

Investigating the impacts of connected and automated vehicles on road carbon emissions: A semi-systematic literature review

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Abstract—Rapid breakthroughs in Connected and Automated Vehicle (CAV) technologies together with the net-zero targets set for the next three decades raise a serious question about the potential impact of CAVs deployment on carbon emissions from road transport. The uncertainties surrounding this dilemma are profound mainly due to the complex interdependencies between technological capabilities, public travel behaviours and policy interventions. Previous modelling and simulation studies suggest a considerable variation in how CAVs may contribute to carbon saving or give rise to CO₂ emissions. This paper aims to constrain the uncertainties and identify the mechanisms through which CAVs may influence road carbon emissions. A semi-systematic literature review was designed and conducted which resulted in identification of 40 relevant publications and documents. Subsequently, 38 mechanisms were ascertained and classified across five major categories: i) number of vehicles manufactured; ii) manufacturing emissions per vehicle; iii) number of vehicle miles travelled (VMT); iv) emissions per vehicle mile travelled; and v) emissions from infrastructure. Several of the identified mechanisms closely relate to vehicle energy consumption (rather than specifically carbon emissions), accordingly they are also applicable for examining potential implications of automated and electric vehicles (AEVs) in the future mobility landscape.

Keywords—Connected and automated mobility (CAM), self-driving vehicles, decarbonisation, carbon emissions, sustainable mobility, Mobility as a Service (MaaS).

I. INTRODUCTION

THE recent technological advancements in computing, Artificial Intelligence (AI) and sensory have made an immense contribution to the development of Connected and Automated Vehicles (CAVs) [1, 2]. CAVs are expected to effect fundamental transformations to future mobility and urban planning [3-6]. While CAVs represent a socio-technical transition in mobility, the

majority of academic studies in the past decade have been focused on their technical and technological aspects with less than five percent of the publications investigating non-technical aspects [7]. CAVs can have substantial impacts on societal and environmental dimensions of mobility [8]. Previous modelling and simulation studies suggest a wide variation in how roll-out of CAVs may either contribute to carbon saving strategies, or on the other hand, give rise to CO₂ emissions. The uncertainty over the overall impact of CAVs on carbon emissions raises a major hurdle in the way of policymakers in designing and implementing strategies to achieve net-zero targets.

Despite the innovations in car manufacturing, road transport still appears as a major contributor to CO₂ emissions producing approximately one fifth of total carbon emissions [4]. The considerable investments in testbeds, legislative initiatives and advent of promising prototypes also indicate that CAVs are going to form the backbone of future transport. Hence, it is vital for policymakers to have an evidence base for identifying opportunities to lower emissions as well as flagging risks of where CAVs are likely to increase emissions. To this end, this paper aims to identify those mechanisms through which CAVs can influence road carbon emissions. The rest of this paper is organised as follows: section II provides a review of previous studies in relation to the potential impacts of CAVs on carbon emissions and identifies the knowledge gap. Section III details the research design and methodology. Section IV presents the findings and finally section V summarises the discussions and recommends directions for future research.

II. RESEARCH BACKGROUND

A. Concerns and uncertainties about the environmental impacts of CAVs

Although many studies have already attempted to examine the impacts of CAVs on carbon emissions, a

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consensus has not been reached yet on whether such a disruptive technology is going to reduce carbon emissions or increase them [9]. The uncertainty surrounding the issue of carbon emissions becomes even deeper when the quantity of various key performance indicators (KPIs) such as VMT and traffic efficiency are tightly dependent on deployment and market penetration rates of CAVs [8, 10, 11]. The deployment rate currently remains indeterminate, and this hinders estimating the performance of CAVs in many ways [6]. Several academic publications [e.g. 7, 9-11, 12, 13] also use an uncertain language in evaluating the net impact of CAVs on carbon emissions and allow for the possibility of either increase or decrease. However, a development of narratives and scenario-based analysis is apparent in those studies. For example, it is asserted in [12] that CAVs can lower energy consumption together with greenhouse gas (GHG) emissions through eco-driving, traffic smoothing and vehicle lightweighting. Likewise, authors in [9] reported that eco-driving and platooning are among the main mechanisms that contribute to GHG emission reduction by up to 35%. Some other studies looked beyond just tailpipe emissions and considered the life-cycle impacts. For instance, Cremer et al. [3] looked into the potential scenarios that CAVs can contribute to carbon emission reduction plans in municipal sphere and considered additional infrastructure and production phase as sources of carbon emissions. This necessitates determining the major sources of carbon emissions throughout the lifecycle of CAVs and identifying pertinent mechanisms that play a role within each source.

