Australasian Transport Research Forum 2021 Proceedings
8-10 December, Brisbane, Australia
Publication website: http://www.atrf.info

Impacts of Autonomous Vehicles on Road and Pavement Design

Son Pham[1], Long Truong[1], Nhu Nguyen[2]

[1]Department of Engineering, School of Engineering and Mathematical Sciences, La Trobe University, Melbourne, Australia

[2]School of Engineering, Deakin University, Geelong, Australia

Email for correspondence: L.Truong@latrobe.edu.au

1.Introduction

Road networks have been increasingly opened to autonomous vehicles (AVs) as AV trials are being conducted worldwide. On-road trials of AVs were legalized in South Australia in 2016. Australia now has AV trials in almost all jurisdictions. Much research has suggested that AVs will disrupt future transport systems by providing mobility, safety, economic, and environmental benefits (Fagnant and Kockelman, 2015, Truong et al., 2017, Morando et al., 2018, Kopelias et al., 2020, Yantao et al., 2021). In particular, AVs are expected to reduce crashes since most crashes are related to human factors, e.g., driver errors and increased reaction times due to fatigue, alcohol/drugs, or distraction (Fagnant and Kockelman, 2015).

Road networks have traditionally been developed with human drivers in mind, and thus they may not be optimal for AVs. The shift from human-driven vehicles (HVs) to AVs can lead to changes in road geometric design parameters, such as sight distance and lane width. Given the same number of lanes, the total road width for AVs could be decreased due to better vehicle control (Intini et al., 2019). In a study using the US' AASHTO highway design standards, Khoury et al. (2019) evaluated the effects of AVs on geometric designs by considering potential differences in perception reaction times between AVs and human-driven vehicles. Given a fleet of fully AVs, a perception reaction time of 0.5s was selected, instead of the typical value of 2.5s for conventional human-driven vehicles. This led to a reduction in decision sight distance (DSD), which in turns decreased length requirements for crest and sag vertical curves. In a recent study in Italy, Guerrieri (2021) considered a perception reaction time of 0.15s and 0.3s seconds for AVs and connected and automated vehicles (CAVs) respectively when calculating stopping sight distance (SSD). It was suggested that various speed limits in certain Italian highway segments could be removed due to the changes in required SSDs.

Recent literature also suggested that autonomous trucks could be able to utilise road pavement surface better, potentially extending pavement life or necessitating smaller, less expensive pavements with AV technology's influence over vehicle lateral positioning (Noorvand et al., 2017). Specifically, the lateral position of the wheels on pavement surface is stochastic with human drivers, but can be controlled with AVs. Chen et al. (2019) studied the effects of autonomous trucks' wheel lateral distribution within the traffic lane on pavement distress and found that appropriate control strategies provide benefits to asphalt pavement through wider use across pavement surface width. Likewise, Gungor et al. (2020) reported that optimising lateral position of autonomous trucks in platoons would extend asphalt pavement life. A framework for flexible pavement design with autonomous trucks has recently been introduced in the US (Gungor and Al-Qadi, 2020), taking into account controlled lateral positions.

Overall, little research has been conducted with respect to the impacts of AVs on road geometric and pavement design. Particularly, the possibility of AVs affecting Australian road networks is one part of the AV debate that has gained little recognition in the literature. This paper therefore aims to investigate the potential impacts of AVs on road geometric and pavement design, using Austroads' design guides.

2. Methods

2.1 Road Geometric Design

2.1.1 Stopping sight distance

The stopping sight distance (SSD) is an essential consideration in road geometric design. According to Austroads, SSD is determined by perception reaction time (R_T), operating speed (V), coefficient of deceleration (d), and longitudinal grade (a). For HVs, R_T ranges between 1.5s (alerted driving conditions and V ≤90km/h) and 2.5s (unalerted driving conditions) (Austroads, 2021). In term of AVs, extensive sensor and computer systems could reduce R_T to around 0.15s to 0.5s (Khoury et al., 2019, Guerrieri, 2021). In this study, it is assumed that all cars are fully AVs and thus R_T for AVs varies from 0.15s to 0.5s, in alignment with previous research.

2.1.2 Crest vertical curve

The required length of a crest curve (L_{crest}) is determined using grade change (A) and K value that in turn is calculated based on SSD, A, driver eye height (h_1), and objective height (h_2). For HVs, the typical value of h_1 is 1.1m (Austroads, 2021). For AVs, it is assumed that the vehicle's eyes with sensors/cameras locate at the roof. AVs' h_1 would thus be increased since it could be calculated as the sum of the roof height and the camera's height. AVs' h_1 was assumed to be 1.7m (Khoury et al., 2019).

