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Socio-technical factors influencing current trends in material throughput in the UK automotive industry

Simone Cooper, Brendan J. Doody, Julian M. Allwood*

Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, UK

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ABSTRACT

This paper investigates why material throughput remains high in the UK automotive industry when there are opportunities for material efficiency improvements. Informed by socio-technical studies of automobility, the paper emphasises the importance of recognising how decisions regarding material use are always shaped by more than simply cost considerations. Drawing on industry interviews, six interconnected socio-technical factors are identified that guide the vehicle design and manufacturing process. These are: (1) customer preferences; (2) market positioning; (3) techno-economic feasibility; (4) supply chain feasibility; (5) regulation and (6) organisational attributes. These factors can provide insights into the current operating context of the UK automotive industry and help explain why the average material intensity of vehicles and vehicle throughput are increasing. Overall, the paper shows that the efficiency of material use in the UK automotive industry is the outcome of complex and advanced design and manufacturing processes. Understanding these processes and the factors that guide them can potentially increase the likelihood of the automotive industry adopting material efficiency initiatives.

1. Introduction

Approximately a quarter of global greenhouse gas emissions (GhG) are released during the transformation of ores into materials, and materials into products and services (Bajzelj et al., 2013). If GhG emissions-intensive materials such as steel and aluminium were used more efficiently, there could be a reduction in industrial energy use and emissions. The Intergovernmental Panel on Climate Change (IPCC, 2014) conclude that industrial material efficiency, improving the ratio of material inputs to deliver products and services, is currently an underexploited GhG mitigation strategy.

The automotive industry is a large source of material demand. Globally the industry uses approximately 130 Mt/y (Wells, 2010). The total amount of material throughput along the automotive supply chain will depend on how much material is embedded in each vehicle (material intensity), how many vehicles are sold (vehicle throughput) and any yield losses that occur during the manufacturing process. Vehicles are manufactured and traded around the world. The UK for example, exports vehicles to over 100 countries. Over half of UK vehicles are sold in Europe (SMMT, 2016).

In Europe, the average material intensity of vehicles is growing (Fig. 1). In spite of efforts to switch to lighter materials and lightweight design, cars have become larger in size and heavier across all vehicle segments. This is partly due to the introduction of new features designed to improve comfort, safety, security and emissions control (Zervas, 2010). Data from the OICA (2016) shows vehicle throughput in the global automotive industry is also growing. Nearly 100 M cars and commercial vehicles were manufactured in 2015, almost double the output in 1997, to meet growing demand for personal mobility. In more mature markets, such as the EU where the stock of vehicles is stable (Eurostat, 2016), demand is also for replacement vehicles. Vehicle production in the UK automotive industry is increasing (ICCT, 2016), to meet both types of demand.

GhG emissions arise during material production, vehicle manufacture, vehicle use and material processing at the end of a vehicle's life. The amount of GhG emissions released at each stage is dependent on the material type and whether it is from primary or recycled sources. At present the ideal material mix is unclear. Switching between materials may lead to lower vehicle weight and in-use GhG emissions, but may result in higher lifecycle emissions depending on how a vehicle is used and how material is manufactured and treated at the end of a vehicle's life (Witik et al., 2011). Material efficiency improvements are complementary to material

* Corresponding author.
E-mail address: jma42@cam.ac.uk (J.M. Allwood).

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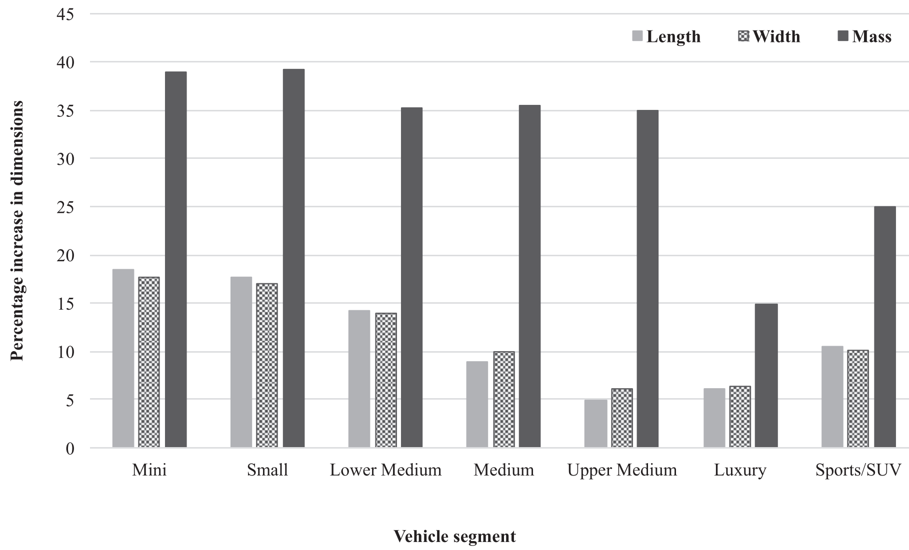

Fig. 1. Percentage increase in average EU vehicle dimensions by segment between the years 2001 and 2014 (ICCT, 2016).

switching as the strategies can be applied to almost any material mix. Allwood and Cullen (2012) detail strategies for material efficiency improvements throughout a vehicle's lifespan. From the outset, vehicle material intensity could be reduced by designing smaller, lighter cars. This could also reduce in-use GhG emissions. Holding all other factors constant, lighter cars have lower GhG emissions (German and Lutsey, 2010) as they require less energy to accelerate to a given speed and have a lower rolling and aerodynamic resistance. As a result, smaller, lighter cars require less fuel (Nieuwenhuis, 2014). During vehicle manufacturing, scrap material from the assembly line could be diverted for other uses and yield losses could be reduced through better tessellation and gripping. During the use-phase, vehicles could be used for longer and more efficiently. Car sharing for example, could reduce vehicle throughput as fewer cars would be needed to deliver passenger kilometres. Components could be reused at the end of a vehicle's life rather than re-melted to avoid further processing. Each of these strategies may require a change in the way the automotive industry designs, manufactures and captures value from cars.

Although these strategies are technically feasible, the increase in material intensity of cars and high vehicle throughput suggests they are not currently widely adopted in the automotive industry. There are a range of factors that influence how cars are designed, manufactured and sold by the industry (Wells and Nieuwenhuis, 2012), which mean that opportunities for GhG emissions reductions via material efficiency improvements may be a secondary consideration.

