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Research Article

Implication of Privately Owned Autonomous Vehicles Adoption in Leeds using System Dynamic Approach

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ABSTRACT

The adoption of autonomous vehicles (AVs) in the UK is potentially rising in the future with no exception in Leeds. With the Leeds City Council aiming to tackle climate change through their transport strategies, the adoption of AVs might introduce positive or negative impacts. Meanwhile, AVs adoption in Leeds is still very little discussed in the transport strategy document. Through the system dynamic approach, the adoption of AVs in Leeds is analyzed based on four main transport strategies targets. Four main scenarios and a sensitivity analysis have been simulated using VENSIM. The result shows that AVs implementation potentially reduces the total vehicle emission with the zero emission power grid and reduces traffic accidents in Leeds which involves SDG 3 and 7. However, a traffic accidents spike should be anticipated in the lower AVs market penetration. Meanwhile, the AVs adoption might generate more traffic where the empty cruising AVs ability can result in additional trips which make the road more congested. Therefore, the local government should provide better alternatives to private vehicles (PV) and implement policies to discourage PV trips which are beneficial to SDG 11. A drastic policy and huge cost might be involved to achieve the sustainability goals.

Keywords: Autonomous vehicles, climate, SDG, system dynamic, transport strategies.

INTRODUCTION

The number of autonomous vehicles (AVs) in the UK is projected to rise in the upcoming future based on the current market trend. This phenomenon can bring new opportunities in the transportation sector, including the improved safety due to the minimal human factor risk involved, reduced transport externalities, and improved traffic performance according to [1], [2], and [3]. Local authorities in the UK such as Leeds City Council composed Connecting Leeds Transport Strategies to address future transport challenges which are climate change, inclusive growth, as well as health and wellbeing [4]. As shown in Table I, four main targets are proposed in the transport strategies. In addition, the document also mentioned the potential presence of AVs but the detailed strategies are yet to be provided. Therefore, the adoption of AVs in Leeds is yet to be understood. Looking at high level AVs with the fully functional driverless abilities that differs from the regula human driven vehicles, they might introduce new behaviors that need to be analyzed and anticipated. It typically revolves around the AVs ability to do driverless vehicle trips which makes empty cruising or return to home trips possible and allow users with no driving abilities to use a car according to [1] and [5]. Furthermore, an unseen disadvantages might also emerged such as the effect of induced demand if the people is more attracted to own the AVs with their additional benefits [6]. This study intends to analyse and understand the implication of the adoption of autonomous vehicles in Leeds within the scope of transport strategies proposed by the city council. For that, the A660 road is selected as the scope of the research. Furthermore, the discussion will revolve around the main targets of the Connecting Leeds Transport Strategies as stated in Table I.

Table 1: Connecting Leeds Transport Strategy Primary Targets

Aspect	Target
Mode Split	Reduce car usage and improve public transport and sustainable modes such as walking and cycling.
Climate Emergency	In 2030, aim to make Leeds carbon neutral.
Distance Travelled	Reduce 30% of car trips in the city which amount to 900 car miles per year on average.
Vision Zero	Reduce fatalities or seriously injured victims of traffic accidents to zero in 2040.

Source: Leeds City Council

LITERATURE REVIEW

Autonomous Vehicles (AVs)

Typically, autonomous vehicles will be divided into several categories based on the levels of human driver involvement and the degree of the automation. Through this technology, there are several benefits and opportunities that might affect the transportation sector. The benefits mainly talked about the improvement of mobility as well as the reduction of energy usage and emissions [7]. However, the advanced impact of AVs adoption might be only limited to the high leveled AVs (Level 4-5) that are able to unlock new transport behavior such as empty cruising and parking finding [8]. The empty cruising or empty trip capabilities allow AVs to drop the passenger on the destination and continue their journey without a driver [9]. Moreover, privately owned AVs can avoid parking costs by sending the car home or to another cheaper parking location, providing some economic benefits to the owner. [10].

