EVTeC 2025
7th International Electric Vehicle Technology Conference 2025
20259097

Quantifying Traffic Congestion Caused by Vehicle Platooning

- A Statistical Approach and Empirical Validation –

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ABSTRACT: As the adoption of electric vehicles progresses towards the realization of a carbon-neutral society, platooning on highways, which involves following a lead vehicle, is recognized as a method that contributes to the reduction of greenhouse gas (GHG) emissions by decreasing air resistance. On the other hand, since two or more vehicles travel in a line, there is a concern that this will occupy long sections of the roadway and create local traffic congestion around them. This paper attempts to quantify the "congestion caused by vehicles overtaking a platoon," proposing a prediction method based on statistical theory formulas and validating it through actual measurements. As a result, the average error was kept under 20%, confirming that predictions based on statistical theory formulas are feasible. Additionally, it was found that congestion due to low-speed platooning is more pronounced, highlighting the importance of selecting the lead vehicle. Overall, to achieve GHG-optimized traffic flow, it is necessary to establish appropriate platooning guidelines.

KEY WORDS: Platooning, Traffic streamlining, Congestion, Reduction of air resistance, Reduction of GHG, Carbon neutral

1. INTRODUCTION

In recent years, as the realization of a carbon-neutral society has become essential in addressing global warming, the adoption of electric vehicles has rapidly advanced. However, even after the widespread use of electric vehicles, it is necessary to pursue technologies and methods that reduce greenhouse gas (GHG) emissions in actual driving environments to achieve a carbon-neutral society.

Among these, platooning is highlighted as a method that can contribute to air resistance reduction, even for existing vehicles. In this driving technique, by positioning oneself behind a lead vehicle, it is possible to reduce air resistance [(1)] [(2)], which can be expected to lead to GHG reductions for individual vehicles. Moreover, since multiple vehicles travel in a line at the same speed, there are research findings suggesting that this could lead to the streamlining of overall traffic [(3)], indicating the potential for GHG reductions from a macro perspective.

However, from a localized perspective, the presence of two or more vehicles traveling in a line as platooning means that they occupy a certain section of the roadway. This raises concerns about localized traffic congestion near platooning areas. To achieve a society where everyone can move safely, smoothly, and freely, it is necessary to address this concern while gradually introducing platooning into society. Previous studies have evaluated the traffic impacts of vehicles through simulations [(4)]. However, there are few examples that specifically discuss the traffic impacts of platooning or validate them against actual measured data.

This study aims to quantify the traffic congestion that platooning generates locally in its surroundings. In this report, first a statistical theory formula to predict the number of vehicles in congestion is built and then present the results of the validation using actual measured data.

2. MECHANISM OF CONGESTION GENERATION EXPECTED IN PLATOONING

In this paper, a congestion scene illustrated in Figure 1 is considered. A platoon consisting of a lead vehicle and a following vehicle (hereinafter referred to as the "platoon group") is traveling in the driving lane (hereinafter referred to as "Lane A"). To overtake the platoon group, Vehicle 1 changes lanes from Lane A to pass through the adjacent lane on the overtaking side of the platoon group (hereinafter referred to as "Lane B"). At this time, the platoon group occupies a certain section of the roadway. As a result, the distance required to overtake the platoon group becomes longer than that needed to overtake a single vehicle. Therefore, the

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time that Vehicle 1 spends in Lane B also increases, and especially when the speed difference between the platoon group and Vehicle 1 is small, a phenomenon occurs where the overtaking lane is blocked for an extended period. This is expected to cause following vehicles in Lane B to catch up to Vehicle 1, leading to congestion.