Using the UK automotive industry as a case study, this paper investigates why material throughput remains high when there are technically feasible opportunities to improve the efficiency of material use. It aims to identify what factors, specific to the UK operating context, are contributing to an increase in average vehicle material intensity and vehicle throughput. This analysis contributes empirical evidence to explain why opportunities for material efficiency improvements may not be realised within industry.

Section 2 of this paper outlines existing studies that have sought to explain the low uptake of material efficiency strategies in different sectors, including automotive. These papers typically employ either a techno-economic or a socio-technical framework. Techno-economic studies examine the barriers preventing individuals and firms from adopting more efficient technologies and strategies. Socio-technical studies examine how the interactions between various elements within a system (e.g. social, technical, political, cultural and economic) stabilise over time, which may result in more efficient technologies and processes not being adopted. Section 3 details the research methods employed in this study. Section 4 outlines six critical factors that guide the vehicle design and manufacturing process, providing insights into the operating context of the UK automotive industry. Section 5 discusses how these factors are contributing to increases in the material intensity of vehicles and vehicle throughput. Section 6 summarises the main research findings and suggests topics for future research.

2. Literature review

Material efficiency can be improved by implementing the six strategies outlined in Allwood and Cullen (2012). These are (1) lightweighting, (2) diverting manufacturing scrap, (3) reducing yield losses (4) using products for longer (5) using products more intensively and (6) reuse without re-melting. Studies which have sought to explain the limited uptake of these strategies typically adopt either 'techno-economic' or 'socio-technical' frameworks. These two analytical frameworks are underpinned by different assumptions, concepts, values and practices. These differences influence how non-adoption of material efficiency opportunities are researched and understood.

2.1. Techno-economic studies on barriers to more efficient material use

Existing research explaining the low uptake of material efficiency initiatives tend to be techno-economic studies. These type of studies assume that individuals and firms are perfectly informed, rational and introduce material efficiency improvements if they are cost-effective. Individuals and firms may experience a number of barriers which distort their behaviour and may mean that cost-effective material efficiency improvements are not adopted. Techno-economic studies aim to identify whether any barriers exist, with a view to removing or reducing their incidence. Techno-economic frameworks have also been applied to investigate barriers to energy efficiency improvements in different sectors and regions. A commonly used typology of barriers to energy efficiency improvements is found in Sorrell et al. (2004). Six categories of barriers are outlined, namely: risk, imperfect information, hidden costs, access to capital, split incentives and bounded rationality. The techno-economic literature on barriers to material efficiency is less developed and no equivalent typology exists. Researchers identify different barriers for each case study under investigation.

Pajunen et al. (2012) conducted semi-structured interviews with industry representatives in Finland and identified the cost of investment and high risk associated with unproven technologies as the two main barriers to effective material use. Shahbazi (2015) used a similar method to investigate barriers to material efficiency in the Swedish automotive industry. The author attributes a general lack of support for material efficiency initiatives to low levels of awareness, inadequate economic incentives and prioritisation of other issues. This can be interpreted as evidence of bounded rationality, split incentives and imperfect information flows within companies. Shahbazi et al. (2016) build on this earlier study by comparing empirical barriers in the Swedish automotive industry to theoretical barriers identified in academic studies. The authors only found empirical evidence for a subset of theoretical barriers. They conclude that these barriers are mainly internal as they depend on a company's characteristics and processes. They include a lack of vision and culture on achieving material efficiency improvements and inadequate communication with employees about potential material efficiency opportunities. In an input-output modelling study of steel use in the UK, Skelton and Allwood (2013) conclude that labour taxation is a large hidden cost and distorts the incentives to improve material efficiency. Theoretical studies such as Allwood et al. (2011) and IEA (2015) also identify various economic, social and political barriers which may impact the decision to introduce material efficiency improvements.

2.2. Socio-technical studies on causes of system continuity

Socio-technical studies do not make a priori assumptions on costs, information or the rationality of individuals and firms. These studies “situate technology and technological innovation in the social contexts in which they emerge” (Moloney et al., 2010). In a socio-technical framework, the decisions made by individuals and firms about material use and other issues are always shaped by their social, technical, political, cultural and economic settings. The process of designing, manufacturing and selling of cars is viewed as part of a wider system of automobility, comprising infrastructures, technologies, markets, practices and regulations that sustain vehicle manufacturing and use (Urry, 2004). Socio-technical systems, including automobility, are often characterised by stability. Individuals and firms are guided by cognitive routines, habits and other heuristics (Geels, 2012) and their actions are also shaped by sunk investments, contracts, standards and expectations (Geels and Kemp, 2007). As a consequence, existing systems tend to favour repetition and inertia, which result in incremental change along predictable trajectories (Geels and Kemp, 2007). This may mean that alternative, more materially efficient approaches are not adopted.

Geels (2012) identifies numerous sources of stability in the current automobility system, including: sunk investments in road infrastructure; vested interests; a general preference for the car; positive cultural discourse and legitimisation of the status quo by policymakers, industry and transport planners. These features help to explain the continued dominance of the car over other modes of transport. Vehicle designers and manufacturers are key actors within the automobility system (Orsato, 2004). Wells and Nieuwenhuis (2012) identify six socio-technical factors that currently encourage manufacturers to maintain the status quo, namely: (1) high sunk costs creating barriers to transformative change; (2) incremental rather than radical change in vehicle design and manufacturing; (3) internalisation of threats by securing supply of resources or disruptive technologies; (4) replication of products and processes throughout the industry; (5) a privileged position with policymakers and (6) continued demand for car ownership and use. As a consequence, the vehicle design and manufacturing process has only changes incrementally (Wells, 2010) and business models are mainly focused on generating revenues at the point of vehicle sale (Orsato and Wells, 2007). Practices in the current automobility system have resulted in many negative environmental and social impacts (Wells, 2010). Car production contributes to resource depletion and GhG emissions. Car use creates air and noise pollution and imposes social costs such as congestion and accidents. These impacts are not always fully reflected in the private costs of driving (Litman, 2009).