To assess the implication of AVs adoption, the market penetration of AVs in the traffic with human driven vehicles (HDV) usually defines to what extent the adoption can affect various factors, positively or negatively [11]. More high leveled AVs in the traffic typically results in the increased benefits such as increased safety, less driver stress, reduced congestion and emissions [12]. Moreover, about fifty percent of the vehicle sales in 2045 are projected to be autonomous, making half of the vehicle fleet autonomous in 2060 [12]. Furthermore, the adoption of AVs in the road can be as early as 2035, depending on various factors including the willingness to pay, tech price drop, and regulation [13]. In this research, the model will simulate different AVs adoption rate and behavior on privately owned AVs. Therefore, only high level AVs with the highest automation (level 5) will be the main focus on the model and will be compared with vehicles with lower level of automation. Furthermore, the market share of AVs will also be analyzed based on the mode choice model.

Potential Impact of Autonomous Vehicles

Typically, AVs can introduce new impact or behavior to the transportation sector. According to [7] and [13], with optimized traffic through platooning abilities, travel time can be reduced and road capacity can be improved when the high leveled AV market penetration is high. Traffic microsimulation analysis on highways shows speed advantage of AVs after 40% market penetration on a road without dedicated AVs lanes [14]. The advantage improved when utilizing the dedicated AV lane on the simulation. Meanwhile, on the urban road, the average speed tends to increase in the medium AVs adoption before it dropped on the higher AVs market penetration based on [13] and [15]. This speed aspect also reflects on the travel time of the studies which shows a similar pattern. Moreover, the utilization of the empty cruising abilities might induce more demand where the vehicle kilometer traveled (VKT) might increase up to 77% [16]. This means that the road potentially becomes more congested as more trips are generated with the implementation of the autonomous vehicles.

From a safety perspective, the impact of AVs adoption might not be completely positive as suggested. With the absence of human factors, the risk of traffic accidents should be significantly eliminated as a human driver is one of the biggest factors on road accident occurrences based on [17] and [18]. On the other hand, several studies indicate that when the traffic between human drivers (HDV) is mixed with fully automated vehicles, the risk of traffic accidents is increased until it reaches a certain point. The behavioral mix between vehicle automation and human driven vehicles on the road result in an increase of traffic accident risk specifically in a low AVs market penetration where the effect gradually decreases with higher AVs fleet penetration in the road according to [19], [20], [21], [22], and [23]. By separating HDV and AV through dedicated AV lanes, the risk of conflict can be reduced as high as 85% in the lower AVs market share [22]. Moreover, when the traffic is filled with driverless vehicles, a very positive impact is expected as it potentially reduces the traffic accident to zero.

Regarding the emission aspect, overall vehicle emissions are reduced in the long run with the adoption of AVs [16]. Furthermore, 20% of fuel can be saved through the AVs platooning ability [7]. In addition, as automation becomes more common on electric vehicles [24], the emission generated will depend on the source of electricity which is generally lower than fossil fuel [16]. Therefore, the vehicle emission needs to be calculated based on the fuel type and emission factor across different types of vehicles.

With the additional advantage of autonomous vehicles, the people's transport mode choice will be affected as the adoption of AVs introduces new features and attributes [25]. Using the mode choice model based on the utility function, the utility of various transport types can be quantified from various observed variables to measure the choice of a transport mode over the other alternatives [26]. In this case, socio-economic traits such as travel cost, income, and travel time are generally used as the main factors to analyze the transport mode choice [27]. These various implications of AVs are summarized in Table II.

Table 2: Expected Simulation Behaviour on the Model

Aspect	**Expected Behaviour**
Mode Share and AVs adoption	Using choice modelling studies to determine the mode share while L5 AVs market share simulated on 3 scenarios, reaching 50% market as early as 2045.
Traffic	Traffic performance depends on the AVs market penetration. Increased VKT due to the empty cruising behavior.
Safety	Higher traffic accident risk on low AVs market share. Very low accident on full AVs adoption.
Emission	Based on the fleet composition as well as vehicle and fuel types.

System Dynamic Modelling

A comprehensive approach is needed to analyze all of the targets from the Connecting Leeds Transport Strategies for the adoption of driverless vehicles in Leeds. In this study, the system dynamic (SD) modelling is used as it can utilize the feedback mechanism to analyze and generate change in the defined system over time [28]. Various different scenarios and policies can be analysed using this approach [29] which will be beneficial in this study. Typically, SD modeling takes the user to set the model boundaries or scope, create and test the model through user-defined scenarios simulation within the software [30].