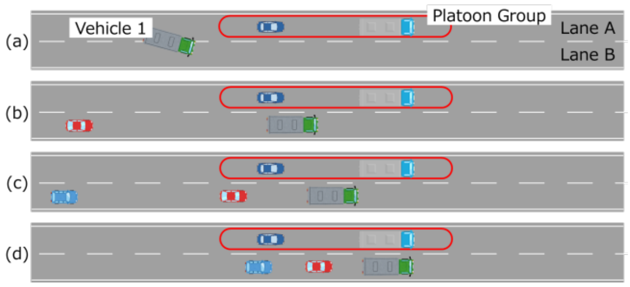

Fig. 1 Mechanism of Congestion Generation Expected in Platooning

3. STATISTICAL THEORY MODEL

In this chapter, congestion is defined as "the number of vehicles in Lane B that catch up to Vehicle 1 during the overtaking process". Then the number of congested vehicles expected is calculated according to the statistics. First, in Section 3.1, the assumptions of the model are explained, and in Section 3.2, the number of vehicles in congestion caused by a single overtaking vehicle is formulated. Finally, in Section 3.3, the concepts from Section 3.2 are extended to the entire set of overtaking vehicles and quantify the final number of vehicles in congestion.

3.1. Assumptions

In this model, a scenario in which a platoon group travels a unit distance in Lane A of a two-lane road is considered. Apart from the "distance required to overtake the platoon group," each vehicle is treated as a point, ignoring the full length of the vehicle. Under this assumption, "a vehicle catching up" is defined as the distance between any two points representing vehicles becoming zero, approaching deceleration is neglected.

The positions of vehicles in each lane are assumed to follow a uniform distribution, and the vehicles continue to travel at a constant speed, maintaining their initial speed. The initial speed of the vehicles is assumed to follow a Gaussian distribution based on the speed distribution of vehicles in each lane. Figure 2 illustrates the speed distribution of vehicles in each lane.

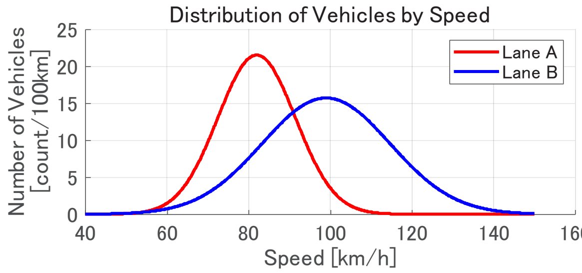

Fig. 2 Image of Speed Distribution of Vehicles by Lane

Main Symbols

V_{PG} : Speed of the Platoon Group [km/h]

N_{LA} : Vehicle Density of Lane A [count/km]

N_{LB} : Vehicle Density of Lane B [count/km]

V_{LA} : Speed of Vehicles Traveling in Lane A [km/h]

V_{LB} : Speed of Vehicles Traveling in Lane B [km/h]

μ_{LA} : Mean Speed of the Speed Distribution of Vehicles Traveling in Lane A [km/h]

μ_{LB} : Mean Speed of the Speed Distribution of Vehicles Traveling in Lane B [km/h]

σ_{LA} : Standard Deviation of the Speed Distribution of Vehicles Traveling in Lane A [km/h]

σ_{LB} : Standard Deviation of the Speed Distribution of Vehicles Traveling in Lane B [km/h]

t : Time Required to Overtake the Platoon Group [h]

L : Distance Required to Overtake the Platoon Group in Lane A [km]

3.2. The Number of Congested Vehicles in Lane B Caused by a Single Overtaking

For simplicity, a single vehicle (hereafter referred to as Vehicle 1) is first considered as an example. Vehicle 1 changes lanes from Lane A to Lane B to overtake the platoon group and travels at a speed of V_{LA} . The number of vehicles that catch up to Vehicle 1 in Lane B can be calculated by the product of the following factors:

・The time required to overtake : t[h]

・The number of vehicles catching up per unit time in Lane B: $N_{\mathrm{A\_r\_1h}}$

First, the time required to overtake t can be expressed by equation (1).

$$t = \frac{L}{V_{\mathrm{LA}} - V_{\mathrm{PG}}} \qquad (V_{\mathrm{LA}} > V_{\mathrm{PG}}) \tag{1}$$

On the other hand, the number of vehicles catching up to Vehicle 1 in Lane B per unit time $N_{\mathrm{A\_r\_1h}}$ [count/h] can be calculated by the product of the following two factors:

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- The number of vehicles traveling in Lane B at speed V_{LB}
- The probability that a vehicle traveling in Lane B at speed V_{LB} is within the distance range to catch up to Vehicle 1 per unit time

As mentioned in Section 3.1, the positions and speeds of the vehicles follow a uniform distribution and a Gaussian distribution, respectively. Therefore, the number of vehicles catching up to Vehicle 1 in Lane B per unit time $N_{\mathrm{A\_r\_1h}}$ [count/h] can be expressed as shown in equation (2).

$$N_{\mathrm{A\_r\_1h}} = \int_{V_{\mathrm{LA}}}^{\infty} \frac{N_{\mathrm{LB}}}{\sqrt{2\pi\sigma_{\mathrm{LB}}^2}} e^{-\frac{(V_{\mathrm{LB}}-\mu_{\mathrm{LB}})^2}{2\sigma_{\mathrm{LB}}^2}} (V_{\mathrm{LB}} - V_{\mathrm{LA}}) dV_{\mathrm{LB}} \qquad (2)$$

By taking the product of equations (1) and (2), the number of congested vehicles $N_{\mathrm{A\_r}}$ [-] in Lane B caused by the overtaking of a specific single vehicle can be expressed as equation (3).

$$\begin{aligned} N_{\mathrm{A\_r}} &= tN_{\mathrm{A\_r\_1h}} \\ &= \frac{L}{V_{\mathrm{LA}} - V_{\mathrm{PG}}} \int_{V_{\mathrm{LA}}}^{\infty} \frac{N_{\mathrm{LB}}}{\sqrt{2\pi\sigma_{\mathrm{LB}}^2}} e^{-\frac{(V_{\mathrm{LB}}-\mu_{\mathrm{LB}})^2}{2\sigma_{\mathrm{LB}}^2}} (V_{\mathrm{LB}} - V_{\mathrm{LA}}) dV_{\mathrm{LB}} \end{aligned} \qquad (3)$$

3.3. The Number of Congested Vehicles in Lane B Caused by All Overtaking Vehicles

The approach discussed in Section 3.2 is extended to include all vehicles overtaking the platoon group. The number of vehicles overtaking the platoon group from the driving lane per unit distance $D_{\mathrm{B\_p}}$ [count/km] does not directly correspond to the number of vehicles on Lane A. Considering the speed distribution of Lane A vehicles defined by the Gaussian distribution and the probability of encountering the platoon group at each speed, it can be expressed as shown in equation (4).

$$D_{\mathrm{B\_p}} = \frac{N_{\mathrm{LA}}}{\sqrt{2\pi\sigma_{\mathrm{LA}}^2}} e^{-\frac{(V_{\mathrm{LA}}-\mu_{\mathrm{LA}})^2}{2\sigma_{\mathrm{LA}}^2}} \frac{V_{\mathrm{LA}} - V_{\mathrm{PG}}}{V_{\mathrm{PG}}} \quad (V_{\mathrm{LA}} > V_{\mathrm{PG}}) \qquad (4)$$

From equations (3) and (4), the final number of congested vehicles in Lane B caused by all overtaking vehicles E_{passed} [count/km], which is the desired outcome of the platoon group traffic impact, can be expressed as shown in equation (5).