These negative impacts have prompted researchers to consider what elements could potentially feature in a more sustainable, low carbon system of automobility (Nieuwenhuis, 2014). This new system may include non-fossil fuel based powertrains, changes in car ownership and use or modal shifts away from the car (Geels, 2012), even leading to a ‘post-automobility system’ (Dennis and Urry, 2009). Wells and Xenias (2015) note these elements will each have different implications for the way that vehicles are produced, distributed, marketed, purchased, owned and used, with secondary impacts on material demand. Alternative powertrains, for example, would require less change to the current vehicle design and manufacturing process and business model than a large-scale modal shift to walking, cycling or public transport. In an exploratory study, Orsato (2004) identifies that existing business models and organisational capabilities of vehicle manufacturers are key socio-technical factors that influence if and how the European automotive industry will become more sustainable. Steinhilber et al. (2013) explores the role electric cars may play in redressing climate change and identifies many socio-technical factors which could inhibit the large-scale deployment of these vehicles in the UK and Germany. These include: a lack of commercially viable technologies; fragmented infrastructure; the absence of standards and regulations and consumer scepticism.

Existing socio-technical studies identify many sources of stability and inertia that may inhibit the emergence of an alternative, more sustainable system of automobility. These studies also illustrate the importance of recognising that individuals and firms are always guided by more than cost considerations. The operating context in which vehicle designers and manufacturers are embedded shapes their decisions and actions in ways that have significant implications for material use in the automotive industry. Improvements in the efficiency of material use could potentially feature in an alternative, low carbon system of automobility, but this has received little attention to date. This paper aims to address this gap in the socio-technical literature by examining the contexts in which vehicle designers and manufacturers in the UK operate. It identifies sources of stability that help explain why some opportunities for material efficiency improvements are currently unrealized. It investigates two interconnected research questions:

1) What socio-technical factors are important in guiding the design and manufacture of vehicles in the UK?
2) How are these factors contributing to current increases in average vehicle material intensity and vehicle throughput?

3. Method

Fig. 2 shows the research methods employed in this study. This approach corresponds with other socio-technical studies on low carbon automobility systems (for example see Orsato, 2004; Steinhilber et al., 2013). The study involved qualitative interviews

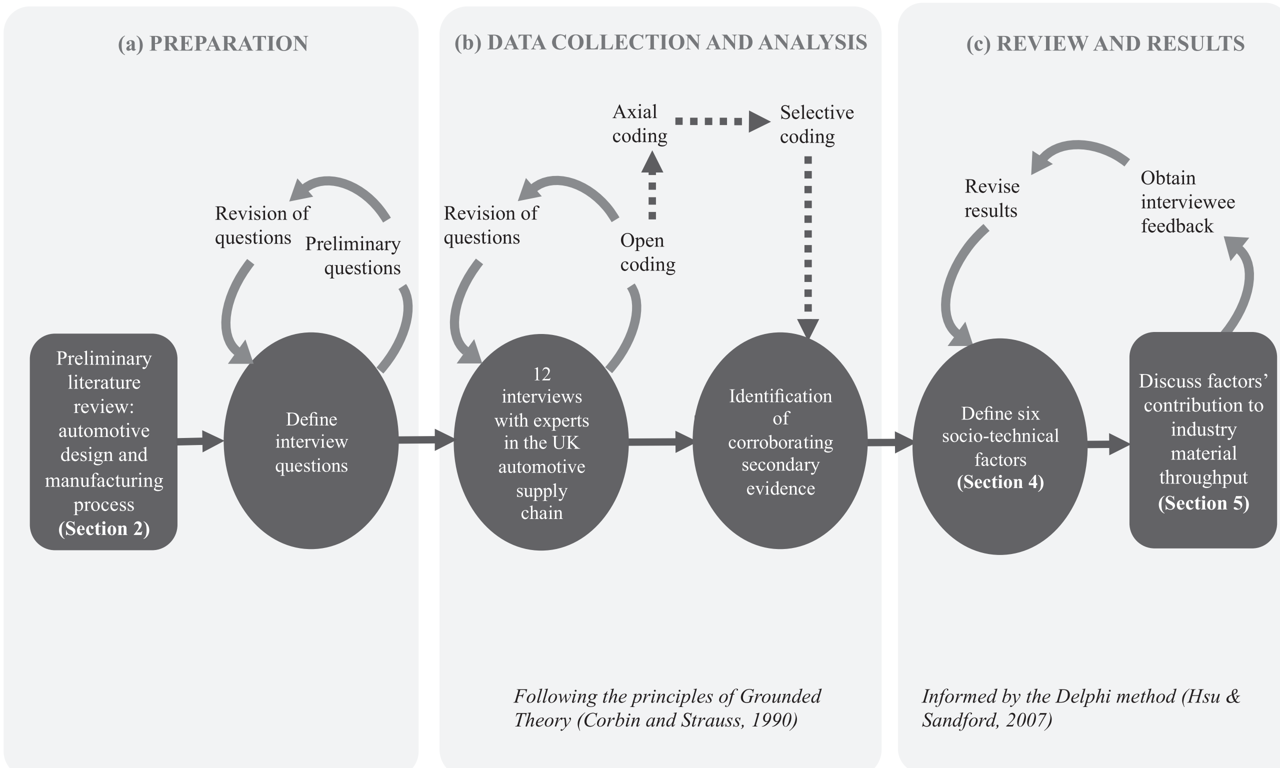

Fig. 2. Study method to derive six interconnected socio-technical factors that guide the vehicle design and manufacturing in the UK and discussion on their contribution to industry material throughput.

with industry experts. The results are qualitative. Data collection and analysis were informed by the principles of grounded theory, a deductive method of theory development. Corbin and Strauss (1990) explain that a grounded theory approach is appropriate for investigating the conditions that contribute to a situation, how actors in a situation respond to changing conditions and the consequences of this. Grounded theory corresponds with a socio-technical framework in at least two ways. First, both do not make a priori assumptions about which factors might be important in explaining why improvements in material efficiency are not realised. Second, both are attentive to the ways in which decisions and actions of individuals and firms associated with material use are embedded in specific social, technical, political, cultural and economic settings.

3.1. Description of method

As shown in box (a) in Fig. 2, a set of interview questions was prepared after reviewing the socio-technical literature outlined in Section 2.2. A preliminary interview was held with a former employee at a vehicle design and manufacturing plant. Following this preliminary interview, the questions were refined to clarify areas of misinterpretation. The next stage in the method involved data collection and analysis, as shown in box (b) in Fig. 2. Thirty individuals were contacted and invited to participate in an interview. These individuals were selected because of their experience and expertise in designing and manufacturing cars in the UK. Twelve of those contacted agreed to participate in the study (Table 1). All individuals were interviewed by the same interviewer.