Recent study on the adoption of autonomous vehicles using SD shows that AVs will eventually replace conventional vehicles as the main mode choice side by side with public transport which still become the majority of people's choice in Australia [31]. However, the impact on the safety and environmental aspects is still not discussed in the model. Meanwhile, another SD modeling on AVs focuses on the economical perspective which can affect the mode choice and traffic [32] while another study analyze the growth of autonomous vehicles market in Beijing, China [30]. It means that different types of models have different use and scope, depending on their own research purposes. In this research, Table II will be treated as the basis behavior that is expected on the model.

METHODOLOGY

This study will mainly utilize the system dynamic to model the impact of AVs adoption in the transportation sector. The construction of the model as well as the simulation will be conducted using the VENSIM PLE program. The main variables to be analyzed in the model are obtained from the key targets of the Connecting Leeds Transport Strategy, which includes all of the aspects mentioned in Table II. After the basic model is built, additional AVs variables are then integrated in the model with the planned model flow shown on Fig. 1. The A660 road segment in Leeds is selected starting from the junction of A6120 to A58(M) junction with a total length of 5.3 km.

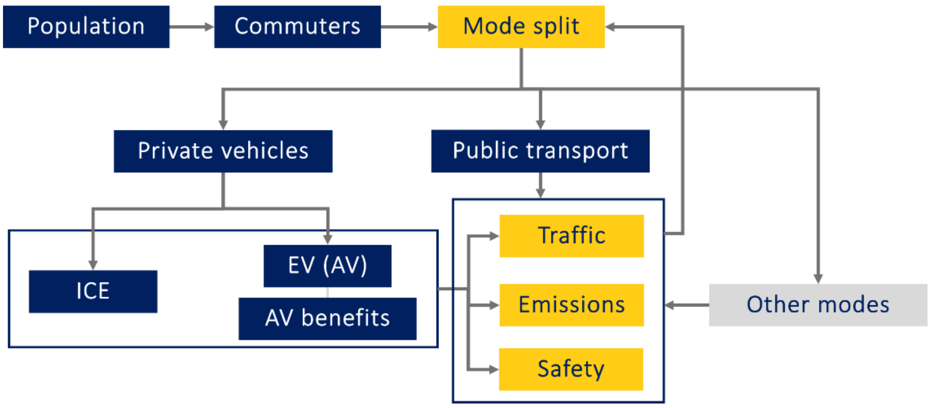

Fig. 1. System Dynamic Model Flow Summary

From Fig. 1, the SD model starts from the population variable which is then filtered to only capture the commuters in the study area. After that, a portion of the commuters will select their mode through the mode split with the focus on private vehicles (PV) and public transport (PT) based on the utility function study [33]. On the PV aspect, there is also a choice model which determines the driver choice on the ICE of AFV which will affect the fleet composition and other variables that will be analyzed further. The ICE and AFV adoption model is based on [34] and [35] for the ICE and AFV utility function.

To support the model, various relevant data for the model will be obtained from official data such as the UK Office for National Statistics, Department of Transport, Department for Energy Security and Net Zero, etc. Relevant variable assumptions are also based on the journal and relevant studies.

The transport related policies as shown in Table III will be implemented in the SD model and will be adjusted according to the proposed scenarios. To analyze the impact of the AVs implementation, several AVs adoption rate is provided as illustrated in Fig 2 based on various studies. From Fig 2, the adoption rates will influence various aspects of the model which will give insight on the key variable performance and will be used for the policy evaluation. This adoption level is then combined with several policies and become the simulation scenarios. The adopted policies are explained in Table III and proposed scenarios are explained in Table IV.

