Temporary traffic management implications of reconfiguring existing motorways to accommodate dedicated Connected Autonomous Trucks (CAT) lanes - A travel delay perspective

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SHORT SUMMARY

Connected Autonomous Vehicles (CAVs) will likely share the same roads with legacy vehicles. There are many options for reconfiguring existing roads to accommodate CAVs, but one model that could be deployed effectively on motorways is to assign a dedicated nearside lane for Connect Autonomous Trucks (CATs). The precise wheel-path tracking capability of CATs permits non-standard width to be used for this dedicated lane, which impacts on the remaining space for legacy vehicles and, hence temporary traffic management (TTM) designs. Currently, there is limited research quantifying and comparing TTM delay implications of different non-standard cross-sections incorporating CAT lanes. This study details performance of various cross-section alternatives under TTM conditions during rehabilitation works. Lane width-speed models are used to calculate delays, and vehicle travel time-cost relationships are applied to determine cost of each scenario. Next, pavement analysis predicts frequency of these rehabilitations. Finally, travel delay cost of each configuration is calculated and compared.

Keywords: Connected autonomous vehicles, connected autonomous trucks, maintenance cost, temporary traffic management, travel time cost.

1. INTRODUCTION

Roadworks are a major part of maintaining the highway infrastructure. In addition to attracting significant parts of highway authority budgets, they have important, inherent implications for road safety and capacity. (Nassrullah & Yousif, 2019). Many research studies on highway design for CAVs support a segregated operational regime, (Davis, 2018; Rad, Farah, Taale, van Arem, & Hoogendoorn, 2020; Ye & Yamamoto, 2018). Under this type of operation, CAVs and non-CAVs occupy different lanes. But there is limited research on how roadworks will be further complicated by modifying the highway and introducing CAVs. Instead, most traffic engineering research on CAVs focus on traffic performance under normal operational conditions. The relatively few publications that focus on work zones do not compare the impact of the different possible alternatives for normal operational, on roadworks.

In a recent study on workzones and CAVs, the University of Wyoming used simulation to analyse the safety performance of CATs under specific weather conditions, finding that CAVs are safer at work zones compared to manual vehicles. The study also found that CAVs improved traffic flow through speed harmonization. (Adomah, Khoda Bakhshi, & Ahmed, 2021). However, the study was based on heterogenous vehicle fleet, rather than segregated lanes.

Other research focus on the use of CAVs as part of the temporary traffic management set up, eg (Tang et al., 2021), hence their findings do not directly apply to the public motorists. Yet another category of research regarding CAVs and work zones, provide insight into the technological system requirements for CAV operations., eg (Park, Marks, Cho, & Suryanto, 2016).

This study seeks to compare the roadworks performance of different highway engineering alternatives for implementing a dedicated CAT lane within an existing highway. The research uses construction costing methods, traffic flow models, economic values of time and predictions for CAVs behaviour, to determine how different vehicle occupants are impacted due the delays caused by road works. A key feature of this research is that it allows a comparison of different cross-section alternatives and penetration rates for CATs.

2. METHODOLOGY

Cross-section designs for normal operations and temporary traffic management (TTM) conditions

During this study multiple engineering scenarios were generated by designing three alternative highway cross-section solutions. The sections were designed such that they would support the incorporation of a dedicated CAT lane into an existing conceptual case study section of motorway in normal traffic operations. A key criterion of this research was that the existing paved area would be maintained, on the basis that widening is likely to incur high costs, which could undo the economic benefits of CATs, and CAVs in general. The case study section used is based on the M3 motorway located in the southeast of England, UK. The study section is a dual 3-lane rural motorway (D3M). A length of 3km was chosen for the analysis as this is the minimum distance required between consecutive junctions to prevent merge/diverge interactions on the mainline when normal traffic conditions are in operation. (Department of Transport, 1995).

The cross-section three alternatives under normal operations are:

- Cross-section Alternative 1 – Standard D3M cross-section, with standard lane widths in accordance with (Department of Transport, 2007)

- Cross-section Alternative 2 – D3M with 5m wide CAT lane, 3.25m manual truck lane and 2.75m inner lane for passenger cars and light trucks.

