if the car body is not a perfect Faraday cage. This observation is supported by [174] which states that cars are designed to act like Faraday cages for protecting passengers when they are struck by lightning.

Although high efficiency and power factor have been obtained, it should be noted that rather high magnitude voltage sources are necessary to maintain the desired power transfer rates. For the case of 20 kW power transfer in particular, two voltage sources of 9.7 kV are required.

The analysis continues with the possibility of increasing the operating frequency of the system to 1 MHz to reduce the magnitude of the required voltage source. Following the same procedure as before, we firstly determined the design option with the minimum parasitic capacitance and then determined the value of the load resistance in order to maximise the efficiency of the system. The derived circuit components and the simulation results are stated in TABLE I-8 and the reader may notice now considerably lower magnitude voltage sources no greater than 3 kV. The EMF exposure to drivers inside the car is restricted below the reference levels at 6 V/m and 4 V/m for the 20 kW and 6.32 kW power transfer application.

EMF exposure to human drivers is less of a concern because the conductive body of cars largely prevents the electric field from penetrating the vehicle. Nevertheless, the car was
The potential for supplying coils by capacitive coupling

removed from the simulation model and the natural decay of the electric field above the road was investigated. The same methodology was followed for this example. The minimisation of parasitic capacitances was followed by the calculation of the circuit components for maximising efficiency and maintaining appropriate power transfer rates.

Despite the fact that high efficiency and power factor were obtained, the magnitude of the electric field above the road surface substantially exceeds the EMF exposure reference limits. In particular, the magnitude of the electric field at 250 mm above the road surface, which is the average height of a passenger car, reaches the level of 5 kV/m; in comparison with the 614 V/m and 87 V/m reference values by IEEE and ICNIRP. The two receiving plates have the same magnitude but opposite sign voltages which matches the large magnitude of the input voltage source $V_s$. A large voltage difference is maintained between the two electrodes which creates a strong electric field regardless of the limited capacitance between them.

Firstly, the adoption of multiple transmitting and receiving plates within a capacitor module to counter-balance the electric fringing field lines was considered. The higher parasitic capacitance was a performance limiting factor.

Then, the adoption of a plate above the capacitor module to restrict the electric field below the surface of the road was investigated. The integrated plate has 1x1.8 m dimensions in order to cover all the available capacitor module area and was inserted 40 mm below the road surface; since 30-40 mm is the depth of potential road charging coil systems. The stray field in the surrounding environment was effectively restricted below the reference levels of IEEE at 250 mm above the road surface with approximately 5% penalty on efficiency.

*Lateral bipolar design*

The bipolar lateral approach was also explored, whereby power is transferred from the hard-shoulder to the road chargers laterally (Figure I-4). The four metal plates had 100 mm height to match the ‘top layer’ of the road pavement and the distance between transmitting and receiving plates was 1.8 m. The effective capacitance between a transmitting and receiving plate, i.e. $C_{13}, C_{24}$, is similar to the parasitic capacitance between two transmitting or two receiving plates, i.e. $C_{12}, C_{34}$. It was therefore necessary to consider only the second charging layout proposed by TRL for motorways whereby 20 kW have to be transferred within 5.7 m (and not 1.8 m). The larger length of the module is particularly advantageous for installing the
electrodes more sparsely and minimise parasitic capacitance. Various designs were investigated for minimising parasitic capacitance and maximising the effective capacitance. The normalised parasitic capacitance of the system was computed for various configurations and it was shown that the transmitting and receiving plates should be 1.8 m in length combined with 0.55 m separating distance. The simulation model is shown in Figure I-28. The origin of ‘x’ axis represents the beginning of the driving lane whereas negative ‘x’ values correspond to the hard-shoulder. The transmitting plates were installed half a metre in the negative direction of ‘x’ axis and the receiving plates were installed at the 1.3 m position inside the driving lane.

Following the same procedure as before, the circuit components were calculated and the finite element analysis was exploited for the model verification. The results are summarised in TABLE I-9. The efficiency of the system reached 79% at 85 kHz operating frequency and 75% at 1 MHz operating frequency. The power factor of the system was computed at 0.99 for both frequencies. The required voltage source \( V_s \) at 20 kW power transfer was calculated at 20 kV at 85 kHz operating frequency and 7.2 kV at 1 MHz.