$$\begin{aligned} E_{\mathrm{passed}} &= \int_{V_{\mathrm{PG}}}^{\infty} D_{\mathrm{B\_p}}\, N_{\mathrm{A\_r}}\, dV_{\mathrm{LA}} \\ &= \int_{V_{\mathrm{PG}}}^{\infty} \frac{N_{\mathrm{LA}}}{\sqrt{2\pi\sigma_{\mathrm{LA}}^2}} e^{-\frac{(V_{\mathrm{LA}}-\mu_{\mathrm{LA}})^2}{2\sigma_{\mathrm{LA}}^2}} \frac{V_{\mathrm{LA}} - V_{\mathrm{PG}}}{V_{\mathrm{PG}}} \\ &\quad \left\{ \frac{L}{V_{\mathrm{LA}} - V_{\mathrm{PG}}} \int_{V_{\mathrm{LA}}}^{\infty} \frac{N_{\mathrm{LB}}}{\sqrt{2\pi\sigma_{\mathrm{LB}}^2}} e^{-\frac{(V_{\mathrm{LB}}-\mu_{\mathrm{LB}})^2}{2\sigma_{\mathrm{LB}}^2}} (V_{\mathrm{LB}} - V_{\mathrm{LA}}) dV_{\mathrm{LB}} \right\} dV_{\mathrm{LA}} \\ &= \frac{CL}{V_{\mathrm{PG}}} \int_{V_{\mathrm{PG}}}^{\infty} \int_{V_{\mathrm{LA}}}^{\infty} e^{-\frac{\sigma_{\mathrm{LB}}^2 (V_{\mathrm{LA}}-\mu_{\mathrm{LA}})^2 + \sigma_{\mathrm{LA}}^2 (V_{\mathrm{LB}}-\mu_{\mathrm{LB}})^2}{2(\sigma_{\mathrm{LA}}^2 + \sigma_{\mathrm{LB}}^2)}} \\ &\quad (V_{\mathrm{LB}} - V_{\mathrm{LA}})\, dV_{\mathrm{LB}} dV_{\mathrm{LA}} \qquad \left(C = \frac{N_{\mathrm{LA}} N_{\mathrm{LB}}}{2\pi\sigma_{\mathrm{LA}}\sigma_{\mathrm{LB}}} \right) \end{aligned} \qquad (5)$$

From Equation (5), it is evident that the number of vehicles in congestion increases in proportion to the distance L required to overtake the platoon group in Lane A. Additionally, the number of vehicles in congestion varies with the speed V_{PG} of the platoon group. Figure 3 illustrates the changes in the number of vehicles in congestion when L and V_{PG} are varied. For the coefficients related to the speed distribution of surrounding vehicles, average values obtained from actual traffic volume data are used.

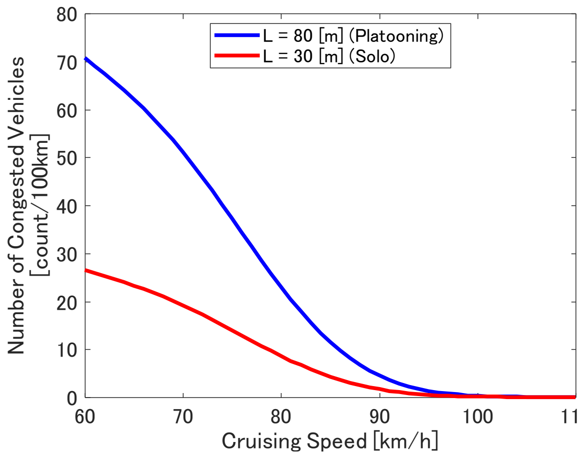

Fig. 3 The Number of Congested Vehicles in Lane B Caused by Overtaking Vehicles

Comparing the red line (L = 30 [m]) and the blue line (L = 80 [m]) in Figure 3, it is evident that as the distance L required to overtake the platoon group increases, the number of vehicles in congestion also increases. Additionally, it is clear that forming a platoon group with slower vehicles has a significant effect on increasing the number of vehicles in congestion.

4. MEASUREMENTS

In actual measurements, directly observing the number of vehicles in congestion in Lane B, as described by the theoretical formulas, is challenging for the following three reasons:

- The definition of "catching up" causes the observed number to vary.
- Due to the limitations of the recognition performance of the observing vehicles, there are scenes where it is not possible to distinguish between vehicles that are in congestion and those that are not.
- Unlike the statistical theory model, some vehicles change lanes and leave Lane B before entering the congestion.

Therefore, the number of vehicles in congestion is obtained by applying a transformation based on an indirect observation

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indicator of "deceleration of vehicles traveling in Lane B." Details will be explained in Section 4.3.