B. Constraining the uncertainties through identifying appropriate metrics

The benefits of extending the analysis to the lifecycle of CAVs are manifold. First, mere consideration of tailpipes can significantly underestimate the emissions from road transport [14]. Furthermore, inclusion of production phase provides a ground for studying the carbon impacts of AEVs. Focusing merely on tailpipe emissions entails the risk of miscalculating the carbon footprints during and after the transition from internal combustion engines (ICE) to electric vehicles (EV) [15]. Finally, expanding the scope of analysis to the lifecycle allows for identifying the most influential mechanisms across the major sources of carbon emissions. For that purpose, it is crucial to specify major factors that affect the amount of emitted carbon throughout the lifecycle of CAVs.

In 2020, Connected Places Catapult (CPC) publicised a report [16] to scope the potential impacts of CAVs on future mobility with an emphasis on carbon emissions. That report highlighted five fundamental factors which directly affect the carbon emissions from road vehicles: i) number of vehicles manufactured; ii) manufacturing emissions per vehicle; iii) number of vehicle miles travelled (VMT); iv) emissions per vehicle mile travelled; and v) emissions from infrastructure. The next step is to

identify and contemplate various mechanisms of CVAs which can be harnessed to decarbonise road transport and mitigate those that are expected to heighten carbon emissions. For example, shared mobility can be significantly facilitated and boosted by CAVs and that can reduce VMT and congestion [8, 10, 12]. On the other hand, several studies [e.g. 5, 8, 12] anticipated an induced demand for travel after CAVs are widely available. These variations clearly underline the need for identifying and classifying relevant mechanisms as well as establishing which of the five variables mentioned earlier can be affected by those mechanisms.

C. Knowledge gap: an integrative approach to ascertain and classify the CAV-specific mechanisms in relation to life-cycle carbon emissions

Although some academic and non-academic studies [12, 16] tried to list the most effective mechanisms in relation to carbon impacts of CAVs, they lack either a systematic and regulated approach or comprehensiveness. This paper suggested a semi-systematic literature review [17] to tackle the lack of methodology and adopted an integrative approach to increase the scope of search. A large and growing number of publications in the field of CAVs and transportation [10] gives grounds for a broader textual and thematic analysis. The contributions of this paper are threefold. First, shaping a narrative and forming a base for more rigorous scenario analysis thereby arriving at the most plausible scenarios. Next, laying a foundation for more rigorous quantitative analysis and modelling by identifying influential mechanisms that can act as a lever in cutting down carbon emissions. Finally, moving from 'unknown unknowns' towards 'known unknowns' and restricting epistemic uncertainties (i.e., lack of fundamental knowledge) [18] around functional, operational and utilisation aspects of CAVs.

III. METHODOLOGY

A. Key underlying assumptions

A set of assumptions were necessary to be made to confine the search area to a narrowed topic and enable the development of narratives based on the provided discussions in the reviewed articles. Such assumptions can be classified into economic, operational and utilisation groups. The major assumptions in this research are as follows:

- i. The automation (or autonomy) level was assumed to be at the highest level (i.e., fully automated/autonomous). This helped the researchers to increase the scope of search and include as many as relevant mechanisms.
- ii. Several studies [e.g., 7] maintain that the safety benefits of CAVs depend on the penetration rates of vehicle automation. Nevertheless, it was assumed that CAVs are going to be safer than

human-driven vehicles (HDV) and the quantity of such improvement would remain homogeneous at different penetration rates.

- iii. While many experts stress the importance of segregating automation from connectivity in studying the impacts of CAVs on road carbon emissions, the assumption here is that both automation and connectivity are enabled during the operation of vehicles. This is because some of the mechanisms such as eco-driving rely on both. A CAV needs to receive data (e.g., through vehicle-to-infrastructure channels) about the traffic situation ahead of it and use its algorithms to decide on an appropriate course of action to increase fuel efficiency. This example shows the reliance of the vehicle on both automation and connectedness.
- iv. In order to avoid overcomplication, we did not involve the interdependencies and reciprocal influences of mechanisms in evaluating the overall impact of each of them on carbon emissions. It is conceivable that some of the mechanisms would strengthen or nullify the impacts of each other. The prime example can be the interactions between travel demand, ridesharing and fleet size.

