Shockwave Detection and Visualization for Rear-End Collision Avoidance

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Abstract

The speed of the invisible shockwaves that propagate across vehicle platoons depends largely on traffic conditions, but can result in traffic flow instability and increase rear-end collision risks in high-density traffic situations. Accordingly, this paper reports on efforts to visualize such shockwaves and discusses a driving assistance measure to mitigate the unnecessary speed reductions they can cause. To accomplish this, the original theory governing shockwave propagation that was proposed in the field of traffic engineering is extended in this paper to cover three vehicles in a car-following situation. More specifically, using numerical simulation results obtained via driving simulator experiments, we could successfully visualize shockwaves and thus formulate an approach that could potentially help create driving assistance measures that will suppress shockwave-induced traffic flow instability – and thus reduce rear-end collision risks. However, the occasional sensitivity of our calculations shows that different characteristics can influence shockwaves, even when most conditions of car-following situations are very similar, which means it will be necessary to modify our proposed equation to eliminate such issues in order to facilitate more stable driving assistance. In summary, we concluded that it is possible to visualize shockwaves using a simple method using only a single vehicle equipped with a measurement device, thus eliminating the need for vehicle detectors (infrastructure devices), multiple probe cars, and the complicated algorithms used in previous studies. Further issues requiring consideration include the formulation of driving assistance measures, verifying the effectiveness of our proposed approach, and investigating an appropriate interface to obtain the desired effects.

Keywords: shockwave; rear-end collision avoidance; shockwave detection and mitigation; driving assistance

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1. Introduction

Simultaneously with the spread of the sustainable development goals (SDGs) in recent years, there have been and continue to be growing demands for environmental measures in the automotive sector. Even in societies where vehicle emissions have been reduced by the spread of electric vehicles (EVs), traffic congestion mitigation and travel time reduction remain critical issues. One element causing traffic congestion is the propagation of shockwaves, which can cause driver speed reductions that are amplified and propagated to the following traffic, thus triggering road structure bottlenecks.

However, since drivers cannot directly see these shockwaves, brake lights are currently the only device for signaling the deceleration of a preceding vehicle to those following it. Since this means that the only way drivers can "see" a shockwave is to observe the brake lights of the vehicle in front of them, it is clear that suppressing such shockwaves could contribute to safer and more stable traffic flows. It is also believed that using sensors to identify and dampen shockwaves could significantly enhance rear-end collision avoidance strategies.

In a previous study, shockwave propagation speeds in traffic flows were theoretically calculated from the density (occupancy) and traffic volume data obtained from vehicle detectors [1]. For this reason, numerous shockwave detection methods use vehicle detector data [2] or integrate vehicle detectors and probe cars [3-4]. However, other methods that do not rely on vehicle detectors have also been proposed. These include: (1) collecting direct shockwave measurements using a large number of probe cars [5], (2) using vehicle-to-vehicle (V2V) transmissions to spread speed reduction data detected by preceding vehicles to those following in order to help equalize traffic density levels across multiple lanes [6], and (3) estimating shockwave propagation speeds by supplementing the speed measurement of probe cars with a compressed sensing method [4]. To alleviate shockwave propagation itself, the following methods have been proposed: (1) encouraging following traffic speed reductions by implementing variable speed limits (VSLs) [2-3], and (2) applying the asymptotic stability method to vehicle traffic flows [7].

However, some of the previous studies were limited to places where vehicle detectors were installed, others utilizing probe car data require a large number of consecutive probe cars, and those focusing on V2V communication systems are not very promising in our current circumstances. Furthermore, scenarios aimed at shockwave damping often require additional infrastructure facilities, which means they cannot be utilized autonomously by vehicles in current systems.

In contrast, this paper reports on a simple shockwave visualization technique that does not require vehicle detectors or a large number of probe cars and investigates its application to driving assistance, with the aim of lessening unnecessary speed reductions caused by shockwave propagation and enhancing rear-end collision avoidance strategies. Such shockwave mitigations efforts can be expected to help stabilize the traffic flow and, consequently, reduce the risk of rear-end collisions. In addition, the possibility of autonomous vehicle shockwave suppression measures that do not require infrastructure facilities is also discussed.

2. Theoretical Background

2.1 Speed of Shockwave Propagation

In the general theory of traffic engineering, a shockwave is generated at the intersection of two traffic flows A (with density k_A and traffic volume q_A) and B (with density k_B and traffic volume q_B), and its propagation speed ω_{AB} is calculated by equation (1). The density and traffic volume are assumed to be measured by roadside-mounted vehicle detectors. The density is the number of vehicles per unit distance, and the traffic volume is the number of vehicles per unit time.

$$\omega_{AB} = \frac{q_A - q_B}{k_A - k_B} \tag{1}$$

Four propagation states are defined by the signs of the denominator and the numerator of equation (1). We focus on the state in which the density of A is higher than that of B, i.e., the state in which a high-density (low speed) traffic flow in front is approached by a low-density (high speed) traffic flow from behind ($k_A - k_B > 0$ and $q_A - q_B < 0$). In this situation, the shockwave propagates backward to the upstream (rearward), and the following vehicles are required to slow down or stop. Therefore, the problem is finding a way to mitigate this backward propagation.

