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A Study on the impact of AV-HDV mixed traffic on flow dynamics of single-lane motorway

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Abstract

Due to the advancement in technology, it is likely to witness a deployment of Autonomous Vehicles (AV) on the road in the near future. High technical capability of AVs is expected to create different behavioral settings than Human-Driven Vehicles (HDV), such as shorter reaction time and time headway. However, considering AV-HDV mixed traffic conditions in the process of the dissemination, radical behavioral settings of AV might have negative impacts on traffic flow. This paper investigates safety, efficiency and comfort impacts of AV on a single lane motorway considering different reaction time, time headway and percentage of AV in a vehicle platoon. Results of Monte Carlo simulation show that with increased percentage of AV, safety, efficiency and comfort can be improved as far as the time headway of AV is similar to HDV under the assumption that AVs have smaller reaction time than HDVs. However, it can be concluded that the smaller desired minimum time headway may cause the unsafe and uncomfortable condition with the longer reaction time. Therefore, the setting of AV should be carefully selected considering the relationship between the reaction time and the desired minimum time headway.

Keywords: Autonomous vehicle, Mixed traffic, Flow dynamics;

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1. Introduction

As the transportation becomes more automated and digital rapidly, original equipment makers and major IT companies are competing at the highest to take the leadership of autonomous vehicles (AV). Technical capabilities of AV may lead to improved behavioral performances (e.g. shorter reaction time and minimum desired time headway), which are better than conventional human-driven vehicles (HDV). Accordingly radical technical settings of AV may bring about desirable effects such as improvement of traffic capacity. However, HDVs that follow the AV may not be able to react that kind of radical behavior appropriately. From the viewpoint of safety, the conservative technical settings of AV should also be considered.

The objective of this paper is to estimate the impact of AV-HDV mixed traffic on flow dynamics of single-lane motorway by using a car following model, and to propose a realistic range of behavioral settings for AV from the viewpoint of safety, comfort and efficiency for mixed traffic scenarios of AV and HDV.

2. Literature Review

Since Adaptive Cruise Control (ACC) was introduced for the first time in 1990s, researchers have investigated the impact of an automated system that detects the spacing with the leading vehicle and controls acceleration/deceleration on the longitudinal motion on motorways.

The setting of AV should be carefully selected considering the stability of the vehicle behavior. Yang et al. (2015) investigated the instability of car followings using the estimated parameters of commercial ACC vehicles with the mixture of HDV, though they have not comprehensively analyzed the acceptable range of the parameter combinations of ACC vehicles. Therefore, the conservative setting of AV is not appropriately as the stability analysis.

To analyze the impact of AV on motorway performance under the radical setting (e.g. shorter reaction time and minimum desired headway), various analyses have been carried out. Zheng and McDonald (2004), Kesting (2006) and Klunder et al. (2009) conducted the simulation on the impact of ACC on the traffic flow. Zheng and McDonald (2004) evaluate the compatibility between the ACC performance and the driver's expectations by using the value of time-to-collision. Kesting (2006) investigated the jam-avoiding trend of ACC, and found that with a constant time headway set for ACC, the efficiency is improved. Klunder et al. (2009) concluded that when all the vehicles on the lane are equipped with ACC system on, the efficiency and safety are improved. Shi and Prevedouros (2016) conducted traffic flow analysis of different percentage of AV cases with the Monte Carlo simulation and concluded that AV is able to increase the capacity, maximum service flow rate, and also level of service can be improved when AV occupy high percentage in the traffic. The results of all papers concluded that the efficiency are safety improved with the increasing the percentage of ACC or AV. Talebpour and Mahmassain (2016) considered the mixed traffic condition which are vehicles with no communication capability, communication ready vehicles and autonomous vehicles by utilizing different acceleration models. They conclude that connected and automated vehicle can improve stability and they can achieve higher throughput. However, the radical settings of AV assumed in these papers may cause the gap between the HDV behavior and AV behavior. That kind of gap could decrease the efficiency and safety.

Past researches on the impact of AV on traffic flow are mostly predicting an optimistic approach, claiming AV will improve efficiency, safety and comfort on the road. However, there are so many challenges and problems that are neglected even on one dimensional flow. For instance, behavioral setting of AV can be set too radical in the future or too conservative at the implementation stage, which might have potentially negative impact on the traffic flow.