The interviews were semi-structured and conducted between January and March 2016 in person or via telephone. A list of questions was tailored in advance of each interview to reflect each interviewee's expertise and experience (Table 2). This list ensured important topics were discussed within the allocated time period, while also providing flexibility to pursue new lines of inquiry if and when they arose during the interview. Questions were designed to stimulate discussions on the process of designing and manufacturing vehicles in the UK and of broader automotive industry trends. Material choice, including from recycled sources, is not explicitly included in the list of pre-prepared interview questions to avoid a discussion on material switching. As discussed in Section 1, material switching is complementary to material efficiency improvements. Very few of the questions explicitly asked how material efficiency could be improved for three reasons. First, every attempt was made to ensure the questions helped to identify factors which may have implications for direct and indirect material use. Second, it was assumed that most interviewees would not be familiar with the definition of material efficiency in Allwood and Cullen (2012). Even if interviewees were familiar, because of the complexity of the design and manufacturing process, it is unlikely they would have been able to explain how current industry practices have direct and indirect impacts on material use. Third, wherever possible the questions were designed not to bias interviewees. Focusing too much on the limited adoption of these strategies may have potentially resulted in exaggerated or defensive responses.

The interviews were transcribed verbatim and then analysed following the principles of grounded theory, a deductive method of theory development. In a definitive guide on the procedures for developing grounded theory Corbin and Strauss (1990) explain the aim is to produce a “well-integrated set of concepts that provide a thorough theoretical explanation of social phenomena under study”. Following the authors' recommendation, the transcripts were reviewed and interpreted for three different purposes. First,

Table 1
Interviewee expertise and experience.

Type of organisation	Years of experience	Expertise	Current role
Academia	20+	Business	Professor
High volume manufacturer	5	Engineering	Product developer
High volume manufacturer	5	Engineering	Product developer
High volume manufacturer	10	Engineering	Product manager
High volume manufacturer	20+	Engineering	Materials engineer
Industry association	20+	Engineering	Chief Executive Officer
Industry association	20+	Engineering	Research & development
Industry association	20+	Engineering	Chief Strategy Officer
Industry association	15	Social sciences	Deputy Chief Executive
Material manufacturer	15	Chemistry	Research & development
Low volume manufacturer	20+	Engineering	Chief Executive Officer
Low volume manufacturer	10	Engineering	Engineer

Table 2
Open-ended questions used during the qualitative interviews.

Personal industry background
(*all*)
How did you come to work in your current role in the automotive industry?
Designing and manufacturing vehicles
(*For automotive designers and manufacturers*)
Please can you tell me about your company's organisational structure
Can you describe the working culture?
What roles do different divisions have in designing and manufacturing a vehicle?
Why do your customers choose your vehicles?
How are they different from your competitors' vehicles?
What are your customers' main needs and requirements?
How do you incorporate customer feedback?
How do you specify components and select suppliers?
How are regulatory requirements taken into consideration during the vehicle design and manufacturing process?
(*For other interviewees*)
What role does your organisation have in the UK automotive industry?
How would you characterise your relationship with others in the industry?
How does your organisation work with automotive industry to design and manufacture vehicles?
UK automotive industry
(*For all*)
How would you characterise the current state of the UK automotive industry?
How has it changed over time? What factors have been important in shaping this change?
What factors might disrupt current practices around the design, manufacture and sale of cars in the UK?
What scope is there to reduce the weight of vehicles further?
What factors enable or constrain the industry from reducing vehicle weight?

common themes were grouped together in categories (open coding). It was challenging to anticipate what would be relevant at the start of the study and there were repeated phases of open coding as each interview was conducted and each transcript was reviewed. A total of 23 categories were identified during open coding. The process of open coding finished when all data had been collected and all relevant parts of the transcripts were covered by existing codes. Some excerpts were ascribed to multiple categories. All text included in the 23 categories was then reviewed a second time to identify connections between themes, including correlations and directions of causality (axial coding). Boeije (2010) explains that there are two primary purposes of axial coding. First to determine which categories are dominant and which are less important in explaining the phenomena under investigation and second to reduce and reorganise the data. The dominance and importance of each category was initially evaluated by reviewing the frequency and consistency of interview excerpts. The 23 open coding categories were then reviewed and condensed to the six socio-technical factors (see Fig. 3). The full transcripts were then reviewed a third time to identify further insights and if the factors need refining (selective coding).

As shown in box (b) in Fig. 2, data collection (interviews) and analysis (coding) occurred concurrently. Although all interviews broadly followed the structure outlined in Table 2, the choice of which questions to include was also informed by the insights from previous interview transcripts. Additional industry and academic studies were sought during interview coding to supplement, substantiate and refine the description of the six factors detailed in Sections 4.1–4.6 (box (c) in Fig. 2).

Industry material throughput and material efficiency can be understood as outcomes of the vehicle design and manufacturing process. Section 5 uses the six socio-technical factors outlined in Sections 4.1–4.6 to structure a discussion on what is contributing to upward trends in vehicle material intensity and vehicle throughput in the UK. Interview quotes and secondary sources of literature and data are used as evidence to inform and substantiate the arguments presented. All interviewees were invited to review and provide structured feedback on a draft summary of these two pieces of analysis. Five interviewees provided feedback and the content was amended. A similar iterative approach is used in Delphi studies. Hsu and Sandford (2007) explain that this helps ensure interviewee responses are accurately characterised and reflect a general consensus.