- Cross-section Alternative 3 – D4M with narrow lanes (2.85m CAT lane, 3.15m manual trucks lane, and two 2.50m lanes for the smaller vehicles.

For each of these normal operations alternatives, the study considered two pavement rehabilitation cases: rehabilitation of the CAT lane and rehabilitation of the manual truck lane. Lighter vehicles impose negligible damage on the pavement structure; hence the impact of pavement rehabilitation of light vehicle lanes is not considered within this study. The result of the TTM designs are shown in Figures 1-3 below. These are based on the UK temporary traffic management requirements. (Gregg, 2007) .

The basis for designing these TTM sections are as follows:

- Provide sufficient working area. For a lane that requires rehabilitation, the full width of the lane is closed off and used as the working area. This will enable all necessary construction equipment to access and move safely within the work area.

- Provision of safety zone between working area and temporary running lanes. 1.2m is generally provided, with the adjacent running lane limited to a temporary mandatory speed limit of 50mph. However, where the 1.2m separation was not achievable, 0.5m safety zone was provided, and the temporary mandatory speed limit reduced to 40mph.

- The aspiration was to provide as many traffic lanes as possible to minimise the delays. However, the absolute minimum lane width of 2.40m (for passenger cars) was implemented. This resulted in instances where one wide lane was shared by all manual vehicles (manual trucks and passenger cars), rather than provide a very narrow car lane and a manual truck lane.