This paper investigates the impact of AV on traffic flow with a realistic point of view, rather than optimistic, through microscopic analysis of minimum time-to-collision, maximum jerk and velocity of shockwave for different percentages of AV with different combinations of reaction time and desired minimum time headway settings.

3. Methodology

In order to analyze the impact of AV, a platoon of vehicles is assumed in this study, with 1 merging vehicle in a single lane motorway at a merging section (Fig. 1). It is also assumed that there is no overtaking that would cause the leading vehicle (LV) to decelerate. Therefore, LV only happens to decelerate the merging section for creating a gap for the merging vehicle. A microscopic simulation model is applied under this condition to evaluate the AV-HDV mixed traffic.

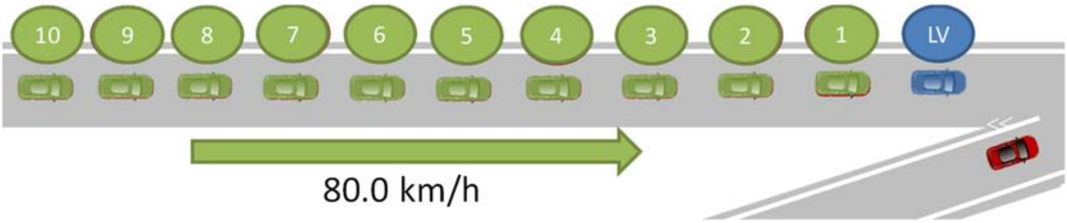


Fig. 1. Platoon of 11 vehicles (1 leading vehicle, 10 following vehicles) at single-lane motorway.

3.1. Hypothesis of vehicle behavior

In this research, the vehicles following behavior is assumed to follow Helly's car following model (1959). Helly's car following model, which defines driver's behavior as a linear function of its speed difference and spacing difference from its desired spacing is used to model the behavior of the following vehicles. The reason for choosing this model is the simplicity of linear model with comparably less number of variables, which makes the stability analysis less complex.

Vehicle i = 1 is the LV and i = 2 to 11 is the following vehicle. Eq. 1 shows the acceleration behavior of the following vehicle according to Helly's model.

$$a_i(t + \Delta T) = \alpha_1 (v_{i-1}(t) - v_i(t)) + \alpha_2 (x_{i-1}(t) - x_i(t) - d - s_i) \tag{1}$$

$$s_i = \delta + \tau v_i(t) \tag{2}$$

$$v(t + \Delta T) = v(t) + a(t)\Delta t \tag{3}$$

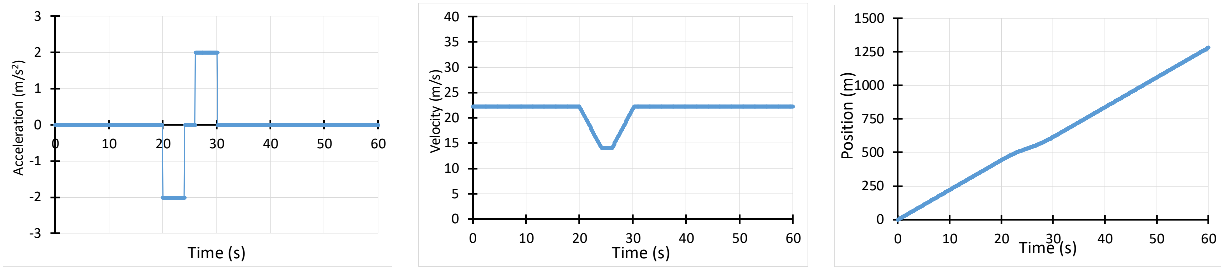
$$x(t + \Delta T) = x(t) + v(t)\Delta t + \frac{1}{2}a(t)\Delta t^2 \tag{4}$$

where, $a_i(t)$, $v_i(t)$ and $x_i(t)$ are acceleration (m/s^2), velocity (m/s) and position (m) of vehicle i at time t respectively, i - 1 is the leading vehicle of vehicle i, ΔT is the reaction time (s), d is the vehicle length (m), $s_i(t)$ is the desired spacing of vehicle i (m), δ is the standstill spacing (m), τ is desired minimum time headway (s), α_1 and α_2 are response parameter for velocity and position and Δt is the time interval (s).

In this paper, there are three types of vehicles (Leading vehicle, Following HDV and Following AV). The vehicle performances of different vehicle types are particularly. The details of the setting are shown below.