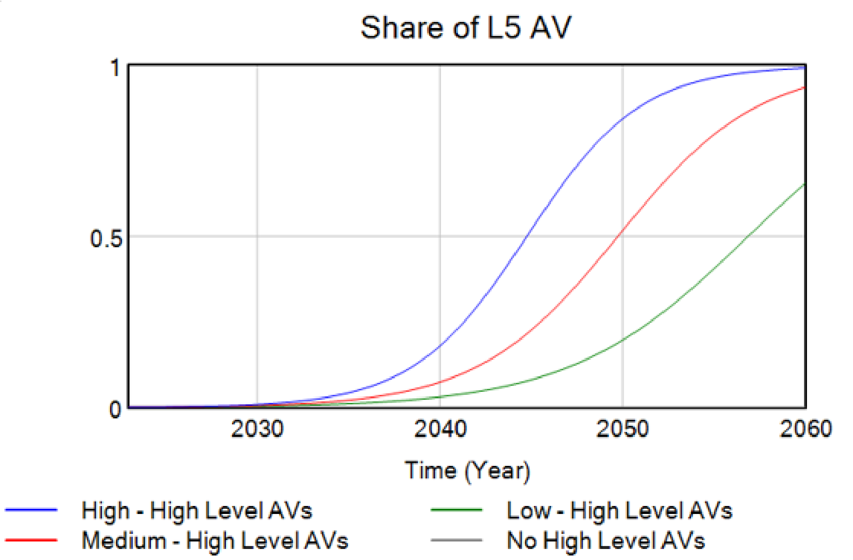

Fig. 2. Level 5 AVs Market Adoption Scenario in the Model

Table 3: Transport Policies in the Model

Policy	Detail
Grant policy	A reduction on the purchase price of alternative fueled vehicles (AFV) by providing grants that affect the utility function of AFV to boost the adoption of AFV.
ICE limitation policy	The ICE sales will be banned in 2035 if activated. Furthermore, ban the usage of ICE in the road if the street ban policy is activated.
Dedicated AV lane	Aims to separate the traffic of AVs with HDV with additional lanes. After 70% high leveled AV market share, the traffic can be combined again.
Public transport prioritiza-tion	Reducing bus fare while also improving the bus operational speed as well as increasing the parking cost for private vehicles.
Green power grid	The AFV emission factor will be set to 0 value in 2035 when the electricity grid is decarbonised.

Table 4: Proposed Simulation Scenarios

Scenario	Summary
Do nothing	This scenario aims to understand the simulation behavior when the policies are inactive.
Vehicle ban	Scenario where ICE sales are banned and further banned from the traffic. AFV grant is also given to see the impact on the AFV adoption.
Mixed	In this scenario, the policies are mixed including the combination of vehicle banning and the usage of dedicated lanes. The AV tech level is also adjusted.
Public transport prioritiza-tion	This scenario will try to assess the impact of public transport prioritization combined with the previous scenarios.