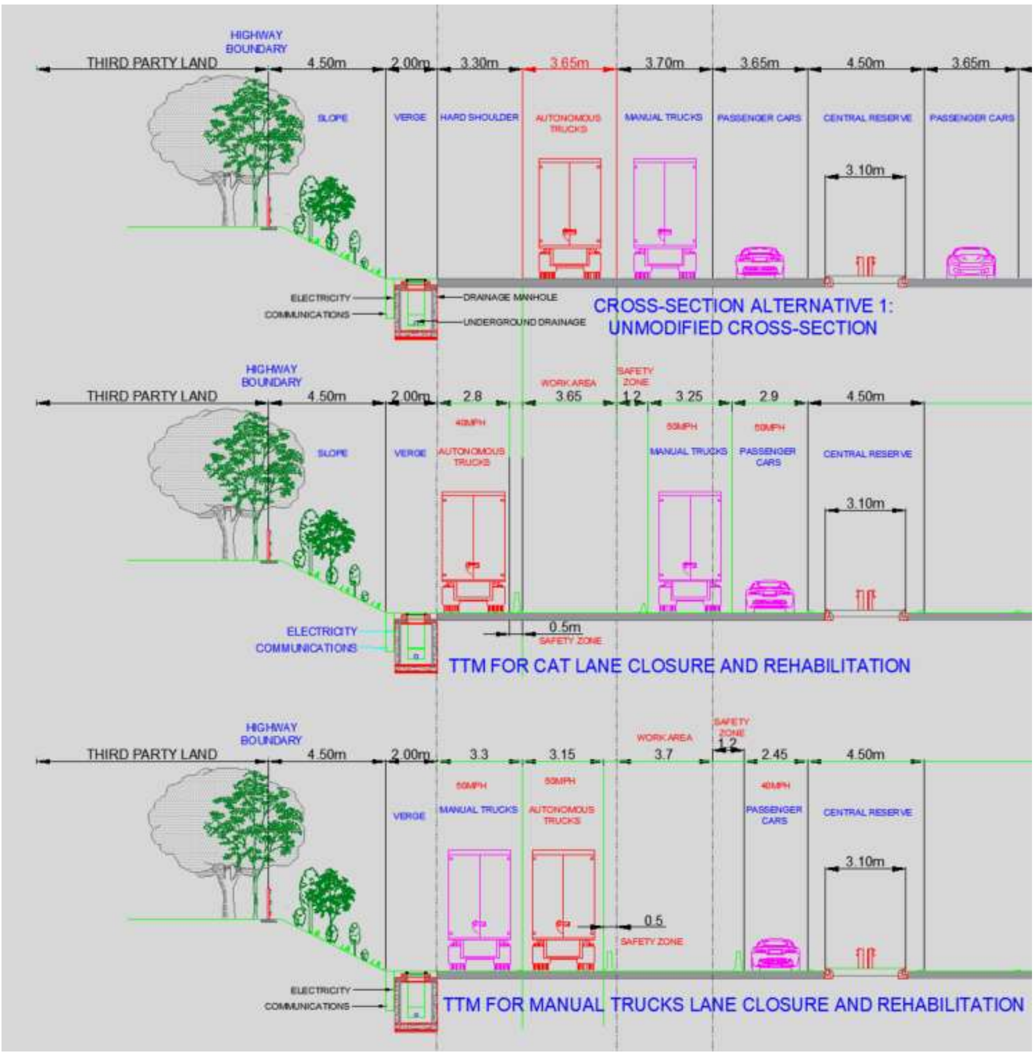

Figure 1: Cross-section alternative 1 (standard lanes) – permanent and TTM conditions