Initial setting of LV should react real world behavior (Initial speed, deceleration profile, and spacing). During the past researches on braking behavior analysis in car following on motorway, 80 km/h is used as the initial constant speed (Wada et al. (2008)). Therefore, in this research, the initial speed of the LV is set to 80.0 km/h, which is also the initial speed of the following vehicles in the platoon.

Since it is a single-lane motorway, there are not cases like lane changing or overtaking that would cause the LV to decelerate. Therefore, it is assumed that LV decelerates to 50.0 km/h with a deceleration of -2.00 m/s^2 for 4.00 s at the merging section to create a gap for the merging vehicle. After a constant speed of 50.0 km/h for 2.00 s, LV accelerates back to 80.0 km/h with a constant acceleration of 2.00 m/s^2. As for the initial spacing between the vehicles, if it is too long, then deceleration of the LV does not cause a disturbance in the flow. 2.40 headway leads to 59.8 m spacing from the Eq. 2, which is in the desired minimum headway limitation set by Vogel (2002).



(a) Time-Acceleration (b) Time-Velocity (c) Time-Space

Fig. 2. Leading vehicle behavior.

The settings of following HDV are used by previous research. Since the reaction time of each vehicle varies from driver to driver, the parameters for HDV follows the real world data distribution taken from Yang et al. (2017). In that research, the author's present estimation framework for car following parameters from observation data collected at Tomei Expressway in Japan. The probability density functions for deriving the variables are as follows:

α_1 = Gamma Distribution: Gamma (1.689480, 4.266007)
α_2 = Negative Exponential Distribution: Exp (26.05566)
ΔT = Gamma Distribution: Gamma (1.7081664, 0.8675302)
τ = 2.40 s
δ = 7.00 m
d = 5.00 m

In order to consider more stable trials as reference in the scenarios, the probability range of ΔT is constricted to 0.00 to 0.70, this corresponds to reaction time between 0.00 to 2.00 s. the value of α_2 is set by using the negative exponential distribution between 0.00 to 0.30. and the value of α_1 is set by using the gamma distribution between 0.00 to 1.00. The minimum value of α_1 is set by using Eq.5 (Brois (2017)). the maximum value of α_1 is set by using Eq.6 (Yang et al(2017)) based on the reaction time.

$$\frac{2-\alpha_2 \cdot \tau^2}{2\tau} < \alpha_1 \tag{5}$$

$$\begin{cases} \alpha_1 < 0.50 & \Delta T > 1.1 \\ \alpha_1 < 1.00 & \Delta T \leq 1.1 \end{cases} \tag{6}$$

The settings of following AV are the same condition except for the reaction time and the desired minimum time headway. The values of the reaction time and the desired minimum time headway are set as follows.

・Reaction time (s) : 0.10, 0.30, 0.50, 0.70, 0.90
・Desired minimum time headway (s) : 1.00,1.50, 2.00, 2.50, 3.00

3.2. Evaluation method

Each evaluation method measures the performance of traffic flow including safety, comfort and efficiency as follows.

The safety measure is evaluated by using time-to-collision (TTC) which is defined as the time that following vehicle make collision with former vehicle if the following vehicles will not decelerate(Eq.7). Hirst and Graham (1997) reports that for one dimensional flow, conflict occurs when TTC is below 4.00 s. In this paper, same threshold (0 < TTC < 4.00 s) is used to define the unsafe situation where the drivers find themselves unintentionally. There can be a possibility that even AVs fail to adapt the behavior of surrounding vehicle due to detection errors. Therefore, even if it is an AV, it is necessary to analyze the safety of its following behavior.

$$TTC = \frac{x_{i-1}(t) - x_i(t) - d}{v_i(t) - v_{i-1}(t)} \quad (7)$$

As for the comfort analysis, the jerk is utilized as a measure. If the jerk as the change rate of acceleration is less, the higher level of comfort. During emergency brakes, rapid deceleration of vehicles reduces the comfort level of both driver and passengers in a vehicle. One way to assess the comfort of passengers on motorway is to calculate the longitudinal jerk vehicle experiences (as the vehicles are assumed on a single-lane motorway, only jerk they experience is longitudinal). JIS (Japan Industrial Standard) D 0801 limits the upper limit of absolute jerk to 2.50 m/s^3 for ACC systems. The same limitation is used for the comfort analysis in this paper. Jerk is defined as the rate of change of acceleration, time derivative (Eq.8).

$$\vec{J}(t) = \frac{d\vec{a}(t)}{dt} \quad (8)$$

As for the efficiency of traffic flow, this paper applies to the difference between the velocities of initial shockwave and recovery shockwave. When two different state of traffic merge, a shockwave is formed. When the LV decelerates, it creates a disturbance on the flow (initial shockwave), creating congestion. During the dissipation of the congestion, there is another change in the concentration, which creates a recovery shockwave. If the recovery shockwave is faster than the no AV condition, AV can improve the congested condition.