3.2. Study limitations

The method was designed to ensure accurate and valid results. However, there are some limitations, common to social research,

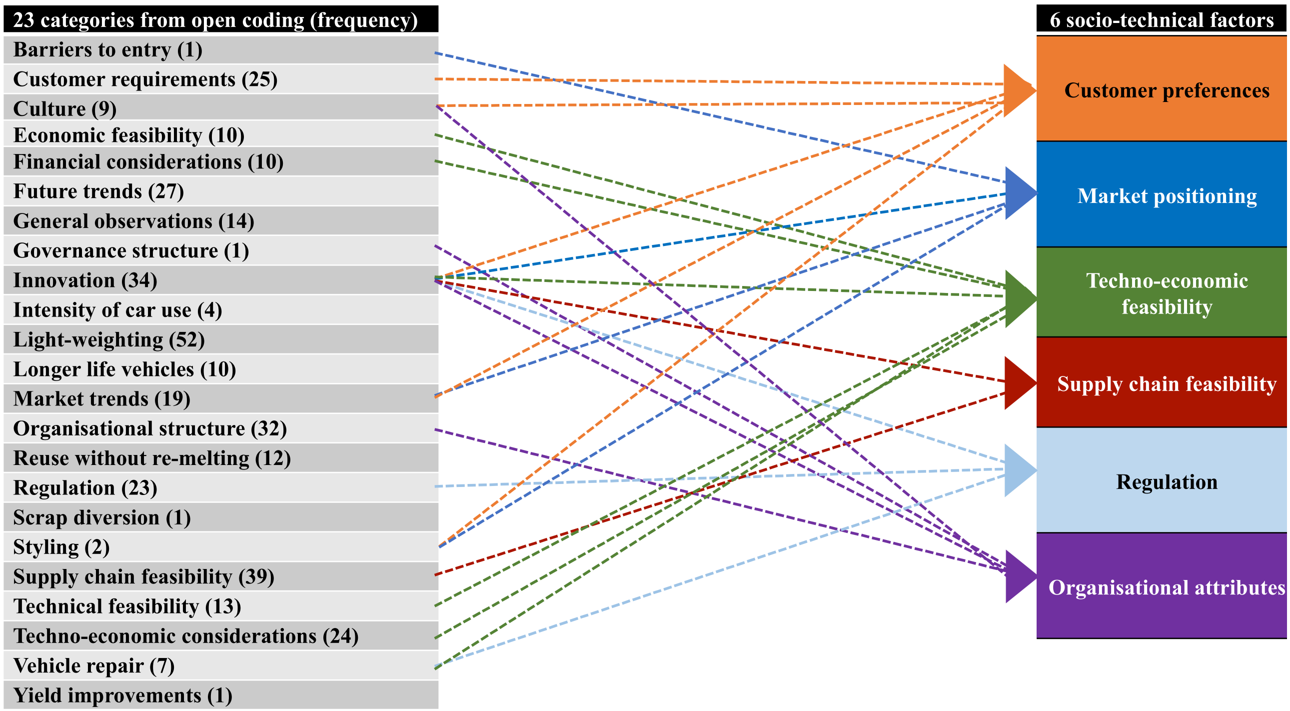

Fig. 3. From open coding to six socio-technical factors.

which should be highlighted as they influence how the results and discussion should be interpreted. First, some participants discussed commercially sensitive matters which were difficult to substantiate and anonymise. These were omitted from the analysis. Second, responses are considered to be representative but not exhaustive because only a sample of individuals were interviewed. Third, the study only reflects the current UK operating context which limits the generalizability of the research findings. There are a number of defining features of the UK automotive industry which mean that the operating context may be different for vehicle manufacturers located elsewhere. These include: national and local policies such as innovation funding for low carbon vehicles (BIS, 2013) and the creation of Local Enterprise Partnerships that support investment and skills development in vehicle manufacture; research collaboration between the automotive supply chain and UK universities and a long industrial heritage. In the UK, there is also a unique mix of: ultra-luxury, racing, small volume specialist and large volume multinational vehicle manufacturers, which creates a unique set of production capabilities and capacities in the automotive supply chain. Corbin and Strauss (1990) highlight that limited generalizability is a common challenge for studies in the ‘social realm’. A grounded theory can be verified but is difficult to replicate exactly because of differing social contexts. Despite this, there is scope for the method to be replicated, which would enable a comparison of different operating contexts.

4. Results

Six distinct but interacting factors were identified that guide the process of designing and manufacturing vehicles in the UK. These are: 1) customer preferences; 2) market positioning; 3) techno-economic feasibility; 4) supply chain feasibility; 5) regulation; and 6) organisational attributes. These factors influence the physical characteristics and volume of cars produced in the UK, which in turn determines the efficiency of material use and total material demand. This section continues with a description of each of the six factors and explains its relevance in guiding the vehicle design and manufacturing process.

4.1. Customer preferences

Customer preferences are shaped by a mixture of different wants and needs. Customer wants are assumed to coevolve with trends in automobility, while customer needs are independent of these trends. Customer preferences will differ across countries, reflecting different driving and styling preferences, which means that a model sold in two different countries may have the same body structure but completely different interiors, vehicle performance and features. Vehicle designers and manufacturers will elicit feedback across all sales regions from both fleet and individual vehicle purchasers to account for these differences in customer preferences.

Customer preferences are some of the earliest considerations in the vehicle development process. Customers may also be asked to provide feedback on early concept designs. Feedback, as one interviewee said, is typically elicited using qualitative research techniques with existing or potential customers:

> “We bring in a focus group of people and we'll ask them about the current vehicle, what they like about it and what they don't … how they rate the current vehicle out of desirability, value for money, drivability”.

The insights gathered through these forums provide a first proxy of demand and willingness-to-pay for different features. This enables the vehicle designer to approximate sales volumes and price ranges for new models.

4.2. Market positioning

Vehicle manufacturers need to know what is currently available in the market so they can design and sell novel or improved vehicles. They will also consider areas of market growth. Vehicle manufacturers will elicit customer feedback on competitors' products to understand which attributes to differentiate and which to replicate. One interviewee explained how this is observable in the marketplace:

> “You will have noticed within [the] automotive [industry] that there's every type of vehicle body style you can imagine. That's [the] manufacturers trying to capture niches to have more market share”.

Complementary to product differentiation is brand differentiation. Together they can be a source of competitive advantage (Porter, 1985). A number of interviewees discussed the competencies of different brands and how this related to different styling and technologies in vehicles. One interviewee also commented on how branding can influence the culture of designing and manufacturing vehicles:

> “Audi have the catchphrase … ‘Vorsprung Durch Technik’ … ‘progress through innovation’. VW has ‘Das Auto’ … ‘the car’ … VW is about moving people and personal mobility; Audi is about moving people in the most innovative way”.

Vehicle designers and manufacturers will be guided by their company's brand identity, which influences what features to differentiate and how.