It is noteworthy that the above assumptions are primary, and several minor assumptions are baked into the conditional statements. For example, if CAVs lower the operational costs, this can lead to more travel demand or encourage private rides over ridesharing and public transport. Another example can be the general assumption about public transport being cleaner (in terms of carbon emissions) than private vehicles, although many factors including occupancy rate, fuel efficiency and combination of travel modes between an origin and a destination (e.g., walking and public transport) play a role here. These assumptions can be considered as one of the limitations of this research.

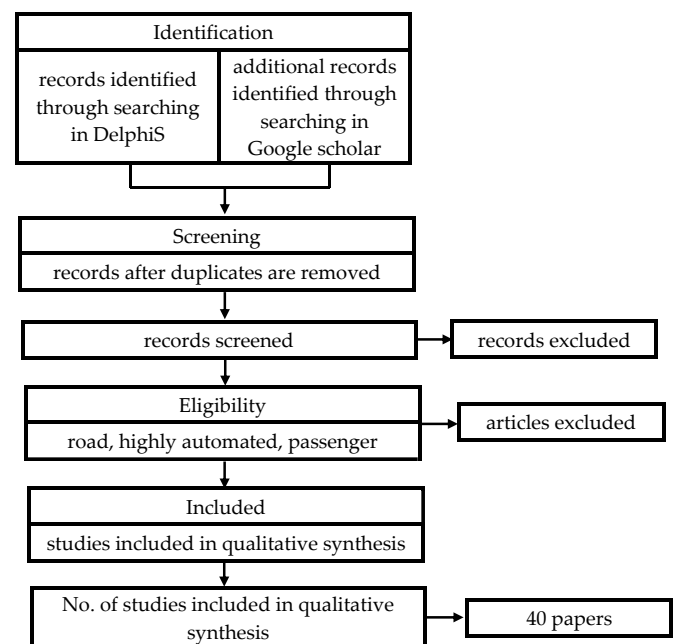
B. Semi-systematic literature review

Literature review, in essence, is adopted to advance knowledge, identify gaps, and recognise patterns and concepts to inform research questions in a framed field [17]. A systematic literature review is designed to answer a specific question and pursues four major objectives [19, p.18]: summarise, analyse, evaluate, and synthesise data. Where conducting a systematic review is not feasible (e.g., due to various multi-disciplinary publications), a semi-systematic (or narrative) review can be utilised to strategise and synthesise a differently conceptualised topic or reflect the progress of a topic in different fields over time. While this approach helps researchers to understand complex phenomena and mainly relies on qualitative data, an outlined research strategy is still necessary to enable

readers to assess both reasonableness of arguments and appropriateness of methodology [20]. The rest of this section describes the steps for searching, selection of publications, and including them in the review process.

To search for relevant publications in the elected database (i.e., DelphiS—internal to the University of Southampton) the following set of keywords were used: “autonomous vehicle*” OR “autonomous car*” OR “automated vehicle*” OR “automated car*” OR “self-driving” OR “driverless” AND “connected” AND “carbon emission*” OR “greenhouse gas”. The search was carried out in November and December 2021 which returned 89 papers using the above keywords. A set of inclusion/exclusion criteria were applied afterwards to single out the most relevant papers for review. Figure 1 depicts the selection process. The main eligibility criterion was inclusion of highly automated road vehicles, and passenger vehicles were prioritised over freight in this manner. After applying selection criteria, 38 papers were selected to be included in the review phase. Two other papers were also found on Google Scholar and were included in textual analysis since they found to be highly relevant to the topic. Therefore, 40 publications in total were selected for review and thematic analysis.

Fig. 1: the selection criteria for identifying papers, adopted from



[21].