2.2 Shockwave Formulation between Three Vehicles

Equation (1) calculates the shockwave propagation speed between two consecutive traffic states at a macroscopic level. Here, we consider the shockwave to be generated by three vehicles and define it as a microscopic shockwave in contrast to the macroscopic shockwave that is propagated across consecutive traffic flows.

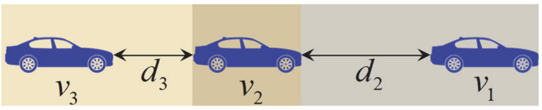


Figure 1: Three-vehicle car following.

Figure 1 shows the three-vehicle car following scenario. First, assuming that the density k is equivalent to the existence of a vehicle per distance, k can be the inverse of headway distance d as:

$$k = \frac{1}{d} \tag{2}$$

Next, the relationship between the traffic volume q, density k, and speed v is expressed by $q = kv$, which gives equation (3), in which q is equivalent to the inverse of the time headway (THW).

$$q = kv = \frac{v}{d} = \left(\mathrm{THW}^{-1}\right) \tag{3}$$

Substituting equations (2) and (3) into equation (1), the microscopic shockwave propagation speed μ, becomes equation (4).

$$\mu = \frac{q_2 - q_3}{k_2 - k_3} = \left(\frac{v_1 + v_2}{2d_2} - \frac{v_2 + v_3}{2d_3}\right) \Big/ \left(\frac{1}{d_2} - \frac{1}{d_3}\right) \tag{4}$$

The subscripts are "1" for the pre-preceding vehicle, "2" for the preceding car, and "3" for the ego vehicle. However, since equation (4) calculates the propagation velocity with respect to the ground, it is converted to the apparent velocity relative to the first vehicle in order to obtain equation (5).

$$\mu = \left(\frac{v_1 + v_2}{2d_2} - \frac{v_2 + v_3}{2d_3}\right) \Big/ \left(\frac{1}{d_2} - \frac{1}{d_3}\right) - v_3 = \left(\frac{v_1 + v_2 - 2v_3}{2d_2} - \frac{v_2 - v_3}{2d_3}\right) \Big/ \left(\frac{1}{d_2} - \frac{1}{d_3}\right) \tag{5}$$

3. Numerical Experiment

3.1. Microscopic Shockwave Visualization

Equation (5) focuses solely on the velocity of the shockwave generated by three consecutive vehicles. In this study, we visualize this value and present it to the driver of the third vehicle through an interface. Based on the most recent implementation of Advanced Driver Assistance System (ADAS) functions, it is assumed that it is possible to measure the distance and relative speed of not only the vehicle directly ahead but also the pre-preceding vehicle [8].

However, even though autonomous driving technology developments have been progressing rapidly in recent years, in principle, vehicle deceleration can still only be recognized from outside the vehicle by observing the brake lights of the vehicle ahead, and this situation has remained almost unchanged since the birth of the automobile. This is important because if the propagation of shockwaves from vehicles in front could be visualized and presented to the driver of the following vehicle, he or she would be able to decelerate before the brake lights of the vehicle ahead illuminate. As a result, the following vehicles would not be required to decelerate unnecessarily.

Equation (5) shows that our proposed algorithm only requires five variables, including the speed and the headway distance of vehicles, to detect shockwaves, and that it does not need large infrastructure facilities, vehicle detectors, or speed display boards. This is important because shockwaves could only previously be detected in areas where vehicle detectors were installed. However, our method makes it possible to detect shockwaves at any location, at any time, in a very simple and cost-effective way.

3.2. Visualization Procedure

Although various processes can be used for shockwave visualization, the procedure used in this study is as described in the steps below and shown in Figure 2.

Step 1: From the current speed and distance between vehicles, calculate the propagation speed μ of the shockwave using equation (5).

Step 2: Next, define a prediction time t_p (e.g., two seconds), and then predict the positions of the three vehicles after t_p. Since this study has not established a prediction method, we set t_p =2 s as the measured value of the position after t_p.

Step 3: The value of μ multiplied by the prediction time t_p is the distance, which is visualized and extended backward from the rear end of the predicted position of the second vehicle. The end of the red portion in Figure 2 represents the expected arrival point of the shockwave after t_p. This arrival point is shown to the driver of the third vehicle, who is expected to take action to prevent his or her vehicle from entering the red portion, thereby dampening shockwave propagation.

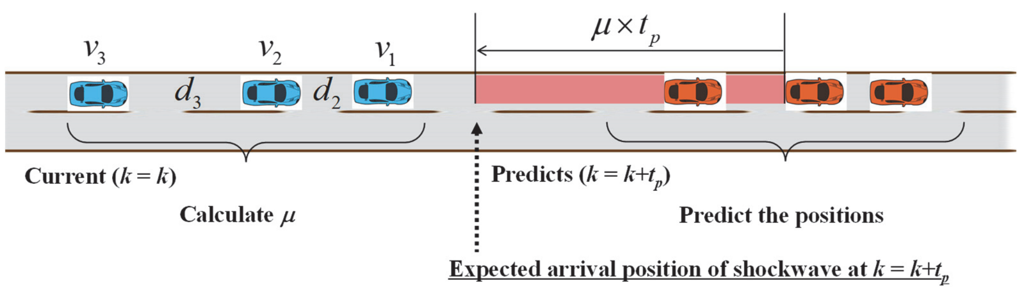


Figure 2: Shockwave visualization.