4.1. Test Section, Period, and Conditions

This test was conducted at approximately 100 km section of the Shin-Tomei Expressway, from Enshu-Morimachi PA to Suruga Bay Numazu SA, spanning about five months from February to June 2024. The test conditions included both solo driving and platooning (with an inter-vehicle time gap of approximately 2 seconds), each at three speed levels of 70, 75, and 80 km/h. The results for each condition were analyzed based on approximately 12 days' worth of data, totaling 1000 km.

Furthermore, this experiment was conducted with permission as part of the framework of the "Demonstration Experiment for Road-Vehicle Cooperation Toward the Era of Automated Driving on Highways." (5)

4.2. Test Configuration and Methodology

Figure 4 shows the test configuration during platooning.

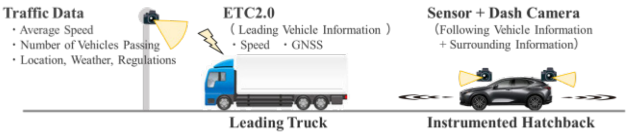

Fig. 4 Test Configuration During Platooning

For the lead vehicle, a commercial large truck equipped to obtain ETC2.0 data was used to acquire the positional information of the platoon group (hereafter referred to as the "lead truck"). For the following vehicle, a hatchback type vehicle equipped with instrumentation to observe surrounding traffic conditions was used (hereafter referred to as the "instrumented hatchback"). The speed of the overtaking vehicle, represented by V_{LBcar} in the subsequent equation (6), was measured using this instrumented hatchback.

The average speed in Lane B, represented by V_{fLB}, and the vehicle density in Lane B, represented by N_{LB}, were calculated from traffic volume data. This data was collected from measuring devices installed approximately every 2 kilometers on the roadway, which recorded the number of vehicles passing and their average speed every 5 minutes for each lane.

The location of the platoon group was detected using ETC2.0 data. This data records information such as the vehicle's latitude, longitude, and speed every 200 meters and is collected via roadside receiver antennas and sent to a server.

The speed of the lead truck was maintained as consistently as possible using the speed limiter function installed on the truck. The following distance was maintained by the instrumented hatchback using the following distance setting of its adaptive cruise control feature. Because the following distance was set based on time headway, the exact distance varied depending on the speed conditions.

For solo driving data, the data obtained when the instrumented hatchback was driven alone was used. Instead of ETC2.0 data, the location was detected using GNSS positional information from the instrumentation installed in the vehicle. The vehicle's speed was maintained using the speed control function of the vehicle's system.

4.3. Analysis Methodology

As mentioned earlier, in actual measurements, it is difficult to directly observe the number of vehicles in congestion in Lane B as indicated by theoretical formulas. Therefore, the number of vehicles in congestion was calculated using the following indicator represented by Equation (6).

$$E_{exp} = \frac{\sum_{\mathrm{LBcar}} N_{LB} \int_0^T (V_{\mathrm{fLB}} - V_{\mathrm{LBcar}}) dt}{D_{\mathrm{trip}}} \quad (6)$$

$$(V_{\mathrm{fLB}} > V_{\mathrm{LBcar}})$$

V_{fLB} : Time- and Location-Specific Flow Speed of Lane B [km/h]

V_{LBcar} : Speed [km/h] of Vehicles Overtaking the Platoon Group Traveling in the Target Section

T : Time [h] that Existed in the Analyzed Target Section

D_{trip} : Total Travel Distance of the Platoon Group Under Analysis Conditions [km]

N_{LB}: Vehicle Density [count/km] of Vehicles Traveling in Lane B

The indicator E_{exp} from Equation (6) was accumulated over the analyzed target section shown in Figure 5.

The basic analyzed target section was defined as the range from 0 m to 50 m in front of the instrumented hatchback vehicle. As shown in areas a and c of Figure 5, vehicles that changed lanes out of Lane B were accumulated within the range up to the point they changed lanes.