C. Thematic analysis

A thematic or content analysis is a widely employed technique and can be broadly defined as a method for detecting, analysing, and reflecting patterns in the form of themes within a manuscript [20]. During the first level of thematic analysis, we tried to figure out in what ways CAVs can impact carbon emissions. This, sometimes, was not straightforward and the text needed interpretation in order to form a conditional statement. For instance, it is expected that if CAVs promote ridesharing, then the

number of manufactured vehicles as well as VMT will decrease. However, there is currently no solid evidence to indicate whether CAVs would dis/encourage sharing rides among diverse communities. While those conditional statements draw attention to the criticality of assumptions, they can lay a foundation for further scenario (or what-if) analysis.

In the second round of analysis, similar themes were merged and then categorised under five major sources of emissions which were discussed earlier. A spreadsheet and colour codes were used to categorise the emerging themes from the reviewed text. The evidence for the overall impact of each mechanism was also attached to the identified themes to signify whether they are likely to increase carbon emissions or reduce them. Wherever available, the quantitative estimates for the potential impact of the mechanisms (e.g., range of changes in emitted carbons or fuel consumption) were also incorporated into that spreadsheet. Those numerical estimates besides the interpretation of text were used to denote the direction for potential changes in carbon emissions. Finally, based on the summarised evidence, the conditional statements were developed to delineate how a mechanism can act as a lever in increasing or decreasing carbon emissions. Figure 2 shows the sequential steps for thematic analysis for identifying, categorising and evidencing the prominent themes.

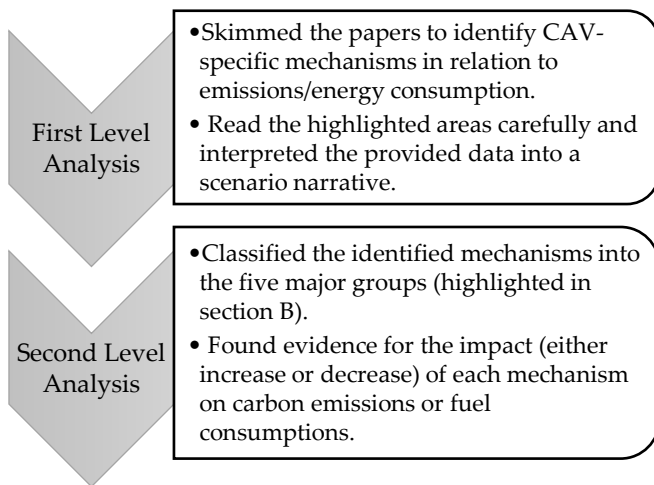


Fig. 2: summarises the main steps of thematic analysis.

IV. RESULTS

The primary findings of this research can be the identified relevant literature. Appendix A summarises 40 academic publications that were chosen for review and further analysis which led to the identification of 38 mechanisms. The first level analysis resulted in recognising 54 themes which after excluding KPIs/policy interventions and merging similar mechanisms, they were condensed to 38 mechanisms. Table I lists the mechanisms against the five sources (factors) suggested by CPC. The green downward arrows indicate a reduction in carbon

emissions, red upward arrows are used to show an increase in carbon emissions, and amber question marks denote contradictory evidence or lack of estimates for a mechanism.

It is anticipated that shared-vehicle services can lead to household vehicle relinquishment (lower private ownership and higher use of robo-taxis or car-clubs such as Zipcar). The results of [22] suggest that shared automated vehicles (SAVs) are likely to reduce GHG emissions up to 90 percent. Ride-sharing can increase vehicle occupancy rates and improve system efficiency and automated taxis could improve the fuel efficiency of fleets by 30–35% [23]. Another major mechanism is eco-driving. CAVs that are programmed to operate in full eco-driving mode (i.e., a modern way of driving that improves vehicle fuel consumption efficiency, safety, and optimal speed) can reduce lifetime fuel consumption between 7 to 16% [24].

On the other hand, the major increase in carbon emissions is attributed to induced travel demand, empty miles, and extra energy consumption (e.g., for sensors, computing and communication devices). CAVs have the potential to induce travel demand by enabling underrepresented areas of the population (e.g., those without driving licence) and improve travel comfort which could encourage further/more travelled miles. This impact on VMT can vary from 3 to 27 percent for various scenarios of development of automated vehicles [25]. Empty miles (also known as zero-occupancy trips) refer to journeys without any passenger and arise when vehicles are traversing from a passenger-drop-off location to the subsequent passenger-pick-up location or traveling before and after the first and last ride-hailing passenger trip [10]. Depending on the adoption rate of CAVs, a 4–51% increase in VMT is reported by [26]. CAVs are likely to consume more energy than conventional vehicles and EVs, due to the requirement for extra sensing, computing and communicating devices (e.g., sensors, cameras, computer, high-definition maps, vehicle-to-vehicle [V2V], vehicle-to-infrastructure [V2I], etc.) which draws from the powertrain and reduces energy efficiency [24]. The increase in life-cycle GHG emissions per CVA is estimated to be 3–20% [24].