3.3 Driving Simulator Experiment

A fixed-motion driving simulator (DS) manufactured by ASTJ Corp. was used in our DS experiments. The experimental scenario was a straight corridor with a single lane in each direction, about 3.5 km in length and 7 m in width, in which we simulated a city street. The ego vehicle follows three preceding cars that repeatedly accelerate and decelerate at speeds ranging between 0 to 20 m/s during the five-minute experiment. During this period, the preceding vehicle decelerates five times. Four of the five decelerations are moderate 0.2 G events, but one is a high (0.5 G) deceleration, which results when another vehicle makes an unexpected cut-in to the simulator lane from the left side of the road, as shown in Figure 3.

The experiment was conducted with the approval of the Ethics Committee of the Nippon Institute of Technology and with the informed consent of the eight participants (mean age: 22 years and mean driving experience: two years), all of whom hold valid driver's licenses. During the experiment, the participants were instructed to follow the preceding vehicle close enough for them to read its four-digit license plate number. As a secondary task, the subjects are also asked to enter text on their smartphones. More specifically, after being presented with the name of a region in Japan, they were asked to enter the name of a prefecture included in that region in the text block. The objective of having the secondary task is to investigate the behavior of the shockwave propagation under the condition in which the driver encounters distractions.

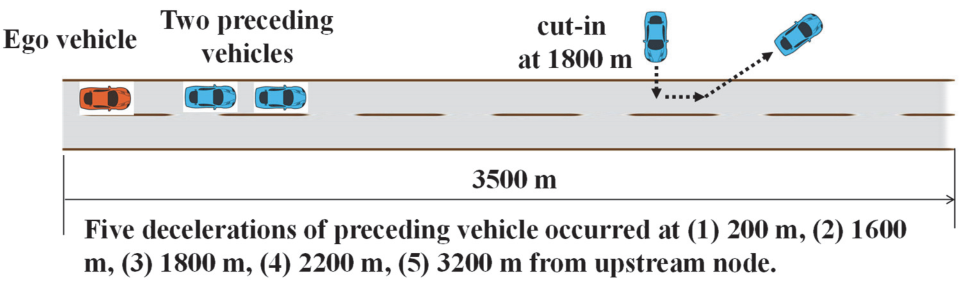


Figure 3: DS experiment scenario.

4. Simulation Results

4.1 Shockwave Visualization Validity

Figure 4 shows an example of the results for Subject C, who was distracted by the secondary task. The position of the pre-preceding vehicle is shown in blue, the second vehicle is shown in orange, and the third vehicle is shown in grey. The bright yellow and red colors are the expected position of the second vehicle two seconds later and the shockwave itself, respectively. Figure 4(b) shows the corresponding speed profiles.

From this figure, it can be seen that the backpropagation of the shockwave occurs at Point (1), reaches the ego vehicle (the third vehicle) at Point (2) about two seconds later, and then reaches Point (3) before being resolved. The fact that the shock wave propagates beyond the ego vehicle does not imply that it is immediately dangerous.

If the propagation of the shockwave can be visualized and presented to the driver at Point (1), where the backpropagation of the shockwave occurs, and if the driver is encouraged to slow down at that early stage, the shockwave can be mitigated and might not be amplified and propagated to the upstream vehicles.