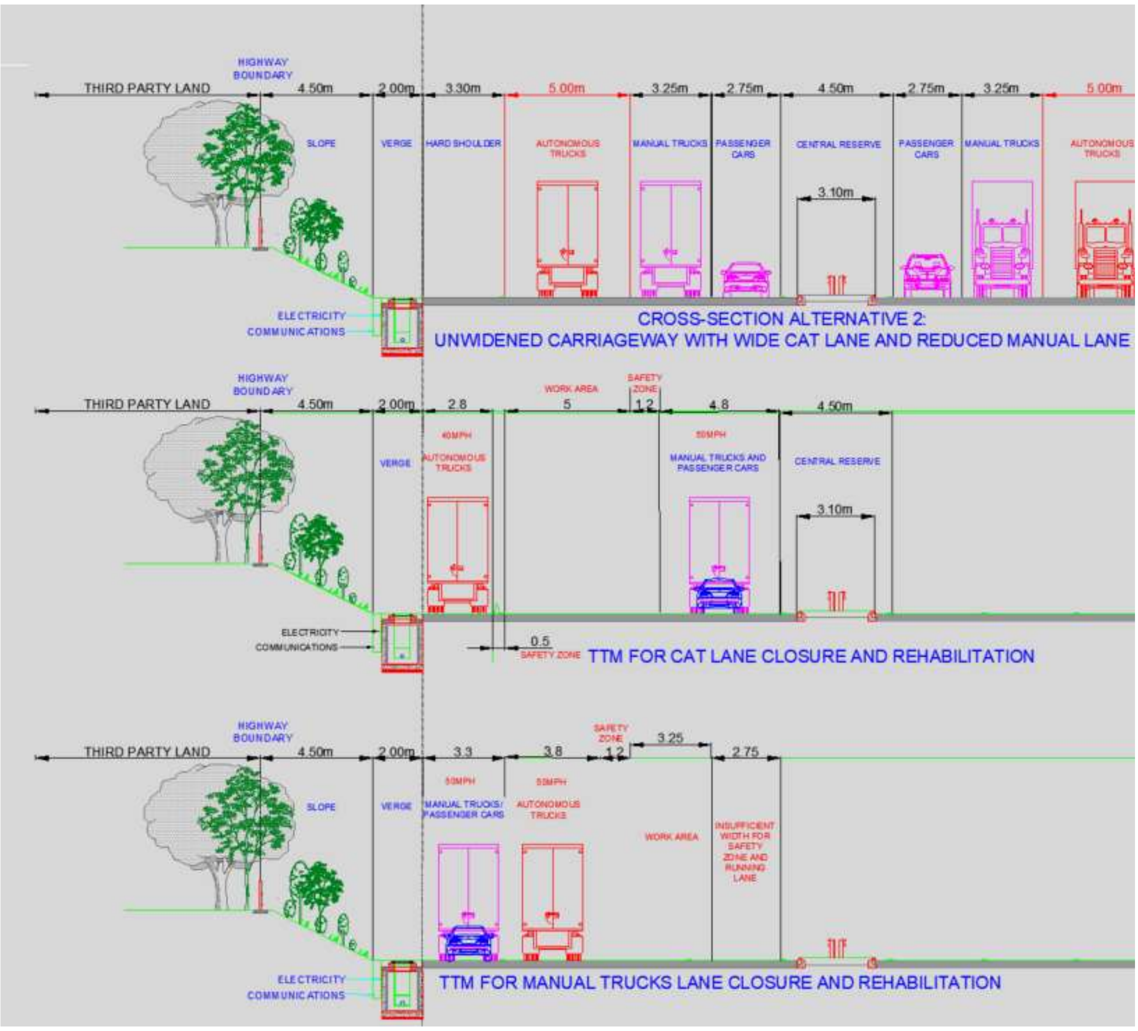

Figure 2: Cross-section alternative 2 (wide CAT lane and narrow manual lanes) – permanent and TTM conditions