Table I: lists the CAV mechanisms that can impact carbon emissions.

No.	Source	Mechanism	Impact
1	No. of vehicles manufactured	Fleet size – CAVs as a service can reduce fleet size	↓
2		Safety Benefits - Less replacement of vehicles from crashes	↓
3		Preference for shared CAVs vs private CAVs	↓

4		CAVs can be a preferable option comparing to public transport	↑
5		Greater Access to travel - Induced demand	↑
6		Ride-sharing	↓
7		CAVs can encourage lower car ownership	↓
8	CO ₂ per vehicle manufactured	Right-sized vehicles	↓
9		Possible modifications/personalisation	↑
10		Additional computing components add to weight of vehicles	↑
11		Larger battery needed to meet computing requirements	↑
12		Safety Benefits - reduction in vehicle mass	↓
13	VMT	Smaller powertrains required for non-human driver	↓
14		Empty miles	↑
15		Reduced cost per mile due to eco-driving can encourage more trips	↑
16		Induced demand due to increased value of travel time	↑
17		Emergence of more Transportation Network Companies (TNCs)	?
18		Shorter travel time and no need for parking	↑
19		Travel demand can go up since CAVs can serve a wider population including those without driving license	↑
20	CO ₂ per VMT	Eco-driving mode can increase speed adaptation and headway distance efficiency	↓
21		Connectedness enables more efficient route planning	↓
22		Altered aerodynamics can cause more air resistance drag	↑
23		Battery consumption can surge due to automation technology requirements & ICT	↑
24		Speed limits may change (commensurate with safety)	?

25		Less traffic congestion (smoother flows) due to more efficient use of road space	↓
26		Smoother de/acceleration	↓
27		Safety benefits - lower congestions due to less road accidents	↓
28		GLOSA (Green Light Optimised Speed Advisory) enabled through V2I	↓
29		Platooning enabled by V2V communication	↓
30		Attractiveness of CAVs encourage uptake of Autonomous Electric Vehicles (AEVs)	↓
31		Additional road infrastructure might be required	↑
32	CO ₂ embedded in infrastructure	Charging infrastructure for AEVs	↓
33		Digital and cybersecurity infrastructure	↑
34		Headway distance can free up more road space (less road construction)	↓
35		Urban planning - parking requirements can be reduced	↓
36		Type/design of roads (e.g., rural, urban, motorway) might need modification	↑
37		No. of roads and road space	?
38		Vehicle-to-grid charging	↓

V. DISCUSSION

A. Limitations and caveats

Although we extended the scope of research to encompass life-cycle emissions of vehicles, no significant evidence was found about decomposition (i.e., scrapping and/or recycling) or maintenance phases in the reviewed literature. Moreover, the focus of our study was merely placed on carbon emissions (i.e., CO₂) and other transport related emissions (e.g., hydrocarbon [HC] and Nitrogen oxides [NO_x]) were not considered. On the other hand, the notion of carbon dioxide equivalent is touched upon in some studies [e.g., 10, 15]. The discrepancies between direct carbon dioxide emissions and carbon equivalent emissions may cause inconsistencies, particularly in quantitative analysis. The direction and magnitude of impacts are highly dependent on the assumptions baked into the function(s) of each mechanism. These assumptions can become obsolete or outdated soon, given the fast pace

of technology and regulatory developments. In addition, it is not guaranteed that automated vehicles will be connected and vice versa. Segregating the impacts of vehicle automation from the impacts that connectedness capability can exert on carbon emissions [10] can add to the robustness of analysis and provide more insights, but for some mechanisms this seems to be impossible. Take eco-routing as an example which requires real-time data (e.g., intersection delays and traffic flows) through V2I communication and relies on a vehicle's complex algorithms to precisely determine the most energy-efficient route [27] and make a trade-off between efficiency and other objectives that it is programmed to achieve.