3.3. Simulation setting

When AV is implemented on motorway, mixed traffic scenarios of AV-HDV will be observed. Starting from the first following vehicle (i = 1), the impact of AV ratio is assumed as: 0%, 10%, 20%, …, 100% with different combinations of reaction time and time headway of AV. In each trial, the distribution of position of AV in the platoon is randomized. Calculation interval is every 0.10 s, in each of the 100 runs during Monte Carlo simulation.

As such cases are unrealistic, and it is important to avoid them as much possible when simulating different scenarios. According to the ITE (2nd edition, 1982), maximum acceleration rate is observed as 3.60 m/s^2 and emergency deceleration is observed to be -2.40 m/s^2. Therefore, in this analysis, unstable condition is defined as, when any of ten following vehicles exceeds the acceleration limit of 3.60 m/s^2 or deceleration limit of -2.50 m/s^2, the trial is accepted as an unstable case. Table.1. shows the sample size with stable condition under the 100% AV. Some trials are unstable in the cases of $\tau \leq 1.50$. From this table, it can be said that the simulation gets unstable if the value of the reaction time is closer or greater than the half value of the desired minimum time headway. The same is true for the following HDV, since the reaction time is probabilistically given in the range between 0.00 to 2.00 and the desired minimum time headway is fixed (2.40s). Therefore, if there are HDV vehicles whose reaction time is greater than 1.20s, the unstable condition will happen.

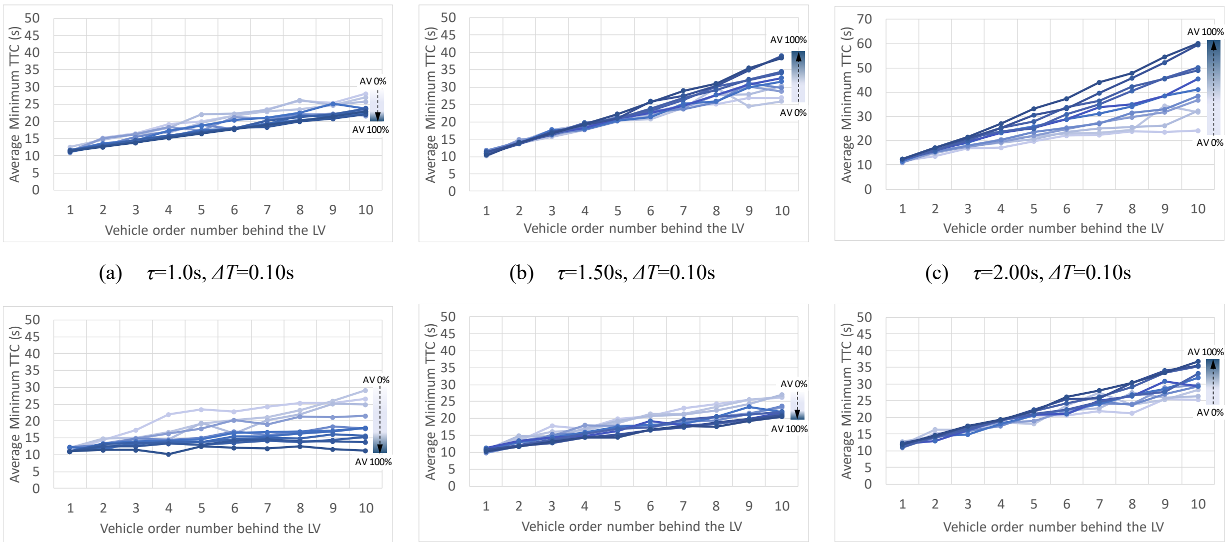
Table. 1. Sample size with stable condition (AV 100%).