2.1.3 Sag vertical curve

Similarly, the required length of a sag curve (L_{sag}) is determined using A and K. However, K for a sag curve is calculated using SSD, A, mounting height of headlights (h), and elevation angle of beam (q). For HVs, an acceptable value of h is 0.65m (Austroads, 2021). In term of AVs, it can be assumed that the sensor's height above the road, measured at 1.7m as aforementioned, takes the place of the headlight's elevation.

2.2 Pavement Design

The critical strain developed in pavements under vehicle's wheel path is the key input parameter of distress models to predict the allowable number of axle group loads. The use of the critical strain in the current design method (Austroads, 2019) implies that all axle group loads will apply to the same location on a traffic lane. Such conservative method is chosen because the lateral wandering of HVs in a traffic lane can hardly be controlled or measured. With the use of AVs, the lateral location of wheel paths can be well programed. This allows us to set a uniform lateral distribution of wheel paths in a traffic lane, smearing damage to a wider pavement area and hence reducing its accumulation rate. To apply this concept to pavement design, a modified design method for AVs is suggested in which the same distress models are used, but the critical strain is now replaced by an actual strain caused by a wheel path wandering at a specific location. The distribution of AVs' wheel path first needs to be identified. In this study, a uniform distribution of wheel path at 5 discrete points varied in the range of ±200 mm is chosen. The strain profile over a pavement cross-section caused by each axle group can be computed using CIRCLY 7.0 software. Based on this, the strain at 5 discrete points can be determined and will be used for the calculation of allowable number of loads. In the traditional method, damage of a pavement material caused by a number of axle group load j of axle group type i is calculated by:

$$d_{ij} = \frac{e_{ij}}{N_{ij}} = \frac{e_{ij}}{\frac{RF}{n}\left(\frac{k}{\mu\varepsilon_{ij}}\right)^m} \quad (1)$$

where e_{ij} is the number of axle group load j of axle group type i applied to the pavement; RF is the reliability factor of the distress model; n is the number of axles in the axle group type i; $\mu\varepsilon_{ij}$ is the critical strain caused by axle group load j of axle group type i; and k is a material constant whose value depends on material types. In the modified design method, the number of axle group load j of axle group type i that causes the same damage d_{ij} is denoted by e_{ij}^{new}. As e_{ij}^{new} is equally divided for 5 discrete points, the total damage is calculated by:

$$d_{ij} = \sum_{t=1}^{5} \frac{e_{ij}^{new}}{5N_{ij}^{t}} = \sum_{t=1}^{5} \frac{e_{ij}^{new}}{\frac{5RF}{n}\left(\frac{k}{\mu\varepsilon_{ij}^{t}}\right)^m} \quad (2)$$

where $\mu\varepsilon_{ij}^{t}$ is the strain caused by axle group load j of axle group type i when the load is located at point t. From Eq. (1) and (2), we have:

$$\frac{e_{ij}^{new}}{e_{ij}} = \frac{5\left(\mu\varepsilon_{ij}\right)^m}{\sum_{t=1}^{5}\left(\mu\varepsilon_{ij}^{t}\right)^m} \quad (3)$$

As $\mu\varepsilon_{ij}^{t} \leq \mu\varepsilon_{ij}$, Eq. (3) proves that the modified method for AVs will give a higher number of allowable traffic loads than the traditional method does.