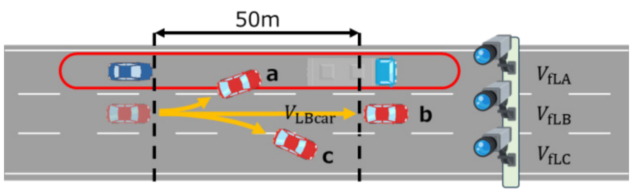

Fig. 5 Diagram Explaining the Analyzed Target Section

The following explains why the indicator E_{exp} signifies the number of vehicles in congestion.

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First, the part of E_{exp} represented by $\sum_{\text{LBcar}} \int_0^T (V_{\text{fLB}} - V_{\text{LBcar}})dt$ accumulates the difference between the average speed in Lane B and the speed of vehicles passing through Lane B within the analyzed range over time. Therefore, it corresponds to the "loss distance" that occurs in the analyzed target section (i.e., the distance lost compared to a scenario where all vehicles in Lane B are traveling at the average speed). A conceptual diagram illustrating the loss distance during speed reduction is shown in Figure 6.

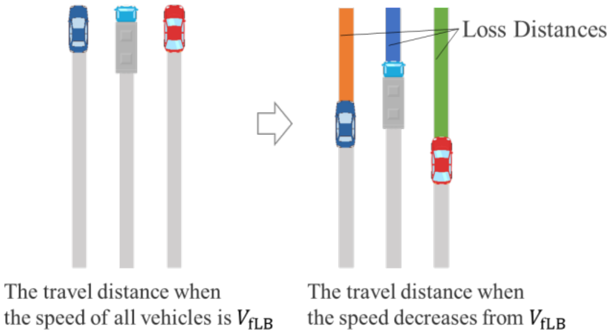

Fig. 6 Loss Distance During Speed Reduction

Furthermore, by dividing the "loss distance" by the total travel distance D_{trip} of the platoon group, it can be interpreted as "the loss distance [km] that occurs in Lane B next to the platoon group for every 1 km the platoon group travels."

This loss distance can be converted into the number of vehicles in congestion using the following approach. The explanation will follow the conceptual diagram shown in Figure 7.

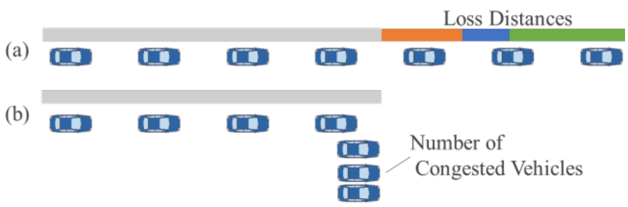

Fig. 7 Conversion Concept from Loss Distance to Number of Vehicles in Congestion

As shown in Figure 7 (a), if no congestion occurs and all vehicles can travel at the average speed of the lane without any speed reduction, then no loss distance is created. In this case, the number of vehicles observed would be distributed over the section as if all vehicles were traveling at the average speed. In contrast, as illustrated in Figure 7 (b), the actual number of vehicles is distributed over the section excluding the loss distance. Therefore, these "vehicles that should have traveled through the section corresponding to the loss distance" are equivalent to the number of vehicles in congestion. Since the average speed and number of vehicles in the time and location where the platoon group was traveling can be obtained from traffic volume data, the vehicle density N_{LB} can be calculated, allowing for the conversion of loss distance into the number of vehicles in congestion.

4.4. Results

Figure 8 shows the number of vehicles in congestion obtained from actual measurements alongside the theoretical values from Chapter 3. However, since the actual measurements maintain a following distance based on a time gap (approximately 2 seconds), the following distance [m] varies with the speed of the platoon group. It is important to note that the theoretical values have also been recalculated to align with the following time, so they may not match the results from Chapter 3.