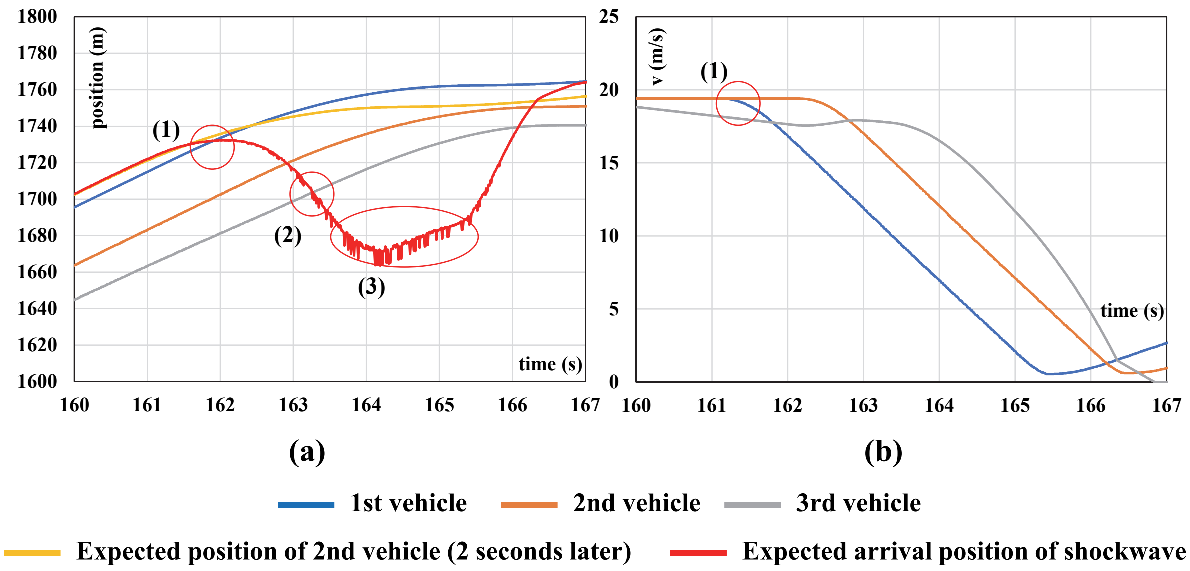


Figure 4: Shockwave visualization for subject C during distraction (*t*=160 – 167).

Figure 5 shows a case involving Subject C, without the distraction, in which the shockwave takes a relatively long time to reach the ego vehicle. Here, a shockwave is generated at Point (1), but due to its low speed, it takes approximately three seconds to reach the ego vehicle at Point (2). Depending on the conditions of the three consecutive vehicles, the shockwave propagation speed will vary, which means the deceleration maneuver to suppress the shockwave will vary as well.

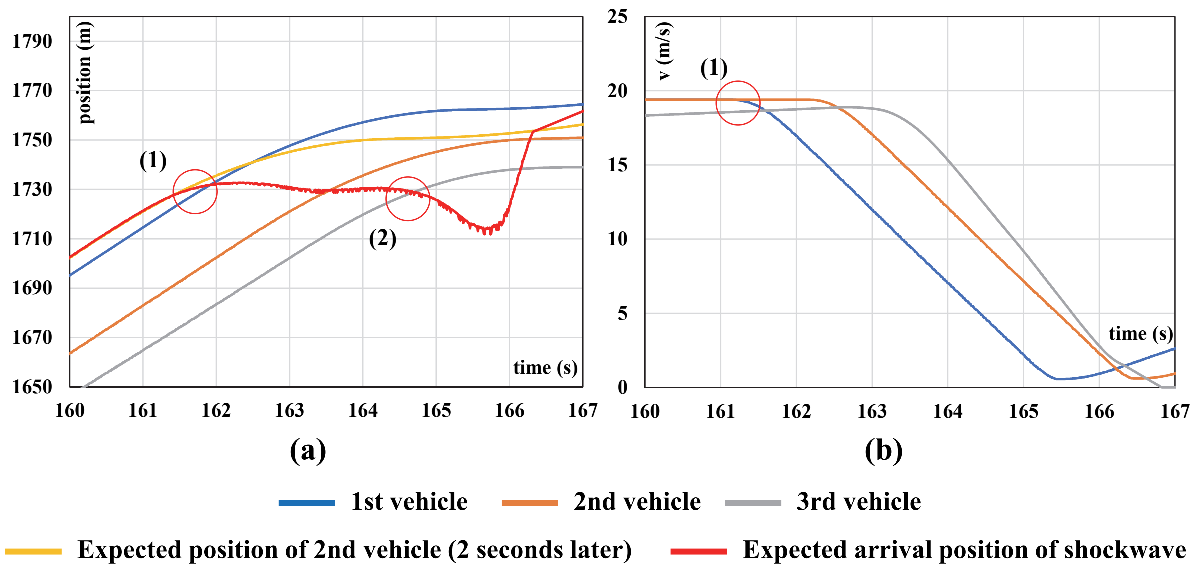


Figure 5: Shockwave visualization for subject C without distraction (*t*=160 – 167).

In Figure 6, Subject C maintains speed during the distraction even though the vehicles ahead have decelerated. In such a case, the shockwave propagates backward at high speed and reaches the ego car in less than one second. However, if the driver is encouraged to begin decelerating at Point (1), as shown in Fig. 6(b), shockwave propagation is likely to be alleviated.