3. Results and Discussion

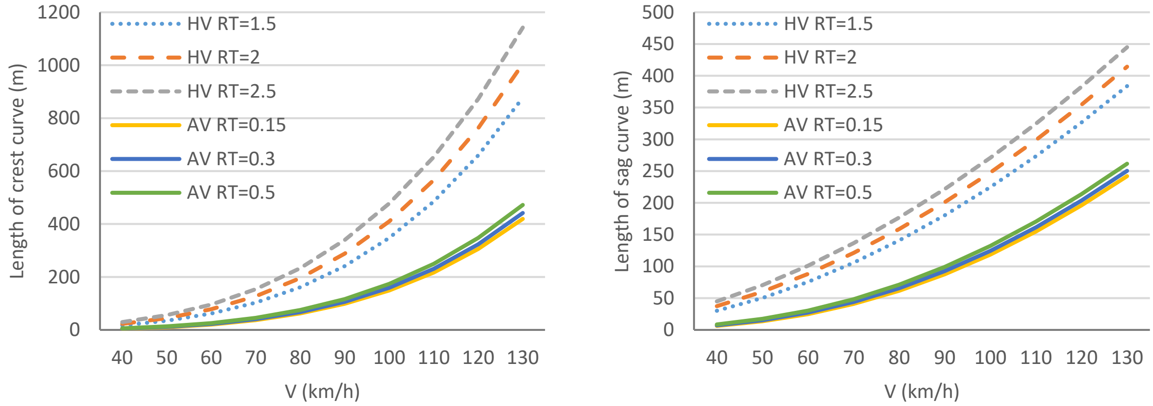
3.1. Impact on Road Geometric Design

Table 1 presents SSDs calculated for HV and AV scenarios with different R_T. These were calculated using d value of 0.36, a commonly used coefficient of deceleration in Austroads and suitable for most urban and rural road types, and a of zero. SSDs for AVs would be significantly lower than SSDs for HVs at all operating speed levels, owning to lower perception reaction times. In general, SSDs for AVs would be like SSDs for HVs at much lower operating speeds, i.e., approximately 20 km/h lower.

Table 1 SSDs (m) for HVs and AVs

V (km/h)	HV			AV		
	R_T=1.5s	R_T=2s	R_T=2.5s	R_T=0.15s	R_T=0.3s	R_T=0.5s
40	34	40	45	19	21	23
50	48	55	62	29	32	34
60	64	73	81	42	44	48
70	83	92	102	57	59	63
80	103	114	126	73	77	81
90	126	139	151	92	96	101
100	151	165	179	114	118	123
110	178	193	209	137	141	148
120	207	224	241	162	167	174
130	239	257	275	190	196	203

Figure 1a shows the length of crest curves for HV and AV scenarios. Common parameters include a longitudinal grade A of 6% (3% for both upgrade and downgrade) and a typical objective height h_2 of 0.2m. Results show that the AVs would require significantly shorter crest curves compared to HVs. Particularly, the difference between the lengths of crest curves for AVs and HVs becomes larger with increasing operation speeds. For example, the length of crest curves for HVs at 80km/h could even be higher than that for AVs at 100km/h. Figure 1b summarises the length of sag curves for HV and AV scenarios, using common A value of 6% and q value of 1^o. Results also confirm that the length of sag curves for AVs would be substantially shorter when compared to HVs. For example, the length of sag curves for HVs at 70 km/h would be almost the same as that for AVs at 100 km/h. These results are understandable considering AVs' shorter SSDs, higher eye height and higher headlight height as aforementioned. Overall, results show that a fleet of fully AVs would require shorter SSDs and vertical curves.



a) Crest curve b) Sag curve

Figure 1 Length of vertical curves for HVs and AVs

3.2. Impact on Pavement Design

The modified pavement design method is applied to calculate the allowable number of the single axle dual tyres (SADT) with the axle group load of 80 kN applied to a pavement. The pavement structure consists of (from top to bottom) an asphalt layer of 125 mm thick with the modulus of 2200 MPa, a cemented granular layer of 200 mm thick with the modulus of 500 MPa, a granular layer of 200 mm thick with the modulus of 210 MPa and in-situ subgrade with CBR = 5. Horizontal strain at 5 discrete points at the bottom of the asphalt layer is shown in Figure 2. The critical strain equals to 114 με (at x = -165 mm), while the strain at other points are 11.2 με (at x = -365 mm), 13.2 με (at x = -265 mm), 32.1 με (at x = -65 mm) and 47 με (at x = 35 mm). Using Eq. (3), we obtain $e_{ij}^{new}/e_{ij} = 4.93$.

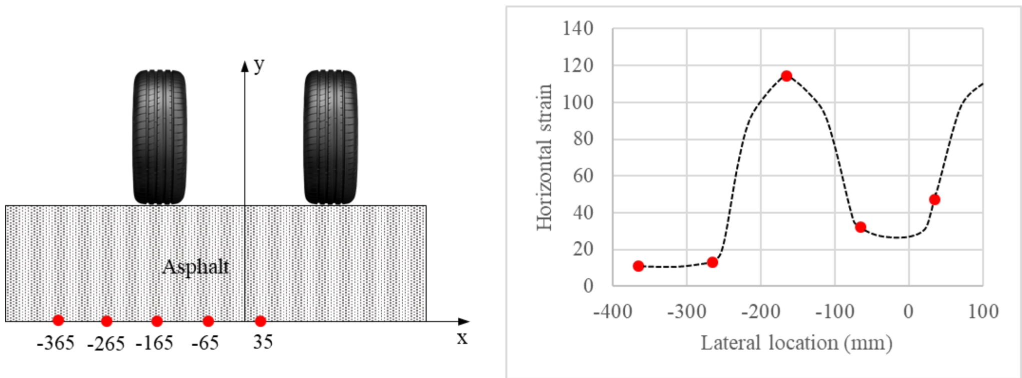


Figure 2: Horizontal strain at 5 discrete points on a lateral cross-section of the pavement

This result indicates that with the same pavement structure, if AVs are used and the vehicle's wheel paths are distributed evenly on 5 discrete points, the pavement could withstand 4.93 times the number of the single axle dual tyres (SADT) with the axle group load of 80 kN as compared to the design number when HVs are used.