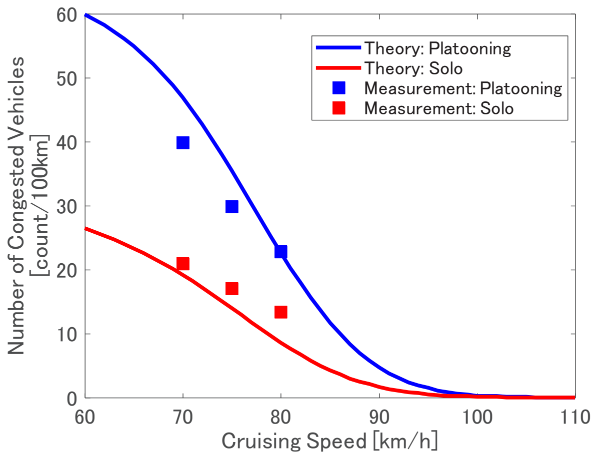

Fig. 8 Number of Vehicles in Congestion in Lane B Caused by Vehicles Overtaking the Platoon Group

First, looking at the experimental values indicated by square plots, it was found that the number of vehicles in congestion during platooning was greater than that during solo driving. Additionally, the results showed that as the speed of the platoon group decreased, the number of vehicles in congestion increased.

Next, when comparing the theoretical values and the actual measurements under the same speed conditions, it was observed that during platooning, the theoretical values tended to be larger than the measured values. On the other hand, during solo driving, the measured values were larger than the theoretical values under all conditions. Table 1 shows the error rates [%] between the theoretical values calculated using Equation (7) and the actual measurements. The average error rate across the six conditions was 19.8%.

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$$Error = \frac{|E_{exp}(V_{\mathrm{PG}}) - E_{passed}(V_{\mathrm{PG}})|}{E_{passed}(V_{\mathrm{PG}})} * 100 \quad (7)$$

Table 1 Error Rates [%] of Theoretical and Measured Values of Vehicles in Congestion

	Speed[km/h]		
	70	75	80
Platoon	15.0	15.9	0.6
Solo Driving	9.6	22.3	55.6

5. DISCUSSION

First, it is considered that the higher number of vehicles measured in congestion during platooning compared to solo driving is attributed to the congestion generation mechanism introduced in Chapter 2. This can be regarded as a rare example of confirming the traffic impact of platooning through actual measurements on an operating expressway.

Furthermore, the results in Figure 8 indicate that it is possible to quantitatively calculate the congestion caused by the platoon group through theoretical calculations to some extent. However, since there is a discrepancy between the measured values and the theoretical values, the factors contributing to this discrepancy are addressed.

Three main factors can be considered as causes for the discrepancy.

The first factor is the difference in length between the theoretical calculation section and the actual measurement analysis section. Figure 9 shows the sections for theoretical calculations and actual measurements. In theoretical calculations, the "distance required to overtake the platoon group" is varied (for solo driving, L=30 , and for platooning, THW=2 [s]) during the calculations, while in actual measurements, both types of driving are analyzed over an equal section of 50 m to confirm the differences between solo and platooning. As a result, the measurement section for solo driving is longer than that used in the theoretical calculations, while conversely, the measurement section for platooning is shorter than that used in the theoretical calculations. This trend is reflected in the relationship between the measured and theoretical values in Figure 8.

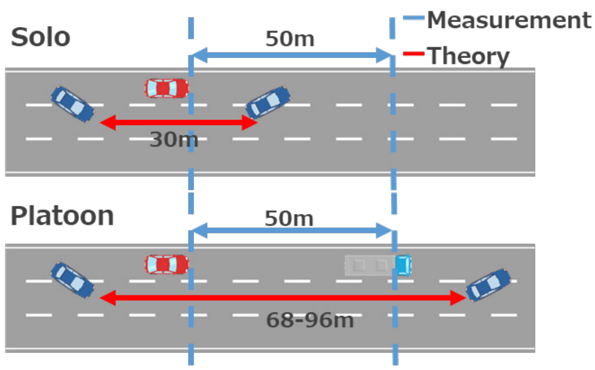

Fig. 9 Difference Between Theoretical Calculation and Actual Measurement Sections

The second factor to consider is that vehicles can evade into the overtaking lane. Since the theoretical calculations are based on a two-lane model, it assumes that all vehicles that catch up in Lane B contribute to the congestion count. In contrast, the actual measurements were conducted on a three-lane road due to contractual reasons. Therefore, when congestion is about to occur in Lane B, it is possible for vehicles to change lanes to the overtaking side, which may create a discrepancy. This difference can be a factor that pushes the measured values lower. It is expected that further investigation will clarify the impact of this factor.