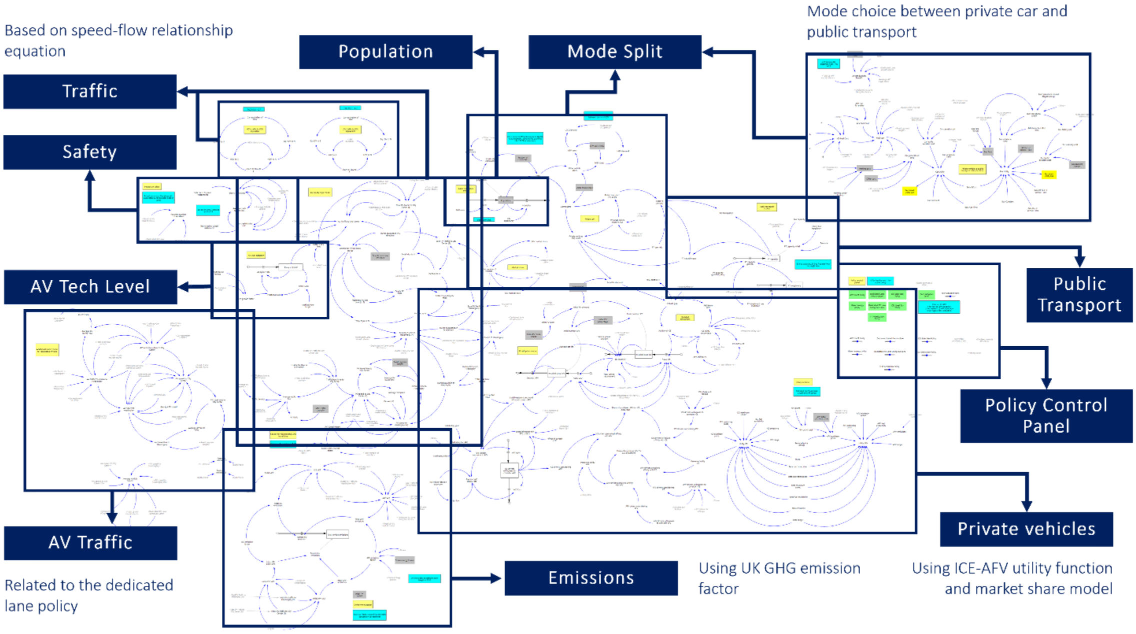

Fig. 3. Full System Dynamic Model and Section Summary

From Fig 3, the full system dynamic model is illustrated which is divided based on the transport strategy main targets with the simulation starting time is 2023 and will end in 2060. Furthermore, a sensitivity analysis will be conducted to understand further implication on the topic. This sensitivity analysis mainly involves the behavior adjustment of empty trips in the model.

RESULT AND DISCUSSION

Do Nothing Scenario

This scenario tries to simulate the impact of AVs in the study area according to the existing trend and without any drastic policy enabled. From Fig. 4, the mode share of buses is increased by the end of the year likely due to the increasing number of L5 AVs that also escalate the risk of traffic accidents on the low market penetration. Without the effect of green power grid policy (DN-UGP), the market share of AFV is still behind the basic do nothing (DN) scenario. However, the difference in utility is not that significant due to the nature of the utility function on the model where purchasing price is still the major factor influencing the choice of vehicle type. Meanwhile, the result on the traffic aspect generates a slight increase on the VKT aspect where the empty trip is slowly increasing. Despite the decreasing number of PV users, the VKT has increased which shows that there are more trips generated even on the low AFV market share. On the other hand, as expected beforehand, the number of traffic accidents have increased as the market penetration of L5 AVs is still low, which affects the driving behavior of HDV on the road. As the adoption of AFV is still low, the trend of vehicle emission is still growing until the end of the simulation year.

Vehicle Banning Scenario

In this scenario, the ICE vehicles can be either sales banned (SLB) or forbidden to enter the road (STB) with the simulation result provided in Fig 4. A huge jump on the private vehicle mode share is seen on the street ban policy with high rate of L5 AVs adoption and AFV grant (STB-High2) as the number of traffic accidents dropped due to high fleet composition of driverless vehicles. PV mode share is shown to drop before the jump caused by the negative impact of traffic accidents on lower L5 AVs market share. Furthermore, the market share of AFV skyrocketed as expected as the street ban policy restricts the usage of ICE vehicles in the study area. Compared with the DN scenario, the AFV and L5 AVs market share is greatly increased through these policies. Meanwhile, the number of bus users falls as PV generates additional benefits from the AVs adoption.

On the traffic aspect, the average travel time is increased as well as the total trips, VKT, and VC ratio. The positive benefit of AVs platooning on average vehicle speed seems to be outweighed by the impact of a more congested road. This is further worsened by the increasing number of empty trips which affect the V/C ratio on the simulation that nearly reached 1. On the other hand, the impact on the safety variable is very positive especially near the end of the simulation year with high penetration of L5 AVs. Moreover, this positive impact on the safety aspect in the STB-High2 scenario is earlier than the other scenarios. This shows that these policies were able to boost the adoption of fully automated vehicles on the road so that the critical stage of crash risk caused by the mix of AV and HDV traffic passed faster. More positive impact can be seen in the emission variable as the SLB scenario is able to moderately reduce the total vehicle emission while STB scenario flattened the emission curve compared with the do nothing scenario. This is expected as the emission trend is based heavily on the composition of vehicles while these policies force the sales of very low emission vehicles as well as restrict highly polluted vehicles. Therefore, when the electricity grid is decarbonised, the impact will be stronger as it makes the emission trend stop growing.