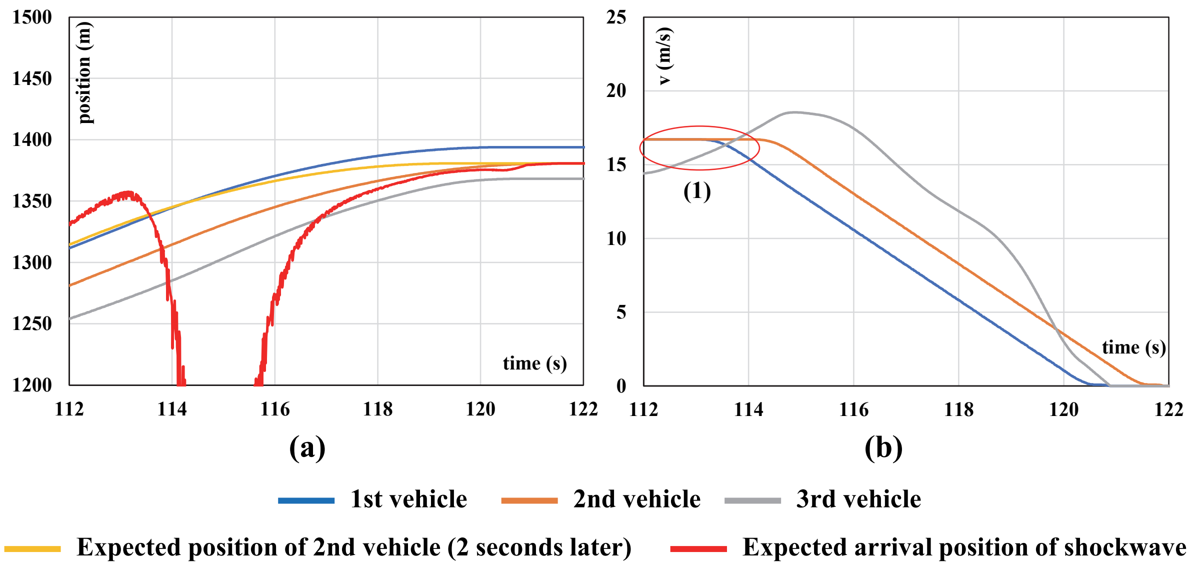


Figure 6: Shockwave visualization for subject C during distraction (*t*=112 – 122).

However, as seen in Figure 7, the shockwave propagation speed is not as high as that seen in Figure 6, even though Subject G continues to maintain speed during the distraction. Similarly, in Figure 8, it can be seen that, even though Subject A maintains speed while the preceding vehicles decelerate, the shockwave never reaches the ego vehicle. This is because the propagation speed varies depending on the car-following situation of the three vehicles. In particular, when the denominator of equation (5) is close to zero, the shockwave propagation speed becomes infinite.

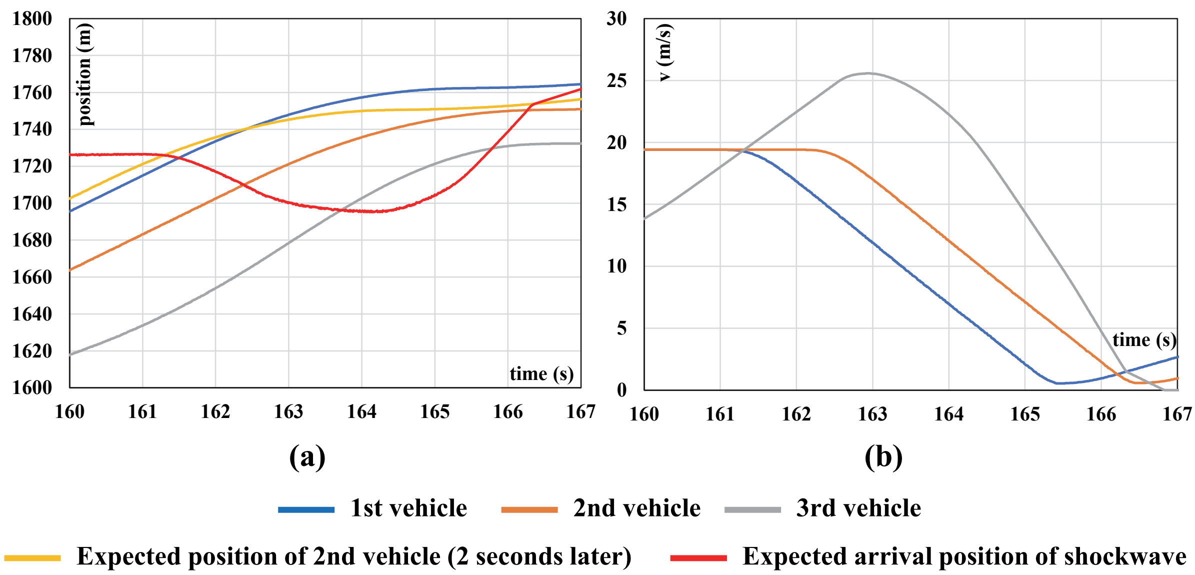


Figure 7: Shockwave visualization for subject G during distraction (*t*=160 – 167).

4.2 Additional Measure against Avoiding Infinite Shockwave Propagation Speed

Some modifications are required to prevent the shockwave speed from going to infinity. In the conventional theory of shockwave as defined in the field of traffic engineering, the shockwave speed never becomes infinity because the numerator of equation (1) approaches zero as the denominator is close to zero. However,