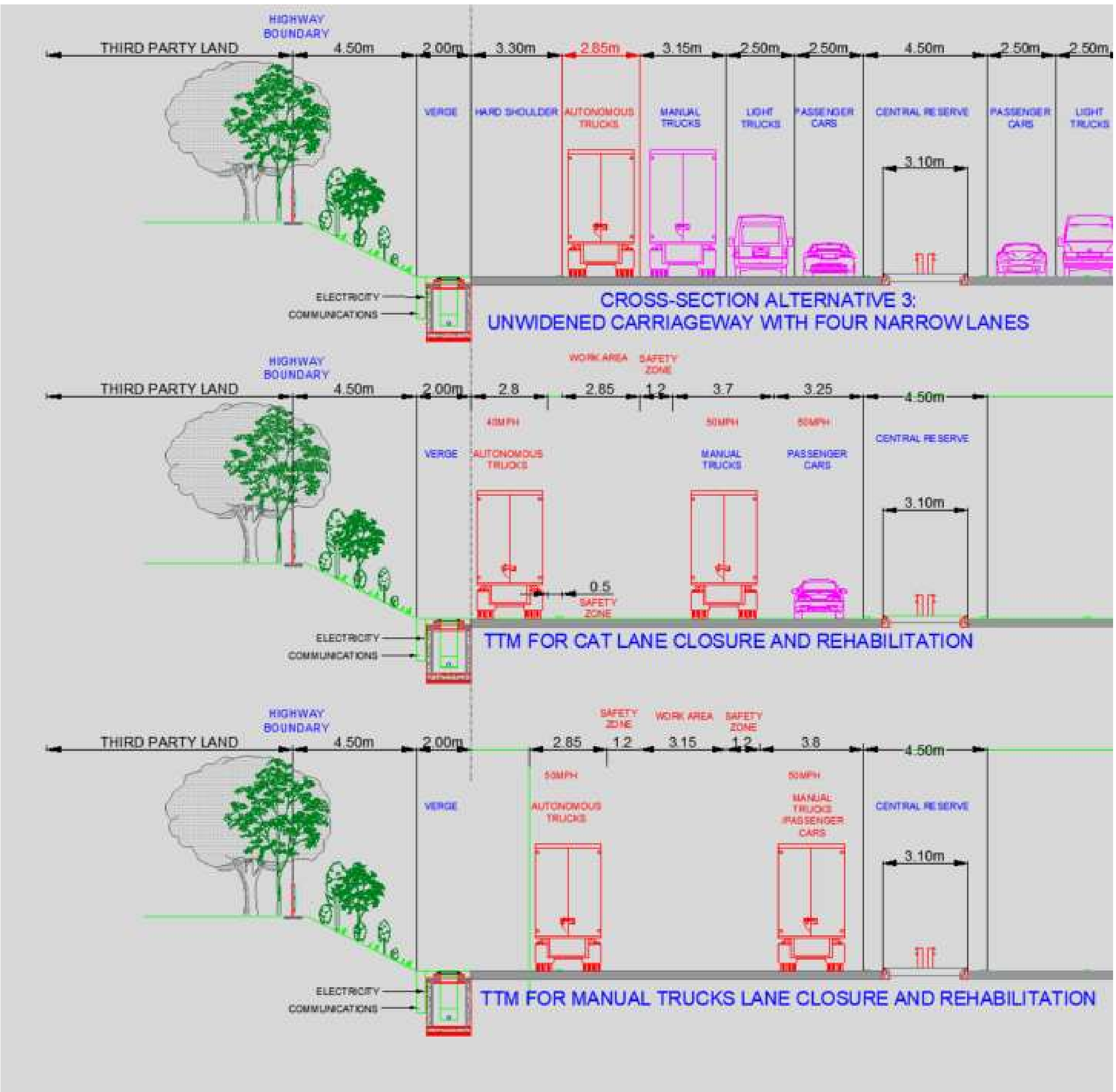

Figure 3: Cross-section alternative 3 (four narrow lanes) – permanent and TTM conditions

Maintenance or rehabilitation frequency

To determine how frequently the pavement rehabilitation works would be required, analyses was conducted using specialist software, Texas Mechanistic-Empirical Asphalt Concrete Pavement Design and Analysis System (Hu, Zhou, & Scullion, 2013). TxME measures failure rates of pavements subjected to CAV driving modes. The analysis was carried out for CAT proportions of 20%, 50% and 80%, to represent low, medium and high penetration rates. The traffic data used were based on typical UK motorway traffic volumes and compositions. (Department for Transport, 2021). The pavement structure used in the analysis was a flexible asphalt concrete consisting of the following:

- 40mm surface course
- 100mm binder course
- 220mm base course
- 200mm granular base
- 15% sub-grade CBR

Delay costing ***Total delay cost (see spreadsheet)***

A number of costing models were applied to determine the annual travel delay cost to motorists as a result of the pavement rehabilitation works.

Industry cost estimation methods for highway projects were used to calculate the works costs - and then total projects costs - for planning off and replacing the layers of damaged pavement. (AECOM, 2021). Then, using the TxME results to calculate failure frequency, the annual cost of rehabilitation for each year, over the 20-year pavement assessment period, is calculated. Traffic flow models relating speeds to lane widths (Chitturi & Benekohal, 2005), and speeds to flow volumes (Horowitz, 2009), are then applied to the various TTM cross-sections. These models were used to calculate the delay experienced by motorists as a result of the TTM. The main assumption adopted during this analysis was that CAT speeds are more determinate and will travel at posted speeds, both during normal conditions and under TTM. Hence, the aforementioned traffic flow models were applied only to the manual fleet.

To determine the duration for which TTM installations were in place for each option, this study applied the Bromilow time-cost (BTC) model. (Kaka & Price, 1991). BTC is a linear regression relationship of the form:

$$T = k \cdot C^{B}$$

where T is the construction time (in working days), C is the construction value (in £m), in this case the total project cost of the rehabilitation works, and k and B are constant coefficients. For major highway projects, k = 258.1 and B = 0.469.

The TTM layout is then designed to UK standards for temporary roadworks design (Gregg, 2007) and this provides the length over which the TTM cross-sections apply.

Using the differential speeds (difference between free-flow speed values under normal conditions and speeds under TTM conditions) and the length of the TTM, delay is calculated. The UK Department for Transport (DfT) models are then applied to obtain the average time cost for each category of vehicle and subsequently, a delay cost. (Department for Transport, 2018). Finally, a Discount rate of 3.5% is applied to each of the annual delay costs, to obtain a Present Value (Treasury, 2020)

3. RESULTS AND DISCUSSION

Cost of undertaking each pavement rehabilitation

Using the cost estimation methods described above, the total cost of removing defective pavement layers and replacing these with new pavement layers are as follows:

Cross-section Alternative 1 – Standard lanes:

- Cost of rehabilitating CAT lane = £409.692
- Cost of rehabilitating Manual truck lane = £415,3042