B. Ambiguities over decisive variables and utilisation models

During the thematic analysis it was observed that several emerging themes were not mechanisms, but related to policy interventions (e.g., fuel pricing strategies) or KPIs (e.g., occupancy rate). Therefore, it is important to distinguish between mechanisms, KPIs and (potential) policy interventions. The impact of many identified mechanisms (e.g., change in speed limits and headway distance due to increased safety) hinges upon the proportion of CAVs to HDVs. Nevertheless, it is difficult to provide an estimation for some of the determining variables such as deployment rate. To the best of our knowledge there is not currently a reliable source and estimate for the deployment rate. There can be several reasons for extreme uncertainty over the deployment rates for CAVs. Lack of sophisticated legal and regulatory frameworks [1], readiness of cities for hosting CAVs [5], and ethical considerations [8] are just a few to name.

Economic benefits (or costs) are major drivers for passengers when deciding their travel mode [1]. The realisation or effectiveness of several mechanisms (e.g., reduced cost per mile and preference for shared CAVs over private CAVs) in table I directly depend on the perceived economic advantages of CAVs. For instance, it is expected for shared mobility to bear lower costs comparing to private vehicles since passengers can share among themselves the costs that characterise a journey [1]. However, if the price of CAVs and/or their operational costs are so high that even split expenses still exceed the cost of private rides, the benefits of shared mobility will be compromised. Whilst such economic factors appear to have a crucial role in forecasting travel behaviours of various socio-economic groups, they remain uncertain, and that uncertainty propagates across several mechanisms. Apart from technology developers and policy makers, TNCs' business models also have an influence on tendencies towards travel modes or any modal shift [11, 17]. This indicates the criticality of involving diverse groups of stakeholders including industry representatives and public in different stages of policymaking.

C. Electrification and automation

It is not inconceivable that the impacts of vehicle electrification overshadow the environmental benefits of automation and connectivity [28]. The ICCT report [29] further concluded that *"only battery electric and hydrogen fuel cell electric vehicles have the potential to achieve the magnitude of life-cycle GHG emissions reductions needed to meet Paris Agreement goals"*. Vehicle electrification, on the other hand, entails increased indirect heat due to electricity generation [28] and wastes within the power grids. The challenges of insufficient charging infrastructure [30, 31], driving range [31] and emissions corresponding to battery production [29] also need to be addressed. Therefore, a synergy between electrification and automation can be achieved through consolidating an increase in shared rides with electrification and optimising automation strategies to reduce vehicle travel as well as energy consumption. Such a synergy could strengthen the likelihood of meeting the net-zero targets [11].

VI. CONCLUSION

There is a significant evidence gap in relation to the environmental impacts of CAVs in general and their potential impacts on carbon emissions. This research tried to restrict the uncertainties by breaking down the technology (i.e., CAVs) into its pertinent mechanisms and help policymakers to locate the opportunities and risks that vehicle automation and connection can pose to achieving the net-zero targets. The scope of our semi-systematic literature review was restricted to highly automated passenger vehicles and the focus was on qualitative research to identify a wider set of mechanisms as possible. Despite a high level of uncertainty, studying various CAV mechanisms in isolation suggests that CAVs can lead to either dramatic decreases or moderate increases in carbon emissions. Some of the largest carbon reduction opportunities lie in cutting down the number of vehicles on roads through encouraging Mobility as a Service (MaaS) which encompasses vehicle sharing and ride sharing. On the other hand, the major risks are expected to arise from growth in number of VMT as a result of more facilitated, more convenient, and cheaper trips. Likewise, there seems to be opportunities in slashing current levels of CO₂ per VMT by exploiting the efficiency improvements that CAVs can bring about. After all, the environmental benefits of CAVs are more likely to occur (or increase) in longer term with increase in penetration rates and maturation of technology.

The residual uncertainties can also be mitigated through modelling to reach a quantified position on the net impact of CAVs on carbon emissions. Some of the identified mechanisms in this research are common between passenger vehicles and freight. Those mechanisms can be identified/prioritised for studying their impacts in a wider context which includes freight besides passenger vehicles.

DISCLAIMER

While this work was carried out as a part of a PhD placement at Centre for Connected & Autonomous Vehicles (CCAV), Department for Transport (DfT), the findings/discussions do not represent views of CCAV/DfT.

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