Mixed Scenario

Through the mixed scenario (Mixed), the benefits of SLB and STB scenarios are further boosted with the dedicated lane policy enabled as shown in Fig. 4. The positive impact of dedicated lanes on the safety aspect is visible as the traffic accident peak is lower compared with the other scenarios without dedicated lanes. This means that the separation of AV with HDV traffic can bring benefits to the road users. However, this benefit also affects the utility of PV so that the mode share of private vehicles is increased further, making the bus more unattractive. Meanwhile, the VC ratio jumped in 2047 as the AVs were allowed to enter the usual mixed car lane with the HDV which affected travel time and other related factors.

Public Transport Prioritization Scenario

With the more attractive public transport through this scenario (PT), the PV mode share is significantly reduced as displayed in Fig. 4. However, with the SLB and STB policy enabled, the impact on the mode share is not long lasting as the utility of PV grows with lower traffic accidents on the road. Compared with the result from the mixed policy, this effect of mode share reduction is still lower. By the end of the simulation year, this policy is able to achieve lower average travel time compared with do nothing scenarios and other scenarios. This might be happening due to the controlled PV users growth while PV oriented policy with AVs adoption will generate higher traffic. Another impact can be seen on the empty trips aspect. With the lower PV mode share, the empty trips value on this scenario is slightly lower. No significant change on the safety and emission aspect compared with the mixed scenario as it relies on the high leveled AVs market penetration.