		Desired minimum time headway : τ				
		1.00s	1.50s	2.00s	2.50s	3.00s
Reaction time : ΔT	0.10s	100	99	100	100	100
	0.30s	100	100	100	99	100
	0.50s	1	100	100	98	99
	0.70s	0	54	85	90	95
	0.90s	0	0	31	65	60

4. Results

4.1. Safety analysis

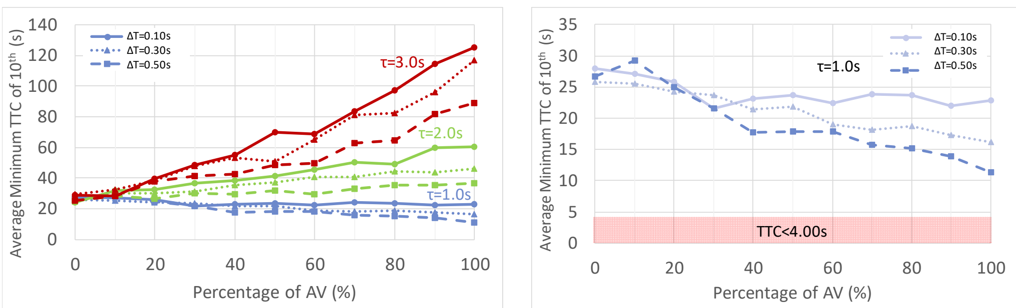
Fig.3. shows the average minimum TTC for each vehicle order number behind the LV, which corresponds to the vehicle number drawn in Fig. 1. When τ is equal to 1.00, the value of TTC decreases with the increasing AV ratio. The similar tendency is observed for the case that τ is greater than 1.00 and ΔT is 0.50 s while the value of TTC increases if ΔT is 0.10 s. Overall, the longer the reaction time becomes, the smaller the average minimum TTC becomes. Therefore, in order to keep the longer TTC even in the higher AV ratio, the smaller reaction time is required under the short desired minimum time headway. Fig.4. shows the result of average minimum TTC of 10th vehicles. It is found the tendency of decreasing the TTC with decreasing desired minimum time headway and increasing the reaction time. Focusing on the case that τ is equal to 1.00, the value of TTC decrease with the increasing AV ratio as mentioned above. However, the value of TTC is still greater than the risky threshold which is 4.00s (Hirst and Graham (1997)). It concludes that safety analysis in this research condition is not a problem.



(a) τ=1.0s, ΔT=0.10s (b) τ=1.50s, ΔT=0.10s (c) τ=2.00s, ΔT=0.10s

(d) τ=1.00s, ΔT=0.50s (e) τ=1.50s, ΔT=0.50s (f) τ=2.00s, ΔT=0.50s

Fig. 3. Average minimum TTC for each vehicle order number behind the LV.



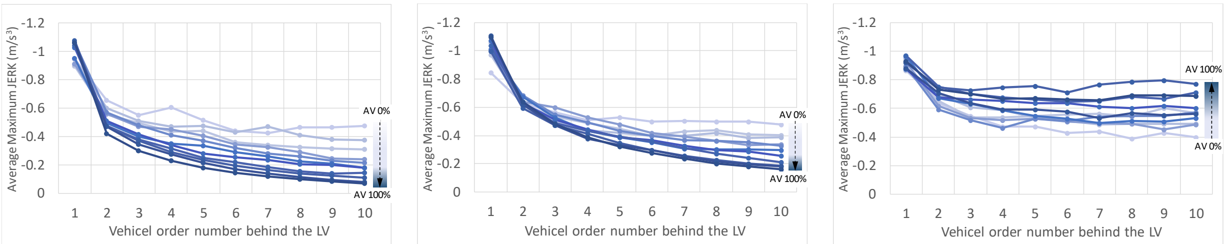
(a) τ=1.00s, τ=2.00s, τ=3.00s (b) τ=1.00s

Fig. 4. Average Minimum TTC of the 10th vehicle.