The large transmitting distance leads to severe field fringing effects. The magnitude of the electric field 250 mm above the road surface reached the level of 80 kV/m at 85 kHz and 40 kV/m at 1 MHz in comparison with the 614 V/m and 87 V/m reference values provided by IEEE and ICNIRP respectively. A variety of techniques were investigated to alleviate the
problem of fringing electric fields but none has been identified as effective enough. These include the adoption of a higher operating frequency, ground plates above or between the electrodes, and multiple sets of capacitors.

Nevertheless, the inclusion of a car in the simulation shows that once again that the EMF exposure inside the vehicle is minimum due to shielding caused by the vehicle body. The EMF exposure to drivers was computed at 376 V/m and 110 V/m at 85 kHz and 1 MHz respectively (TABLE I-9). These values exceed the ICNIRP reference levels for human exposure to EMF but they are within the IEEE reference levels.

| TABLE I-9: Circuit components and simulation results - bipolar lateral design with car |
|-----------------------------------------------|-----------------|-----------------|
| Frequency                  | 85 kHz          | 1 MHz           |
| 
| [C12, C13, C14, C15] (pF) | [20, 35, 8, 39] | [13, 24, 6, 36] |
| [C34, C45] (pF)            | [9, 93]         | [5, 80]         |
| [Rc12, Rc13, Rc14, Rc15] (Ohms) | [3841, 2670, 13370, 630] | [602, 465, 2072, 74] |
| [Rc34, Rc45] (Ohms)        | [18070, 263]    | [3474, 37]      |
| L13-L24 (mH)               | 98.3            | 1.0             |
| RL13-RL24 (Ohms)           | 1100            | 132             |
| [Lpiptra, Lpirc] (mH)       | [79.8, 50.1]    | [0.7, 0.6]      |
| [RLpiptra, RLpirrec] (Ohms) | [850, 535]     | [88, 75]        |
| RLOAD (kOhms)              | 64000           | 7600            |
| Power (kW)                 | 20              | 20              |
| Vs (kV)                    | 20.1            | 7.2             |
| EMF exposure to drivers (V/m) | 376            | 110             |
| COMSOL efficiency (%)      | 79              | 75              |
| COMSOL power factor        | 0.99            | 0.99            |

I.3.3 Supplementary Work

*Hard-shoulder EMF exposure*

The conductive body of a car largely prevents the electric field from penetrating the vehicle. The high electric fields would interfere with unprotected road users, such as cyclists and pedestrians, and with living creatures locates in the hard-shoulder area.

The bipolar vertical design with included car was chosen to investigate the intensity of electric fields in the hard-shoulder area. The simulation model used earlier shown in Figure I-13 was chosen for demonstration in this section. The circuit components and simulation results of that model are summarised in TABLE I-8. It was shown that exposure to EMF on human drivers is negligible which is as low as 24 V/m and 6 V/m for 20 kW power transfer rate at an operating frequency of 85 kHz and 1 MHz respectively.
However, electric fields in the hard-shoulder area exceed the reference levels for human exposure when the 20 kW power transfer application at 85 kHz operating frequency is adopted. The highlighted area of Figure I-29 shows the magnitude of electric field that exceeds the 614 V/m IEEE reference level for human exposure to EMF. It is noticed that potentially hazardous electric fields penetrate the hard-shoulder, which is the area starting from the origin of ‘x’ axis and extending to the left. The analysis showed that electric fields above 614 V/m do not penetrate the hard-shoulder when the 6.32 kW power transfer application at 85 kHz is adopted or the 20 kW/6.32 kW power transfer applications at 1 MHz are considered.

![Figure I-29: Electric field higher than 614 V/m – bipolar vertical design at 85 kHz](image)

A top view perspective of the two receiving plates is shown with the two heavy black rectangles in the middle of the lane.

It was shown that one thin strip of metal plate between the drive lane and hard-shoulder area captures the fringing electric lines. The simulation model is shown in Figure I-30. The metal strip was 1.8 m in length to cover the entire length of the capacitor module, it had 5 cm width and it was installed at the origin of ‘x’ axis. It was embedded in the ‘top layer’ of road.