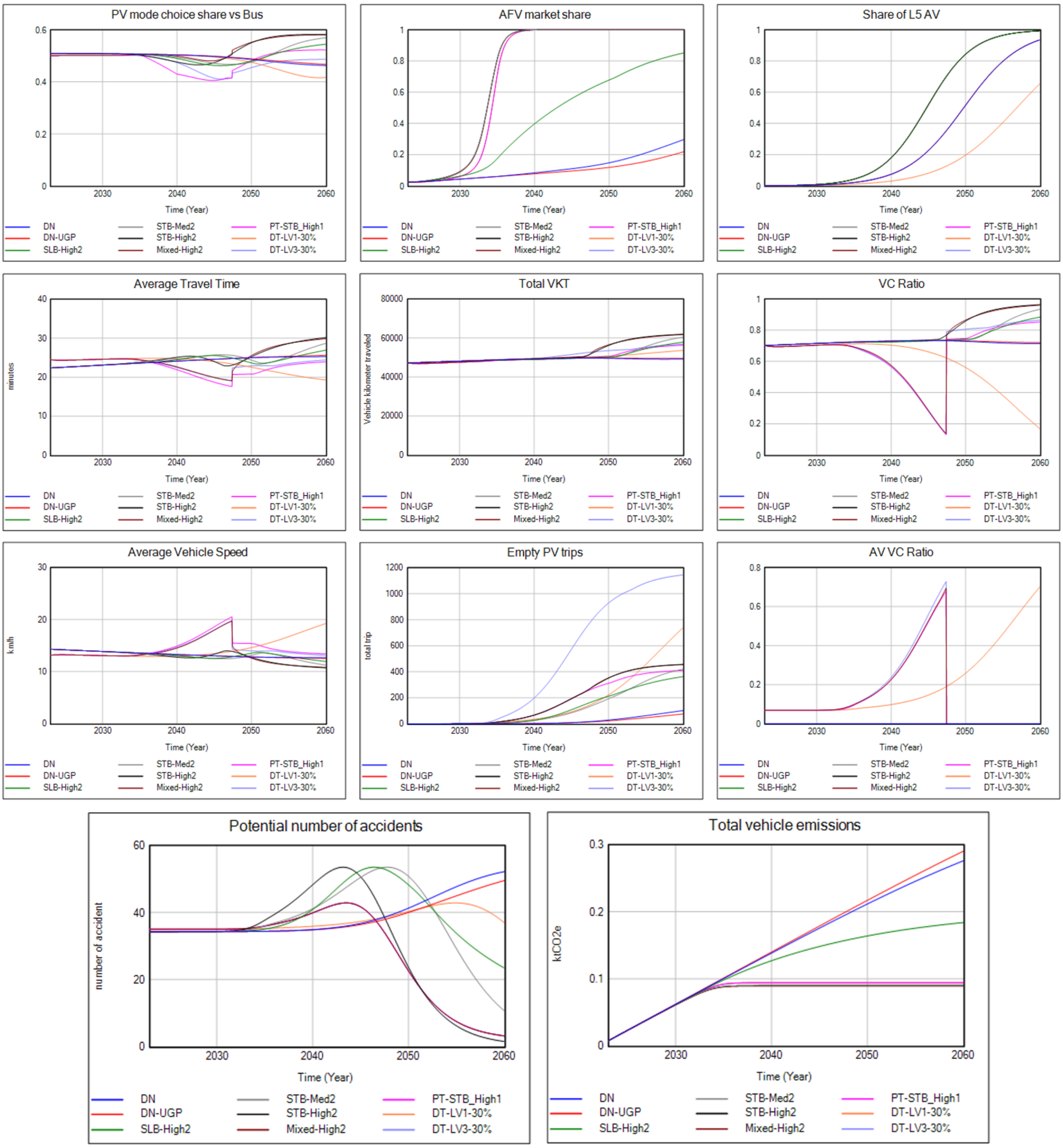

Fig. 4. Simulation Results on Selected Scenarios

Sensitivity Testing

After all of the scenarios are simulated, a specific variable is further analyzed, especially the empty trip variable (DT) with the result provided in Fig. 4. As the base model simulation sets the double commuting value to 10% of total trips, the sensitivity analysis tries to simulate a scenario when that value is set between 0% to 30%. With no double commuting happening, the safety is improved while the PV mode share is consequently increased. However, when the value is increased to 20% and 30%, the PV mode share is further reduced compared to the do nothing scenario. The lower number of PV mode share is actually caused by the higher fuel cost due to the double commuting behavior so that the generalized PV cost increased. Meanwhile, the public transport remains unchanged so that it becomes more appealing to commuters. If the PV and AVs benefits on the fuel consumption and productivity is not taken into account in the utility function, the mode share of PV might increase further so that the congestion can be worse. On the safety aspect, the impact is typically positive according to which L5 AVs adoption rate is used. Faster L5 AVs adoption means that the impact on traffic accidents can be achieved earlier than the other adoption rate. Furthermore, the effect of the decarbonised power grid is quite similar to the other scenarios. However, as the double commuting value is adjusted, on a higher value, the emission trend might be much worse if the power grid is not decarbonised as the VKT is increased from the additional empty trips.

IMPLICATIONS TO THE POLICY ASPECT

The sensitivity analysis result on Fig. 4 shows various effects on the adoption of driverless vehicles in Leeds. From these results combined with the result from the discussion section, the policy implication and recommendation will be discussed in this section.

Mode Share Aspect

According to the Leeds City Council target, the mode share in this study needs to be reduced to 42% share of PV in 2030 compared to bus. The simulation result shows that the combination of policies that encourage the usage of public transport and discourage the usage of PV with additional cost imposed on PV users generates the desired outcome. This means that the related stakeholder may consider to reduce the bus fare and improve the bus facilities and operations to attract more users while also increasing the cost of parking. Moreover, looking at the current fleet, the bus is still able to accommodate additional users that potentially shift with these policies with bus occupancy still below 60%. However, the benefits of AVs will start to appear in the later year in several scenarios which might attract the bus users back to the private vehicles. In addition, the increased parking cost might also encourage the private AVs owner to do the return to home tips to avoid additional charge. Therefore, the local authorities need to consider additional means to discourage the usage of private vehicles such as the utilization of road charging which might be able to maintain the desired mode share in the long run.

Traffic Aspect

With AVs abilities to do return to home trip, the Leeds City Council goals to reduce the VKT might be hampered. As shown in the simulation result, the total number of trips and VKT are increased in general which also reflect the traffic condition in the study area. Furthermore, even if the double commuting is not implemented, the AVs are still able to attract more PV users so that the VKT increase is also expected. Moreover, the behavior of AVs returning home can be detailed further. In one case, the AVs' empty cruising abilities might encourage a household to reduce the number of private vehicle ownership as one vehicle can be used on several different trips. This behavior might introduce economical benefits to the user depending on the scenarios [5]. For example, when the parking cost in the destination is based on an hourly pricing basis, the user might choose to send their AVs back home to save the parking cost or be used by another household member [5]. Therefore, other policies that affect the cost of parking might encourage the AVs owner to make the AVs return to home trip, making the traffic more congested. The simulation result on Fig. 4 on the Mixed-High2 scenario shows the V/C ratio approaching 1 with 10% of AVs trips doing the return to base behavior. This implies that if more users are doing the same behavior, the traffic condition might be much worse. Therefore, the city council needs additional means to control the traffic flow on the existing road.