4.2. Comfort analysis

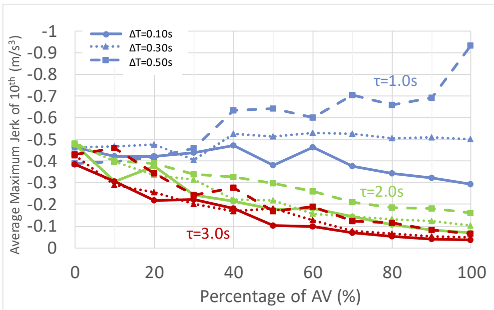
Fig.5. shows the results of the average maximum jerk for each vehicle order number behind the LV, which corresponds to the vehicle number drawn in Fig. 1. The desired minimum time headway is not largely influenced by the value of jerk. Therefore, the impact of the reaction time is discussed in the followings. When the reaction time decreases, the value of jerk of the first vehicle is greater than that of 0% AV and it gradually decreases until the 10th vehicle. However, when the reaction time is equal to 0.90s, the value of jerk of the 10th vehicle remain the same value as the value of the 2nd vehicle. It concludes that the penetration of AV with shorter reaction time can absorb the jerk. As the reaction time of AV is longer than that of HDV, the value of jerk could not decay more than the 0% AV.

Fig.6. shows the average minimum jerk of 10th vehicles. The jerk tend to increase with the decrease of the desired minimum time headway and increase of the reaction time. Regarding the case that the τ is equal to 1.00, the value of jerk increase with the increasing AV ratio as mentioned above. It concludes that the penetration of AV with longer reaction time and shorter desired minimum time headway cause the reduction of the comfort.



(a) τ=2.00s, ΔT=0.10s (b) τ=2.00s, ΔT=0.50s (c) τ=2.00s, ΔT=0.90s

Fig. 5. Average Maximum jerk for each vehicle order number behind the LV.



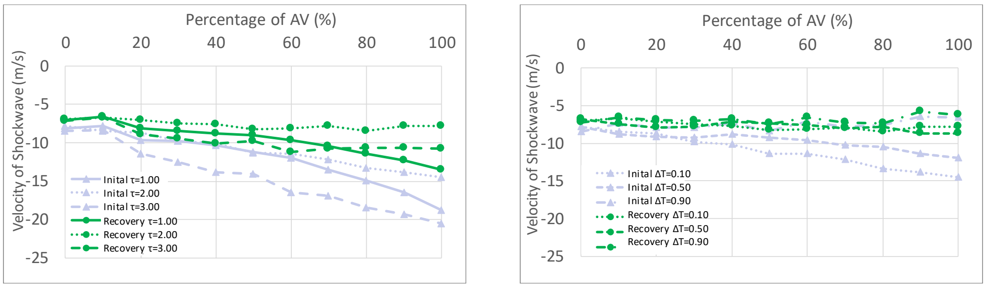
τ=1.00s, τ=2.00s, τ=3.00s

Fig. 6. Average Maximum jerk of the 10th vehicle.

4.3. Traffic flow analysis

Fig.7. shows the shockwave speed for different reaction times (a) and the desired minimum time headways (b). The velocity of shockwave increases with increasing value of desired minimum time headway. It's because the vehicle with longer desired minimum time headway starts reacting to the leading vehicle from a distance. The velocity of initial shockwave decreases with the increase of the reaction time. However, the velocity of recovery shockwave is not sensitive to the change of the reaction time.

If the velocity of recovery shockwave varies depending based on the setting of AV, it can be concluded that the setting of AV is influenced by the traffic flow. However, the relationship between AV setting and the shockwave speed was not clear under the scenarios conducted in this research.



(a) Shockwave with ΔT=0.10 (b) Shockwave with τ=2.00

Fig. 7. Initial and Recovery Shockwave speed.

5. Conclusions

The objective of this paper was to estimate the impact of AV-HDV mixed traffic on flow dynamics of single-lane motorway by using a car following model, and to figure out a realistic range of behavioral settings for AV from the viewpoint of safety, comfort and efficiency for mixed traffic scenarios of AV and HDV. The values of TTC in overall scenarios were greater than 4.00s and thus the examined conditions of AV (ΔT=0.10 to 0.90, τ=1.00 to 3.00) are safe. Regarding the comfort analysis, as the reaction time increases, the decreasing trend of jerk becomes not obvious. In the traffic flow analysis, it can't be realized the velocity of shockwave increase based on the setting of AV.

In the end, it can be concluded that the smaller desired minimum time headway may cause the unsafe and uncomfortable condition with the longer reaction time. Therefore, the setting of AV should be carefully selected considering the relationship between the reaction time and the desired minimum time headway.

More analysis must be conducted to have the variation of HDV setting in the future because the above findings are based on the fixed setting of HDV. Another future work would be conducted in other type of section like two-lane motorway which the lane changing behavior or the other interaction between AV and HDV are influenced safety, efficiency and comfort.

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