4.3. *Techno-economic feasibility*

Designing and manufacturing vehicles is expensive. Each new manufacturing plant costs an average US$1500 M and each new model generation is approximately US$1000 M (Wells, 2010). New designs and components are only manufactured when they are considered to be both technologically and economically feasible. These two types of feasibility are evaluated together. As one interviewee said:

> “So you sort of have to pick between the ultimate efficient thing for us to make, which only costs us £100 and what the customer wants. It's usually a balance between finding what satisfies the customer and what's going to be feasible to manufacture”

Technical feasibility relates to physically engineering a component in a particular way and ensuring its performance during prototyping and testing. Economic feasibility refers to the potential profitability of a design. This is dependent on costs and customer willingness-to-pay. Willingness-to-pay will in part be influenced by product and brand differentiation, while costs can be more directly influenced by the manufacturer.

Interviewees discussed various cost reduction strategies used by the industry to improve the techno-economic feasibility of new designs and components. These included: achieving economies-of-scale via bulk purchases; shared and modular platforms; replicated features across models and reduced design time through iterative rather than radical changes to existing products. The perceived techno-economic feasibility of a new vehicle design will also be dependent on existing models and brands. As one interviewee noted:

> “most cars we're developing are based off something we already have … it's about what can be done for the greatest benefit without spending much money”

Techno-economic feasibility is not static. Vehicle designers will also consider emerging technological trends. Interviewees discussed new component production processes, alternative powertrains and autonomous vehicles as promising future technologies for the sector. As technologies mature and diffuse, learning and economies-of-scale accumulate and there is the potential for costs to fall (Grubb et al., 2014).

Interview quotes show that vehicle designers and manufacturers jointly consider the technical and economic feasibility of a new component or product design. This builds the business case to opt for one design and manufacturing process over another.

4.4. *Supply chain feasibility*

Vehicle manufacturers will either produce or buy the thousands of individual components that make up a car. Supply chain feasibility relates to whether the materials for internally made components, or purchased finished parts, can be designed, manufactured and delivered at cost and to schedule. It became apparent from the interviews that each company will have its own supplier selection process. However, desirable supplier attributes which were commonly discussed included: reliability, flexibility, capacity, capability, delivery performance and cost effectiveness. Important product attributes related to: costs, quality and durability alongside a range of other criteria. One interviewee said:

> “Typically a company will have 30–40 criteria … The front end of that is definitely technical. 'Can we build using this material?', ‘What's the effect on the production system?’ … But all the way down here you've got a whole bunch of other issues”.

The supply chain works together to design and manufacture component parts. This requires significant forward planning by vehicle manufacturers, as selecting suppliers and specifying and testing a product is a lengthy process. There is often close and longstanding collaboration between suppliers and component purchasers. Existing working relationships are another important consideration when selecting suppliers. One interviewee suggested:

> “A lot of the OEMs [Original Equipment Manufacturers] have fairly sophisticated purchasing … They know the guys and girls out there. It's fairly mature.”

There is also some degree of supplier lock-in because, as discussed in Section 4.3, components are often shared across models as a way of increasing economies-of-scale and reducing costs.

4.5. *Regulation*

Manufacturers need to ensure vehicles and their component parts meet a range of different hard, soft and self-imposed regulatory requirements. These requirements include safety (e.g. crash performance) and environmental regulation (e.g. tailpipe emissions, the use of hazardous materials, noise), as well as more functional whole-vehicle attributes such as speed, drivability and style. This creates a complex process of testing and approval. To illustrate one interviewee remarked:

> “I had 300 regulations, requirements and rules to go through … with my one small component … Some say you have to test it in a lab … some require results to be sent off to a certification body … others are kept within the company”.

‘Soft’ regulation includes codes of conduct and guidelines and may come from industry bodies. For example, EuroNCAP (2016), a voluntary safety performance assessment program backed by the European Commission, was frequently mentioned during interviews. One interviewee observed that one of the major brands models ‘”got 4 stars” on this assessment and “they were gutted”. Another explained that there was an industry wide perception that “if you're not competitive with your EuroNCAP score you won't sell vehicles”. Self-imposed regulation comes from standards and established production processes set internally in a company.

4.6. Organisational attributes

Individuals will be strongly influenced by their organisation's governance structure, institutional memory and other features of the context in which they operate. Multidisciplinary vehicle design teams balance top-down strategic guidance on material choice (e.g. aluminium versus steel body) and technical constraints (e.g. platform choices) with bottom-up techno-economic and supply chain considerations. As one interviewee noted this often gives rise to “very, very complicated” governance structures which staff often “don't fully understand”.

Vehicle manufacturers will build expertise and experience over time as a way of managing product and process complexity. This institutional memory may relate to vehicle testing, component design or previous experience with suppliers. Organisational attributes relate to company culture, structure and relationships and interactions between individuals throughout the supply chain. These contribute to the formation of routines, habits and other heuristics which guide the vehicle design and manufacturing process.

4.7. Connections between factors

The six factors are distinct but not independent, they interact and influence each other. For example, Nieuwenhuis (2014) proposes that regulation has partly driven innovation in alternative powertrains and the inclusion of lightweight materials. Innovation, and the investment it requires in personnel and manufacturing technologies, can change the techno-economic feasibility of a technology or production process. In the UK, vehicle and designers can be involved in shaping innovation priorities through the Automotive Council, a platform to strengthen dialogue and cooperation between the UK government and automotive industry. This example highlights that vehicle designers and manufacturers interact with a network of actors in a broader socio-technical system that they also help to shape. Fig. 4 provides further examples of the ways in which these factors are interconnected.

5. Discussion

Materials are physical inputs to the vehicle design and manufacturing process. Section 4 has shown this process is guided by six connected socio-technical factors. This section now examines how these six factors are contributing to current levels of material demand in the UK automotive industry and why opportunities for material efficiency improvements may not be realised. As discussed in Section 1, total material throughput along the automotive supply chain depends on vehicle material intensity (Section 5.1) and vehicle throughput (Section 5.2).

5.1. Material intensity

Material intensity depends on a vehicle's size and the amount of material embedded in it. Fig. 1 shows that the average material intensity of new vehicles in Europe, the UK's main export market, has increased over the past 20 years. This upward trend in material intensity is occurring in spite of EU regulation on CO_2 tailpipe emissions (EC, 2009), which according to one interviewee is “driving a lightweight approach on the next generation of vehicles” along with innovation in “powertrain efficiency and aerodynamic design”. The increase in the average vehicle material intensity might have been even higher without this regulation.