Cross-section Alternative 2 – Wide CAT Lane, 2 narrow lanes for manual trucks passenger car lanes:

- Cost of rehabilitating CAT lane = £561,222
- Cost of rehabilitating Manual truck lane = £364,794

Cross-section Alternative 3 – Four narrow lanes

- Cost of rehabilitating CAT lane = £319,896
- Cost of rehabilitating Manual truck lane = £353,570

Essentially, wider lanes incur more rehabilitation cost. This is because, in addition to the increased works cost due to more items involved in higher quantities, they also require more time to complete, which increases the cost of non-work items, including preparation/preliminary costs, and Design and Supervision costs. (AECOM, 2021).

Pavement performance under normal operations

The results of the part of the study that analysed the pavement rehabilitation frequency are presented in Table 1. These results show that, during normal operations for CAT lanes, the wider lanes deteriorate slower, as the wheel loads spread over a wider area; scenarios with higher CAT proportions caused the CAT lane to deteriorate quicker due to the higher number of imposed wheel loads. For the manual truck lane, failure was almost exclusively dependent on the CAT proportion as this is what directly affects the volume of manual trucks.

Table 1: Pavement rehabilitation and travel time/delay cost during TTM

CAT %	**Pavement Rehabilitation Freq (…years)**		**Delay cost to vehicles when CAT lane is closed for Rehabilitation**			**Delay cost to vehicles when Manual Truck Lane is closed for rehabilitation**			**Total discounted cost**
	CAT Lane	Manual Trucks Lane	CAT	Manual Trucks	PCs	CAT	Manual Trucks	PCs	
Cross-section Alternative 1									
20	9.1	2.25	£176,737	£293,482	£888,929	£177,868	£268,247	£3,200,271	**£27,897,071**
50	4	3.25	£441,842	£183,426	£888,929	£444,670	£167,654	£3,200,271	**£24,182,802**
80	2.16	8.5	£706,947	£73,371	£888,929	£711,472	£67,062	£3,200,271	**£19,091,470**
Cross-section Alternative 2									
20	21	2.25	£204,846	£988,465	£4,095,326	£66,949	£807,639	£3,346,145	**£31,894,583**
50	10	3.25	£512,116	£910,428	£6,002,978	£418,432	£157,762	£4,904,820	**£34,143,098**
80	6.16	8.5	£819,386	£528,048	£8,673,691	£267,796	£431,450	£7,086,965	**£32,040,828**
Cross-section Alternative 3									
20	4.16	2.25	£157,374	£111,911	£508,241	£65,975	£795,888	£2,255,830	**£18,981,530**
50	1.16	3.25	£393,436	£69,944	£508,241	£164,937	£733,055	£5,081,810	**£83,355,778**
80	1.1	8.5	£629,497	£27,978	£508,241	£263,900	£425,172	£9,153,514	**£163,219,438**

Travel delay cost

Overall, Cross-section Alternative 3 (four narrow lanes) with low CAT penetration rates (20%) presents the best case for travel delay cost during temporary traffic management operations, closely followed by cross-section Alternative 1 with high (80%) CAT proportion. At the other end of the cost spectrum, cross-section Alternative 3 produced prohibitive delay costs to motorists during TTM, for increased CAT proportions (50% and 80%). This is mainly attributable to the very narrow CAT lane under normal operations (2.85m) failing rapidly. This increases the frequency of rehabilitation to approximately once every year, meaning TTM is required much more often than for the other scenarios.

4. CONCLUSIONS AND FURTHER STUDIES

The study examined different cross-section arrangements that can accommodate a dedicated CAT lane under normal traffic operational conditions. The results showed that at low rates of CAT penetrations, the permanent cross-section solution that minimises delays under temporary works condition is the four narrow lanes solution. Yet, this solution is wholly unsuitable for higher penetration rates as the travel delay costs will be prohibitive to the motoring public. This result suggests that adapting existing highways for CATs, and CAVs in general, may have to include dynamic solutions, where lane re-distribution is required over time, depending on level of penetrations.