4. Conclusions

This paper has investigated the potential impacts of AVs on road geometric design and pavement design by modifying Austroads' design guides. Results showed that a fleet of fully AVs would have lower geometric design requirements, i.e., shorter stopping sight distance, shorter vertical crest curve and sag curve. This suggests not only significant cost reductions in building new roads for AVs, but also speed increases on existing roads from a geometric design perspective. Results also confirm that AVs could better utilise pavement structure as the same pavement structure could withstand much higher AV traffic loading than HV traffic loading. In other words, given the same traffic loading, pavement thickness would be reduced for AVs. Overall, the findings of this paper suggest AVs' potential towards better utilisation of existing road infrastructure. It should be acknowledged that as AVs and related technologies (e.g., sensing and vehicle control) are evolving, the assumptions in this study would need to be updated. Future work should also look at the potential impacts of the mixed fleet of AVs and HVs, considering the long-expected transition to fully AVs.

References

AUSTROADS 2019. Guide to Pavement Technology Part 2: Pavement Structural Design. Sydney, NSW.

AUSTROADS 2021. Guide to Road Design Part 3: Geometric Design. Sydney, NSW.

CHEN, F., SONG, M., MA, X. & ZHU, X. 2019. Assess the impacts of different autonomous trucks' lateral control modes on asphalt pavement performance. *Transportation Research Part C: Emerging Technologies,* 103**,** 17-29.

FAGNANT, D. J. & KOCKELMAN, K. 2015. Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice,* 77**,** 167-181.

GUERRIERI, M. 2021. Smart Roads Geometric Design Criteria and Capacity Estimation Based on AV and CAV Emerging Technologies. A Case Study in the Trans-European Transport Network. *International Journal of Intelligent Transportation Systems Research,* 19**,** 429-440.

GUNGOR, O. E. & AL-QADI, I. L. 2020. Wander 2D: a flexible pavement design framework for autonomous and connected trucks. *International Journal of Pavement Engineering***,** 1-16.

GUNGOR, O. E., SHE, R., AL-QADI, I. L. & OUYANG, Y. 2020. One for all: Decentralized optimization of lateral position of autonomous trucks in a platoon to improve roadway infrastructure sustainability. *Transportation Research Part C: Emerging Technologies,* 120**,** 102783.

INTINI, P., COLONNA, P., BERLOCO, N. & RANIERI, V. 2019. Rethinking the main road design concepts for future automated vehicles native roads. *European Transport,* 73**,** 1-28.

KHOURY, J., AMINE, K. & ABI SAAD, R. 2019. An Initial Investigation of the Effects of a Fully Automated Vehicle Fleet on Geometric Design. *Journal of Advanced Transportation,* 2019**,** 6126408.

KOPELIAS, P., DEMIRIDI, E., VOGIATZIS, K., SKABARDONIS, A. & ZAFIROPOULOU, V. 2020. Connected & autonomous vehicles – Environmental impacts – A review. *Science of The Total Environment,* 712**,** 135237.

MORANDO, M. M., TIAN, Q., TRUONG, L. T. & VU, H. L. 2018. Studying the Safety Impact of Autonomous Vehicles Using Simulation-Based Surrogate Safety Measures. *Journal of Advanced Transportation,* 2018**,** 6135183.

NOORVAND, H., KARNATI, G. & UNDERWOOD, B. S. 2017. Autonomous Vehicles: Assessment of the Implications of Truck Positioning on Flexible Pavement Performance and Design. *Transportation Research Record,* 2640**,** 21-28.

TRUONG, L. T., DE GRUYTER, C., CURRIE, G. & DELBOSC, A. 2017. Estimating the trip generation impacts of autonomous vehicles on car travel in Victoria, Australia. *Transportation,* 44**,** 1279-1292.

YANTAO, H., KOCKELMAN, K. M. & TRUONG, L. T. 2021. SAV Operations on a Bus Line Corridor: Travel Demand, Service Frequency, and Vehicle Size. *Journal of Advanced Transportation,* 2021**,** 5577500.