Increases in vehicle sizes may be partly explained by an ageing European population with changing customer needs. One interviewee surmised “we've seen car doors get bigger, seat heights getting taller … because they're [vehicles] easy to get in and out of if you're old”. Wells and Xenias (2015) already noted that an ageing driver population impacts the design of vehicle features. They characterise innovations such as parking sensors and collision avoidance systems as “enablers of continued motorisation for the elderly”. Evolving customer wants are also driving increases in vehicle material intensity. As one interviewee observed, “what car makers have been doing for years is shave out the steel and add in something the customer wants”. Interviews revealed that these ‘wants’ may relate to specific features such as “electric seats … which add 20 kg” or they may be more abstract and open to interpretation. Interviewees spoke of designing vehicles that offered “comfort”, “compatibility with customer lifestyles”, “desirability” and “drivability”. Delivering these attributes could drive increases in vehicle weight or size. The interviews provided some evidence of this. One vehicle manufacturer suggested engine sizes are larger than necessary because “customers like the feeling of having surplus power”. Another explained that the boot size is designed with “suitcases and golf clubs” in mind to reflect their customers' lifestyle. Advances in the mechanical performance of vehicles mean designers and manufacturers are placing more emphasis on aesthetic and ergonomic characteristics to create an affective response among new car purchasers (You et al., 2006). Once this response is established it may be challenging to alter. When asked about the scope for reducing vehicle weight one interviewee explained that the ‘nice-to-haves’ could be dropped but “customer satisfaction would drop because they [the customers] have become accustomed to extra features”.

Vehicle manufacturers may also be reluctant to drop these ‘nice-to-haves’ because of increasing market competition. In the UK, for example, there was a threefold increase in the number of model variants on sale between 1994 and 2009 (Wells, 2010). When describing the process for selecting features, one manufacturer explained that “[my company], basically end[s] up with a big table saying ‘feature x, y, z’, … doesn't matter how much it costs, we have to have it because our competitors have it and all the customers want it”. This response to customer feedback means that new features, which can add weight, may be replicated throughout the industry. Feature replication may also occur for cost saving reasons as it can lead to economies-of-scale. As one interviewee suggested, “They [vehicle manufacturers] are more likely to spend money on a feature or platform if it can be used across a range of vehicles”.

There are opportunities to reduce vehicle material intensity during the manufacturing process through further improvements in lightweight design and materials. Although this is technically feasible, interviewees indicated that optimising the material intensity of each new car model through lightweight design would be prohibitively costly. It would require more design time, which means additional costs, and reduce purchasing economies-of-scale if components are not transferable across models. Cost considerations also influence material selection. For one interviewee this meant achieving “the right balance of cost, weight, formability”. Lighter materials tend to be more expensive. To illustrate, carbon fibre can be used in structural parts of the vehicle such as the frame,

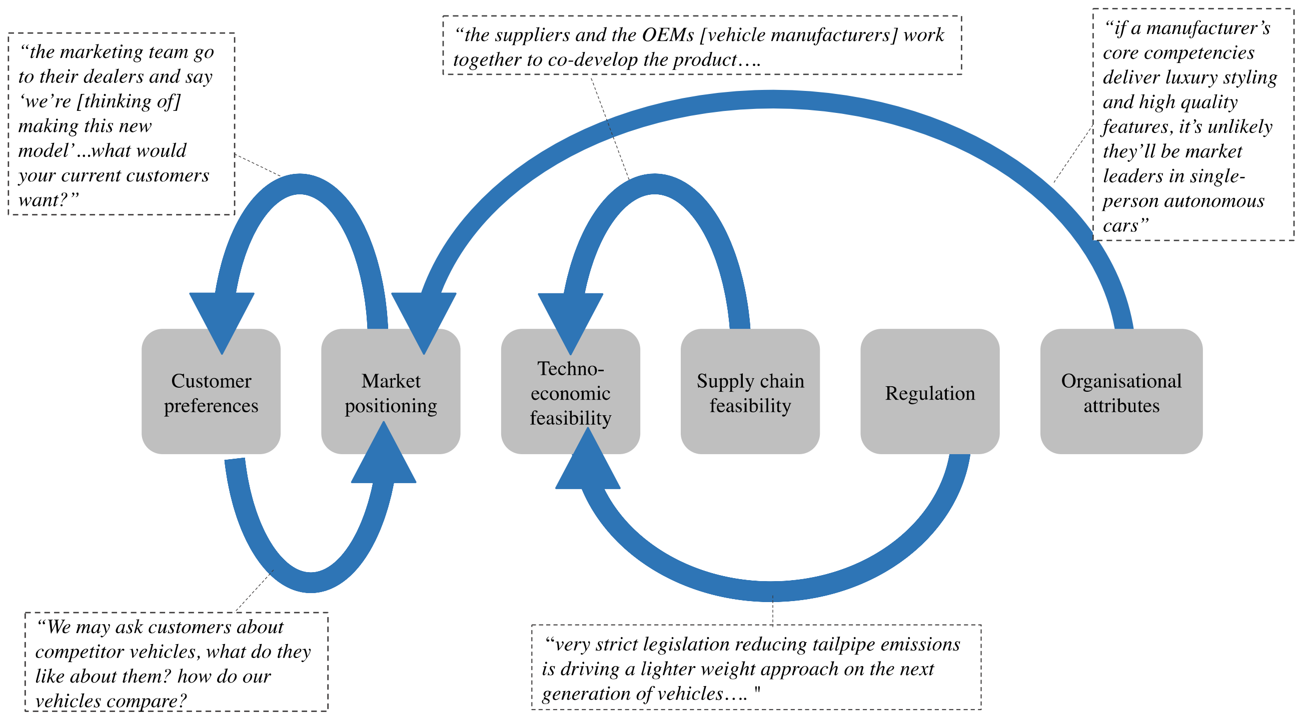

Fig. 4. Interview quotes illustrating connections between factors.

hood or tailgates and is 50% lighter than steel but in 2012 was around 570% more expensive (McKinsey, 2012). This price differential explains why carbon fibre and other lightweight materials such as aluminium are used more by luxury vehicle brands (e.g. Jaguar and BMW), who can pass on these costs via higher vehicle prices. As a result, there has a been a relatively smaller increase in average weight among luxury vehicles (Fig. 1).