This study is part of a PhD doctoral research seeking to device a decision-making framework to re-design highways for CAVs. In addition to these travel delay costs during temporary traffic management situations, initial construction costs will be included in the analysis to complement the work. Further work will also include safety assessments, emissions and travel delay costs during normal traffic operations.

The work is limited to CAT, and excludes other (smaller) connected autonomous vehicles. The effect of placing the dedicated CAT lane within the offside of the road cross-section has also not been analysed here, neither has merge/diverge and lane change maneouvres been accounted for.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: H. Jehanfo, I. Kaparias, J. Preston, A. Stevens. data generation: S. Hu and F. Zhou; analysis and interpretation of results: H. Jehanfo, S. Hu and F. Zhou; draft manuscript preparation: H. Jehanfo.

REFERENCES

Adomah, E., Khoda Bakhshi, A., & Ahmed, M. M. (2021). Safety impact of connected vehicles on driver behavior in rural work zones under foggy weather conditions. *Transportation Research Record*, 03611981211049147.

AECOM. (2021). *Spon's Civil Engineering and Highway Works Price Book*.

Chitturi, M. V., & Benekohal, R. F. (2005). Effect of lane width on speeds of cars and heavy vehicles in work zones. *Transportation Research Record, 1920*(1), 41-48.

Davis, L. (2018). Optimal merging from an on-ramp into a high-speed lane dedicated to connected autonomous vehicles. *arXiv preprint arXiv:1809.01226*.

Department for Transport. (2018). WebTAG Databook. Retrieved from https://www.gov.uk/government/publications/tag-data-book

Department for Transport. (2021). Table TRA0104 - Road traffic (vehicle miles) by vehicle type and road class in Great Britain, annual 2020. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/981972/tra0104.ods

Department of Transport. (1995). DMRB TD42/95 Geometric Design of Major/Minor Priority Junctions. In (Vol. Volume 6): HM Stationery Office.

Department of Transport. (2007). DMRB TD27/05 Cross Sections and Headrooms. In (Vol. Volume 6): HM Stationery Office.

Gregg, D. (2007). Working with the revised chapter 8 of the Traffic Signs Manual. *ASPHALT PROFESSIONAL*(29).

Horowitz, A. (2009). Delay–Volume Relations for Travel Forecasting: Based upon the 1985 Highway Capacity Manual. FHWA, US Department of Transportation, March 1, 1991. In.

Hu, S., Zhou, F., & Scullion, T. (2013). *Development of Texas mechanistic-empirical flexible pavement design system*. Retrieved from

Kaka, A., & Price, A. D. (1991). Relationship between value and duration of construction projects. *Construction Management and Economics, 9*(4), 383-400.

Nassrullah, Z., & Yousif, S. (2019). Development of a microsimulation model for motorway roadworks with narrow lanes. *IEEE Transactions on Intelligent Transportation Systems, 21*(4), 1536-1546.

Park, J., Marks, E., Cho, Y. K., & Suryanto, W. (2016). Performance test of wireless technologies for personnel and equipment proximity sensing in work zones. *Journal of Construction Engineering and Management, 142*(1), 04015049.

Rad, S. R., Farah, H., Taale, H., van Arem, B., & Hoogendoorn, S. P. (2020). Design and operation of dedicated lanes for connected and automated vehicles on motorways: A conceptual framework and research agenda. *Transportation Research Part C: Emerging Technologies, 117*, 102664.

Tang, Q., Cheng, Y., Hu, X., Chen, C., Song, Y., & Qin, R. (2021). Evaluation methodology of leader-follower autonomous vehicle system for work zone maintenance. *Transportation Research Record, 2675*(5), 107-119.

Treasury, H. (2020). *The Green Book: appraisal and evaluation in central government: Treasury guidance*: Stationery Office.

Ye, L., & Yamamoto, T. (2018). Impact of dedicated lanes for connected and autonomous vehicle on traffic flow throughput. *Physica A: Statistical Mechanics and its Applications, 512*, 588-597.