Finally, the third factor is the difference in phenomena that are not accounted for in the theoretical values. The theoretical calculations only estimate the number of vehicles in congestion caused by vehicles changing lanes from Lane A to overtake the platoon group. On the other hand, actual measurements also observe congestion among vehicles that are overtaking each other and among vehicles that were originally traveling in Lane B. This difference can lead to higher measured values. However, it should be noted that some of the vehicles observed in the distribution of speeds in Lane B should include those that changed lanes from Lane A and are in the process of overtaking, so it cannot be definitively stated that these factors were not accounted for. The congestion among vehicles in Lane B is also likely to have a small impact due to the small speed differences. As vehicle recognition performance improves in the future, allowing for accurate separation between vehicles that are overtaking from Lane A and those that were originally traveling in Lane B, it is expected that the accuracy of the actual measurements will increase.

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6. FUTURE CHALLENGES

In this paper, the hypothesis that platooning causes local congestion in adjacent lanes by examining the "number of vehicles in congestion caused by vehicles changing lanes from Lane A to overtake the platoon group in Lane B" was confirmed through both theories and actual measurements, thereby supporting the hypothesis from both perspectives. It was also confirmed that the impact of the platoon group traveling at lower speeds is more pronounced.

However, to comprehensively evaluate the overall impact of platooning, it is necessary to consider the effects on Lane B when the platoon group itself changes lanes. Using a calculation method similar to that in Chapter 2, the "number of vehicles in congestion generated in Lane B when the platoon group enters Lane B" can be calculated as a theoretical value. Even in the comprehensive results considering this effect, the conclusion remains that the lower-speed platoon group has a greater congestion impact. This consideration provides a new insight into the "continuity of platooning."

As the lead vehicle of the platoon group increases in speed, the number of lane changes also increases, making it more labor-intensive to continue following the same lead vehicle. Therefore, it cannot be simply stated that "the lead vehicle should be one that travels at high speed."

Furthermore, in pursuit of the larger goal of GHG reduction, high-speed driving often does not serve the purpose. Thus, it is inappropriate to argue that "platooning should be conducted at high speeds" solely based on surrounding congestion, making it crucial to select the lead vehicle appropriately.

Moving forward, it is essential to further develop the insights gained regarding congestion impacts revealed in this paper and clarify the total GHG emissions from traffic flow due to acceleration and deceleration caused by congestion. Ultimately, it will be necessary to introduce appropriate mechanisms and guidelines to ensure that not only the effort and GHG emissions of the vehicles implementing platooning but also the overall GHG emissions from the traffic flow are optimized.

7. SUMMARY

(1) Through actual measurements the hypothesis that platooning causes localized congestion in adjacent lanes is comfirmed, thereby supporting the hypothesis.

(2) It was demonstrated that the "number of localized congestion occurrences in adjacent lanes due to platooning," as observed in actual measurements, can be quantitatively predicted through statistical theoretical calculations.

(3) It was shown that the congestion impact on adjacent lanes caused by platooning with lower-speed vehicles is more pronounced, indicating that the selection of the lead vehicle is crucial for introducing platooning into society while minimizing traffic impacts.

(4) Considering the continuity of platooning and its impact on traffic congestion, it is necessary to establish both appropriate technology application guidelines and policies to achieve an overall GHG-optimized traffic flow.

ACKNOWLEDGMENT

In conducting this study, we received support from many individuals and organizations. We would like to express our deep gratitude to Central Nippon Expressway Company Limited for providing the traffic volume data and Asahigaoka Transport Co., Ltd. for their cooperation in supplying the lead truck for our tests.

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