When purchasing component parts from the wider automotive supply chain, vehicle designers and manufacturers could specify lightweight design and materials but this will be constrained by supply chain capabilities. These were judged to be "weak' in the UK (AC, 2013). One interviewee shared a recent experience whereby "we said 'yeah that's easy' … then it came out that no supplier had the equipment to do it, or they wanted to charge us thousands of pounds per piece. So we had to use a less ideal choice because of supplier capability". A heavier design may be selected if weight is superseded by more critical supplier or product attributes.

Opportunities to reduce the material intensity of a vehicle may also remain unrealized due to vehicle manufacturers' organisational attributes. Interviews revealed it may be less risky to modify, test and incrementally reduce the weight of existing vehicle and component designs, which could disadvantage more radical lightweight designs. One interviewee explained for them, there were "[personal] risks to a new [lightweight] design being wrong … having to do it again or spending lots of money to fix it" which contributed to their opinion that "there's no point in doing something completely different when you know that something works already". A complex approval process may also disadvantage radical lightweight designs. For one interviewee, approval was needed from, "my manager, then my manager's manager and then to my counterpart abroad and then to his manager". Many individuals with different organisational priorities would need to be convinced of the merits of radically different designs over existing ones. As a consequence, vehicle manufacturers tend to focus on optimising existing designs rather than starting with a blank piece of paper and considering what might be most materially efficient approach.

5.2. Vehicle throughput

Material throughput in the automotive industry will also depend on how many vehicles are manufactured and sold. Vehicle throughput in the UK automotive industry is increasing (ICCT, 2016). Although customers will choose when to retire their current vehicle, or make the decision to purchase a new vehicle for the first time, these decisions can be influenced by vehicle manufacturers. Rather than consider all of the factors which motivate customers to purchase new cars, this section is limited to a discussion on how the vehicle design and manufacturing process can influence vehicle longevity. There is also a discussion on other features of the industry's operating context which favours high vehicle throughput.

Demand for new cars would fall if the existing fleet of vehicles were kept for longer. Many vehicles have a shorter lifespan than is technically possible (Nieuwenhuis, 2014). The interviews revealed that this is partly due to an industry focus on the preferences of the first customer. The design of a vehicle and its components, however, will influence lifecycle operational and repair costs. One interviewee observed that "the things that are surprise and delight for a new car buyer are usually shock and disappointment for a used car buyer. They break and cost a fortune to fix". This assertion is supported by evidence in automotive trade publications that as vehicles become filled with more complex electronic features, they become costlier to repair (Fleetnews, 2014; Allen, 2010). It can also be difficult and costly to get replacement components for older vehicles as improved product designs and production processes become techno-economically feasible over time. To illustrate, one interviewee discussed how much seats have changed over the last 30 years, "When we looked at the base of the (1980s) seat … even the ergonomics had completely changed …. It looked unrecognisable, like a metal bench … [it] wouldn't give you the level of performance and comfort and safety you get with a modern seat".

Older components may be incompatible with newer replacement parts which could also increase the cost of repair relative to the value of the vehicle, which may favour scrapping.

Techno-economic factors and longstanding organisational attributes also encourage high vehicle throughput. The large size of sunk investments in the automotive industry means plants are most profitable when they operate close to full capacity to experience economies-of-scale. One interviewee speculated that "[manufacturing plants] need to run at [approximately] 85% capacity or they're not making money". The UK automotive industry has over a hundred years of experience designing and mass manufacturing vehicles and deriving revenues at the point of sale. Even luxury vehicle manufacturers based in the UK are manufacturing thousands of customised built-to-order vehicles per annum. Interviewees referred to this process as "advanced", "optimised" and "based on volume". Reorientation to alternative business models and forms of value capture based around lower vehicle throughput requires complex organisational change and may be perceived as riskier, as the potential profitability is less well understood. In spite of these risks, the industry is beginning to explore alternative business models to supplement revenue from vehicle sales. Both Ford and BMW recently launched car sharing initiatives in the UK, where drivers pay for vehicle access. If all cars were shared rather than owned, there could be a reduction in vehicle throughput. In 2015, there were only 4200 car sharing vehicles in the UK (Carplus, 2016). By comparison, the UK automotive industry manufactured 1.5 M vehicles in 2015 (SMMT, 2016), demonstrating the continued dominance of a business model focused on high vehicle throughput.

6. Conclusions

Material throughput in the UK automotive industry depends on how much material is embedded in each vehicle (material intensity) and how many vehicles are sold (vehicle throughput). Although reducing the material intensity of vehicles and vehicle throughput may be technically feasible, material throughput is increasing.

This paper shows that increasing vehicle material intensity is partly due to an ageing driver population and evolving customer preferences for features which increase vehicle weight and size. Market competition means these features are often replicated across brands. There are a number of reasons why vehicle designers and manufacturers may opt for more material-intensive designs. Using lightweight materials may be technically feasible but they are often more expensive. Reducing the weight of components for each new vehicle increases design and purchasing costs, particularly if there is limited supplier capacity. This paper also found some evidence that more material-intensive designs that are proven and tested may be preferable to novel untested lightweight designs. Vehicle throughput could fall if cars were kept for longer but as vehicles become filled more features the cost of repairs increase and may incentivise vehicle scrapping. This paper shows that high sunk costs, longstanding experience and expertise in high volume manufacturing and sales and complex organisational structures make it challenging to transition to new business models based on lower sales volume.

Material throughput and the efficiency of material use in the UK automotive industry are outcomes of a complex, advanced design and manufacturing process, involving thousands of individuals in a supply chain with long established routines, experience and relationships. Any initiatives seeking to improve the efficiency of material use are unlikely to be successful if only the technical feasibility is understood. Further research could focus on: connections between factors, the applicability of factors to other geographies and sectors and the stability or variability of each factor over time. There may also be transferable insights from energy efficiency studies on how quantify the contribution of each factor to vehicle material intensity. Dehning et al. (2017), for example, develop a multiple linear regression model to identify and evaluate the relative influence of different factors on the energy intensity of automotive plants. These future topics for research would provide further clarity on why material efficiency remains an underexploited GhG mitigation strategy in industry.

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