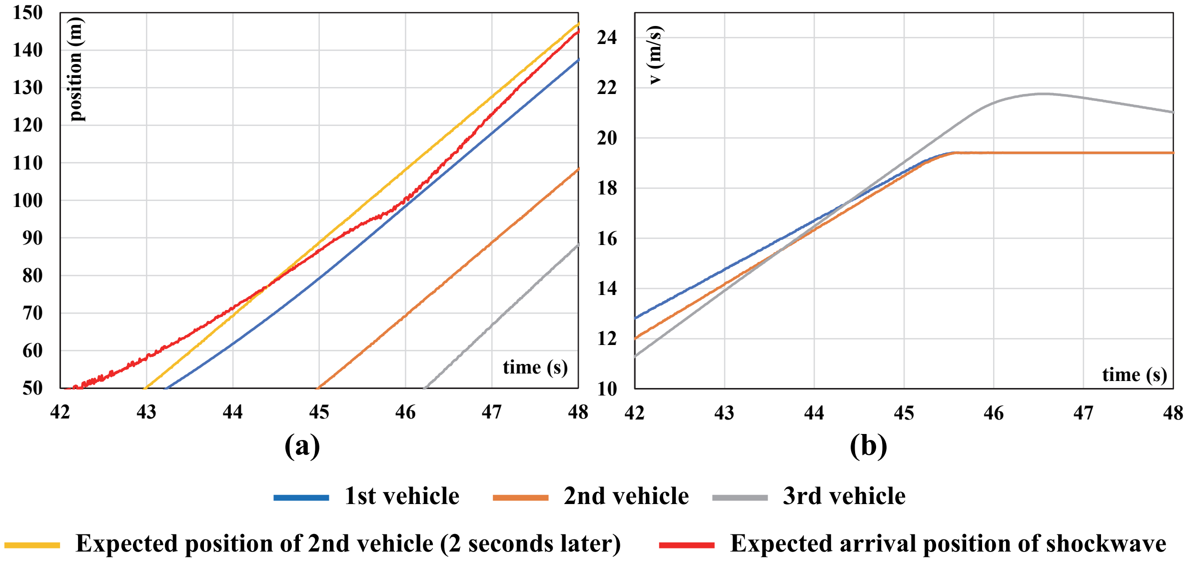


Figure 8: Shockwave visualization for subject A without distraction (t=42 – 48).

equation (5), which extends the macroscopic shockwave of the traffic flow to the microscopic level of three vehicles, does not always guarantee this relationship between the numerator and denominator.

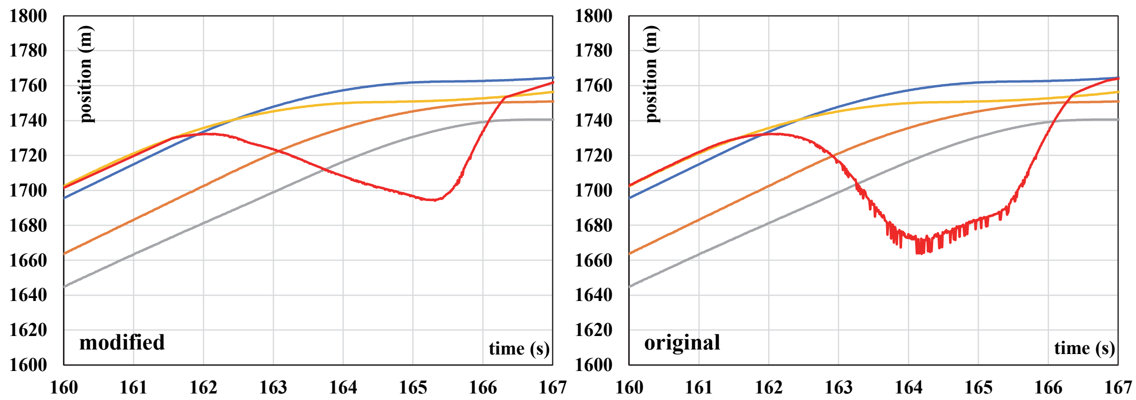
Since it is theoretically impossible for the velocity of the shockwave to be infinite, the denominator in equation (5) is allowed not to be less than d_{min}. In this paper, d_{min} = 0.01 was chosen by trial and error, but this choice is arbitrary and can be adjusted to any user-defined value.

Figure 9 visualizes the shockwave propagation before and after modification for the two selected cases of subject C during distraction. In both scenarios, the unstable behavior of the shockwave was clearly eliminated, and the modifications also significantly prevented the propagation speed from going to infinity. We confirmed that the introduction of d_{min} in the denominator of equation (5) yielded the stable visualization of the shockwave.

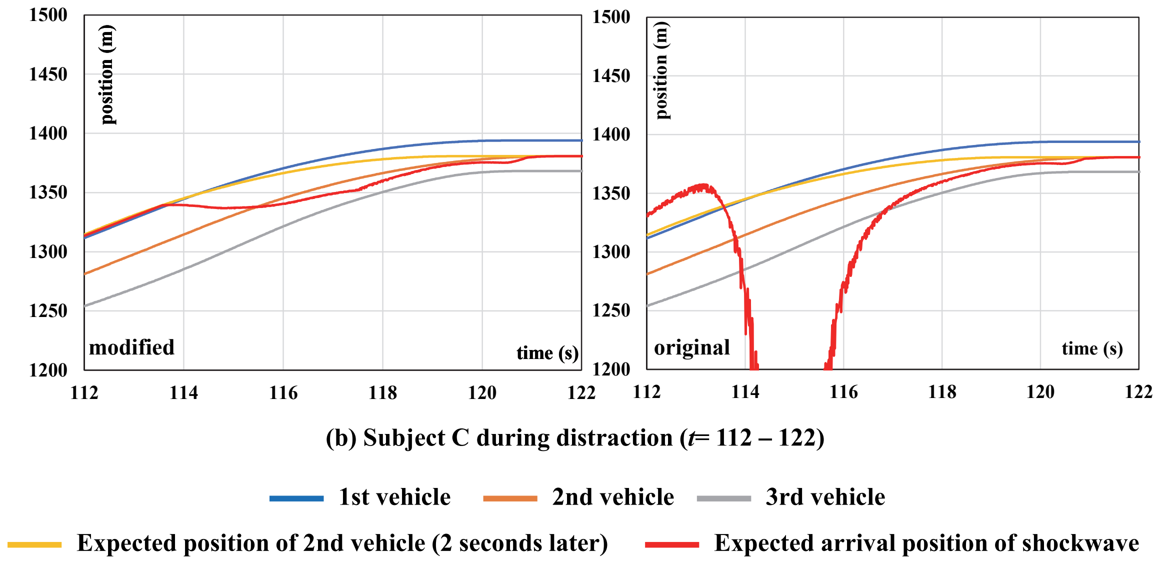
4.3 Simulation to Alleviate Shockwave Propagation