Safety Aspect

The impact on the safety in this model relies heavily on the interaction between AVs and HDVs so that the market penetration of L5 AVs becomes the key parameter. Therefore, any policies that boost the adoption of AVs should be able to reap the benefits while a half-hearted approach might increase the risk of traffic accidents. As various studies and simulation results show a traffic accident peak on a lower L5 AVs market penetration, the city council and related stakeholder should anticipate this surge if they want to achieve the vision zero target in 2040. Meanwhile, the traffic accident peak can be further lowered with the implementation of dedicated lane policies which basically separate the two main sources of traffic accident risk in the road. Looking at the existing road, additional lane construction might not be possible or cost effective. Therefore, the existing bus lane might be considered by the local authority to be used with the AVs but further studies are required. As traffic accidents number might increase with the presence of AVs, the local authorities can consider limiting the speed in the study area to reduce the risk of fatalities. In addition, the city council might encourage commuters to use alternative modes of transport at least until the market penetration of AVs is already on the level that generates minimal number of traffic accident risk. Further studies are also needed in the field of vehicle safety as vehicle failure can also hinder the intended benefits of AVs [12].

Emission Aspect

The simulation result of this study shows potential benefits on the environmental aspect especially when the adoption of AFV and AVs is favored. Low effort on AFV adoption affects the emission trend slightly better compared to the do nothing scenario. However, combined with the decarbonisation policy on the power grid, the impact is significantly higher as the vehicles should not emit emission anymore, directly or indirectly. This implies the importance of the power grid decarbonisation if related stakeholder aims to achieve the net zero target with electricity as its main power source. Meanwhile, subsidies provided for AFV adoption only help to boost the shift to cleaner vehicles slightly. Different story with the vehicle banning policies, it can encourage PV users to shift to AFV drastically. However, it is still not taking into account the potential policy refusal from the perspective of existing PV users. Therefore, combined with the decarbonisation of the energy sector, these policies will effectively boost the reduction of vehicle emission trends. However, if the city council wants to achieve the target according to their timeline, these policies might need to be implemented before 2030 which is surely a challenge for the related stakeholders.

CONCLUSION

Overall, the presence of autonomous vehicles in Leeds potentially can help the city council achieve the 4 key targets of the transport strategy. However, additional time might be needed as the utilization of AVs might interfere with some of the key targets, especially the traffic and mode share aspect. An opposite effect is introduced as the trips and the mode share of private vehicles is potentially increased. Leeds City Council need to further analyze this potential impact if AVs is included in their strategies with more resources potentially required to mitigate the negative risk from the AVs adoption. However, this should be further analyzed through the cost benefit analysis as this might introduce additional benefits especially regarding the SDGs. With reduced vehicle emission and traffic accidents, it will contribute to the SDG 3 and 7. Moreover, SDG 11 can also be improved by providing better public transport to the people.

It should be noted that this study still has some limitations with its limited scope. As there are very limited studies regarding utility function of mode and vehicle choice in Leeds, the outcome might not accurately reflect the condition in Leeds. This includes the utility function on the private vehicle choice that is very sensitive so that the impact from the total VKT and empty trips increase might not be properly reflected. Meanwhile, the calculation on the risk of traffic accidents should also incorporate the total trip for its variable so that it not only depends on the market penetration of L5 AVs. However, these assumptions should be based on the actual research on the study area so that the relevant stakeholder should work together to assess the detailed impact of AVs adoption in Leeds.

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Engineering for specialization in transportation. As for the foreign universities that will be addressed, the University of Leeds through the Institute for Transport Studies (ITS) which provides master's programs in various fields of transportation expertise.

Data Availability

This research use public data available from the official UK government website including the UK Office for National Statistics, UK Department for Transport, and UK Department for Energy Security and Net Zero.

Conflict of Interest

There is no conflict of interest in this study that was declared by the authors.

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