![Figure I-30: Simulation model - bipolar vertical design with metal strip](image)
This thin floating potential electrode captures the fringing electric lines and as it is revealed in Figure I-31 the electric flux does not penetrate the hard-shoulder area. The penalty on the efficiency is less than 1% compared with the original design.

By contrast, the same technique cannot control the EMF exposure on the hard-shoulder for the lateral design because the transmitting plates are already located in the hard-shoulder. Some form of detection should de-activate an operating module when humans or animals are located within the potential hazardous zones.

**Wet conditions**

The following analysis explores the performance of the capacitive connections under wet conditions. The values of the relative permittivity and electrical conductivity of the materials involved are increased significantly due to the existence of water in the system. These values are stated in TABLE I-2 in the section of Assumptions.

The performance of the bipolar vertical design with a car included in the model at 85 kHz was investigated. The same circuit configuration developed for dry conditions was studied without any alterations to the circuit components. The results indicate that both the efficiency and the power factor of the system are reduced drastically reaching a low value of 50% and 0.50 respectively. Subsequently, new circuit components were calculated based on the higher capacitances and series resistance between the electrodes of the system due to the new
operation conditions. The power factor of the system improved considerably reaching the figure of 0.99 but the efficiency of the system remained low at around 60%.

### I.4 Conclusions

It was shown in this appendix that the adoption of the capacitive coupling technique to supply road charging coils for the CoM transport application has limited potential for further investigation and consideration. A variety of designs were investigated based on the unipolar and bipolar approaches and different options were developed both for vertical and lateral power transfer applications. The examples were evaluated according to their performance and their EMF exposure pollution.

The analysis showed that the adoption of the unipolar approach is not feasible for supplying the vehicle charging coils wirelessly. It was shown that the circuit current must be restricted to low values to meet the reference levels of human exposure to EMF. This requires the employment of abnormally high voltage sources.

More promising results were presented for the bipolar capacitive coupling approach with included car in the simulation model. It was shown that the drivers’ exposure to EMF is very limited due to the fact that car bodies act as a Faraday cage. Circuit configurations were developed for 20 kW and 6.32 kW power transfer rates and additionally, vertical and lateral power transfer applications were developed. For the vertical design, it was shown that efficiencies between 80-86% could be obtained at 1 MHz and 85 kHz respectively across a 250 mm gap. Power factor of 1.00 was achieved for both operating frequencies. Similarly, 75-79% efficiency and 0.99 power factor were obtained for the lateral design at 1 MHz and 85 kHz respectively and a 1.8 m separation distance.

EMF exposure to human drivers is less of a concern because the conductive body of cars largely prevents the electric field from penetrating the vehicle. Nevertheless, stray fields for the vertical configuration can be controlled within the acceptable reference levels above the road surface without the protection of cars. This would require the installation of a plate above the capacitor module to capture the stray electric fields. This technique reduces the efficiency of the system by 5%.

The high electric fields in the hard-shoulder area need to be addressed when the bipolar vertical configuration of 20 kW at 85 kHz is adopted. It was shown that the installation of a
metal strip at the beginning of the hard-shoulder restricts the leakage electric field to penetrate the hard-shoulder area. This technique has less than 1% penalty on the system’s efficiency. The lateral design would require other techniques, such as motion detectors in the hard-shoulder area, to prevent potential exposure of humans and animals to EMF.

Operation under wet conditions might not be a problem provided the road pavement has effective drainage systems in place. If that is not the case, the performance of the system is affected substantially due to high dielectric losses.

Overall, this chapter shows that issues of dielectric losses, stray fields and operation under wet conditions need to be addressed effectively before capacitive coupling becomes a viable proposal for supplying coils for charge-on-the-move.
References


INTIS, “EVs Unplugged,” *IHS-Automotive Hybrid-EV Anal.*, vol. 6, no. 5, pp. 8–11, 2015.


Transport Research Laboratory, “Preparing the Strategic Road Network for increased use by electric vehicles,” 357(4/45/12)HALC, 2015.


H. G. Grunjes and M. Birkner, “Electro mobility for heavy duty vehicles (HDV): The


References


frequency Electromagnetic fields, 3 kHz to 300 GHz,” IEEE C95.1 2005, 2005.