In the future, we plan to propose appropriate interfaces for drivers to mitigate shockwave propagation. As a preliminary step, this study examines the effects on shockwave propagation mitigation using a simple car-following simulation, assuming appropriate but very primitive driver behavior. The scenario involves a driver decelerating at a constant rate one second after a shockwave is generated in three consecutive vehicles.

Figure 10 right shows the original shockwave propagation, and the left shows a simulation of the 3rd vehicle beginning to decelerate early one second after the shockwave is detected. The deceleration rate is set at 1.5 m/s^2. Here, the upper graph is the shockwave whereas the lower graph is the vehicle speed. The results show that early deceleration shortens the arrival position of the shockwave and reduces its propagation velocity. It is found that the shockwave is significantly mitigated due to the early deceleration. Figure 11 also shows that when the driver slows down more at 2 m/s^2, the propagation of the shockwave is also more relaxed and does not reach the third car itself. However, further studies will be carried out to determine the appropriate and optimal deceleration to mitigate the shockwave. This simulation is only an example of constant deceleration without considering advanced algorithms.



(a) Subject C during distraction (t= 160 – 167)



(b) Subject C during distraction (t= 112 – 122)

Figure 9: Comparison of modified and original shockwave propagations for two scenarios.

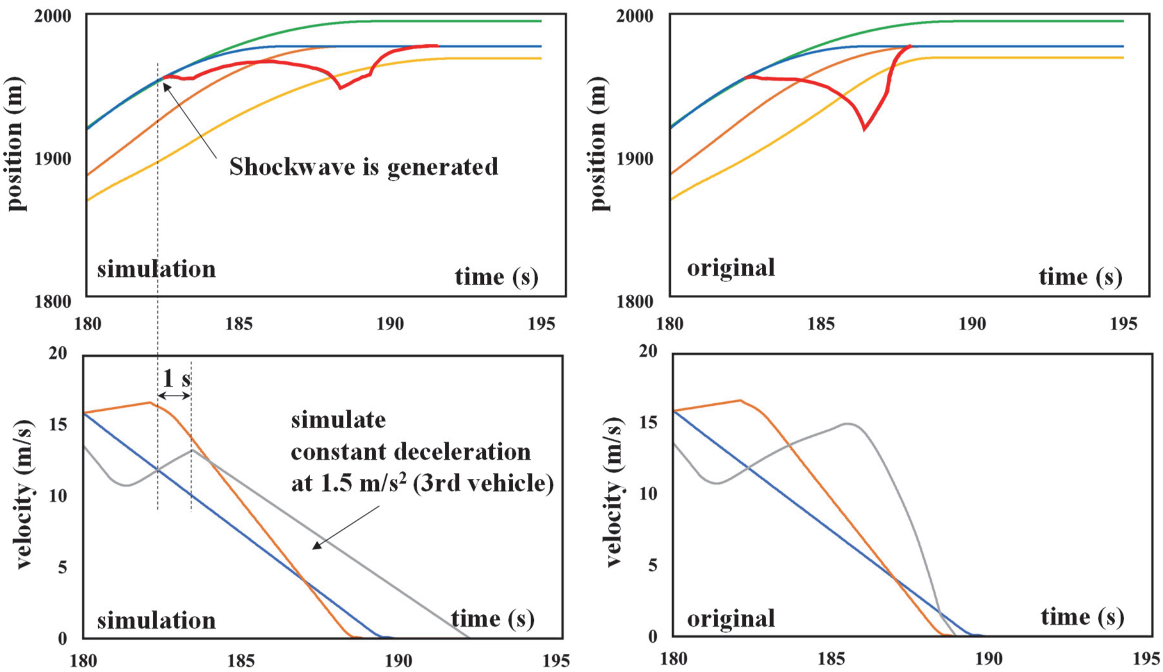


Figure 10: Simulation in which the third vehicle begins to decelerate at a constant speed of 1.5 m/s^2.

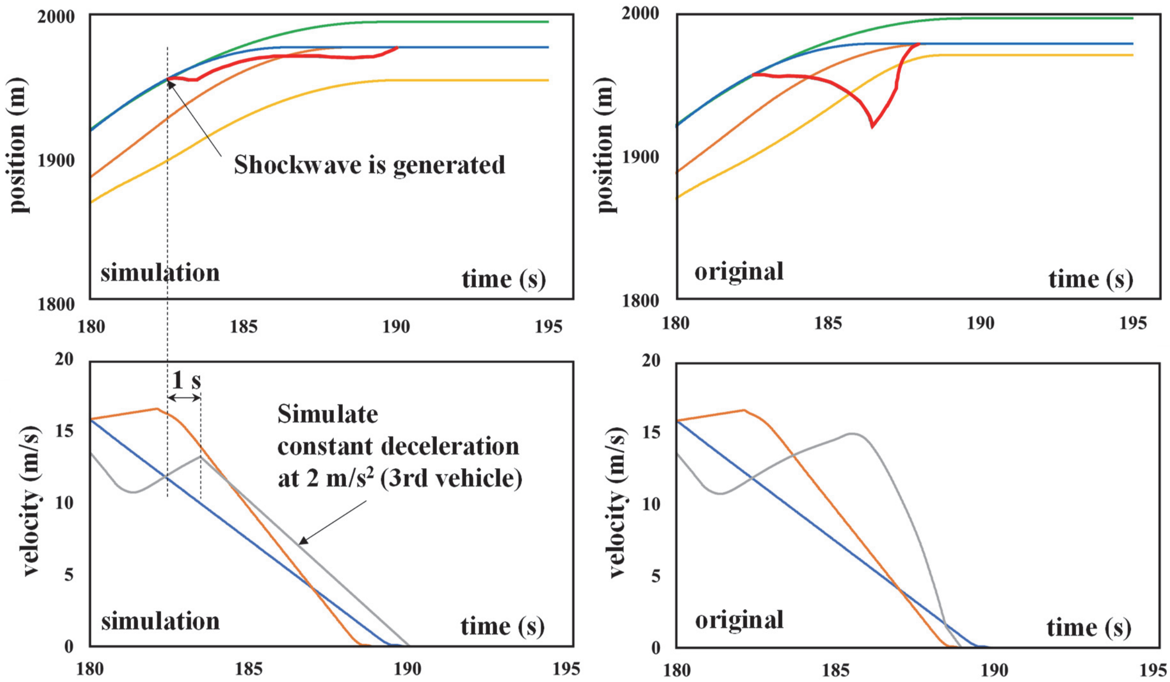


Figure 11: Simulation in which the third vehicle begins to decelerate at a constant speed of 2.0 m/s^2.

However, in some cases, drivers may not be able to avoid entering the shockwave even if they start decelerating earlier. Further consideration should be given to the fact that it is not always necessary to avoid entering the shockwave to mitigate it.

4.4 Discussion

We confirmed that the entirely invisible shockwave that propagates across the three vehicles could be recognized by our proposed approach. More specifically, if the vehicle begins to decelerate early and thus avoids entering the shockwave, propagation is suppressed at that point. As a result, it will not be transmitted to the following vehicles, so traffic flow stability will be maintained and the risk of rear-end collisions will be reduced.

However, as we found from the results shown in Figures 6 to 8, shockwave propagation has different behaviors and characteristics even in very similar situations. More specifically, depending on the numerator and denominator combination of equation (5), cases can occur in which the propagation speed is the same even though the situations of the three vehicles are different. Alternatively, there may be cases where the propagation speed is different even though the conditions of the three vehicles are the same. This difference is caused by the difference in headway distance of the second and the third vehicles: d_2 and d_3. It is known that when a shockwave is generated, the propagation of the shockwave is different when $d_2 < d_3$ and when $d_2 > d_3$. Further studies are required to determine which car-following situations should be targeted for shockwave visualization and driving assistance.

5. Conclusion

Assuming that the suppression of shockwaves in traffic flows contributes to the mitigation of traffic congestion and instability, this study focused on visualizing the shockwaves generated by three vehicles. Based on the results of numerical simulations, we found that it is possible to visualize the shockwaves using a simple method in which only one vehicle is equipped with a measurement device. This means the vehicle detectors (infrastructure devices), numerous probe cars, and complicated algorithms used in previous studies are not required. In terms of the driving assistance measures, we also found our proposed method has the potential to alleviate shockwave propagation and thereby reduce rear-end collisions. Specifically, we determined that risks could be reduced by encouraging early deceleration in the seconds before the shockwave arrives.

Some sensitive behavior in shockwave propagation, such as infinite shockwave velocity, was significantly mitigated by restricting the denominator in equation (5) to a certain value. However, there are situations where the same car-following conditions yielded different shockwave speeds and vice-versa. Accordingly, further developments will be needed to modify the algorithm used for shockwave speed calculations in order to avoid such inappropriate situations.

In the future, we will also consider a driving assistance measure that suppresses shockwaves, verify the effectiveness of the method in advance, and investigate the interface needed to obtain an appropriate effect. These developments require careful consideration of appropriate human-machine interfaces to avoid driver distraction. In addition, experiments using driving simulators need to be conducted with subjects of all ages. After that, we will integrate DS and traffic simulation experiments to verify the effects of shockwave suppression on traffic jam mitigation, traffic flow stability, and the suppression of unnecessary deceleration.

Acknowledgment

This work was supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI Grant Number 19K04926.

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