Collective Dynamics

Relationships and Characteristics of Self-Organized Vehicle Groups and Other Remaining Vehicles in Disordered Heterogeneous Traffic

Akihito Nagahama[1] · **Kenji Tanaka**[1] · **Katsuhiro Nishinari**[2]

[1] The University of Electro-Communications, Tokyo, Japan
E-mail: naga0862@uec.ac.jp, kenjitanaka@uec.ac.jp
[2] The University of Tokyo, Tokyo, Japan
E-mail: tknishi@mail.ecc.u-tokyo.ac.jp

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Abstract This study examines the relationships between self-organized vehicle groups and remaining vehicles (referred to as “remains”) within heterogeneous, disordered traffic flows, and compares their characteristics. The findings reveal that leader–follower relationships are less prevalent among the remains, whereas connections with grouped vehicles are more frequent in both groups and remains. Additionally, groups form longer leader-follower networks with diverse pathways for the propagation of acceleration and deceleration waves. Furthermore, the results suggest that a typical vehicle platoon comprises a sparse distribution of remains interspersed around longer groups. Moreover, owing to their extended network lengths and varied densities, groups are likely to feature amplified acceleration and deceleration waves. The findings also suggest that some remains may gradually disperse, hindering the backward propagation of waves. Thus, this study provides novel insights into the formation and dynamics of groups and remains in disordered traffic, with the aim of enhancing traffic-flow modeling.

Keywords Disordered heterogeneous traffic · mixed traffic with weak-lane discipline · leader–follower relationships · vehicle groups

1 Introduction

The proliferation of vehicles in the 21st century is boosting the global economy and enhancing our daily convenience and travel experience. However, the surge in the number of vehicles has resulted in traffic congestion, which is a growing issue in many developing countries, and it has many drawbacks, such as economic loss and health problems [1–3]. A notable characteristic of traffic in developing countries is a heterogeneous mix of vehicles, including motorcycles, three-wheelers, and cars, that often demonstrate weak lane adherence. This is termed “disordered heterogeneous traffic” in this study.

Several studies have demonstrated variations in spatial and temporal behavioral patterns among different vehicle types [4–8]. Meanwhile, researchers have proposed mathematical models [9–16] to simulate heterogeneous disordered traffic. Recently, these models have been advanced to incorporate autonomous vehicles on disordered roads [17, 18]. Heterogeneous-traffic models have shown that behavioral differences among various traffic participants influence the macroscopic properties of heterogeneous traffic, including flow rate and the formation of stop-and-go waves [19–21]. Although these studies [19–21] concentrated on heterogeneous ”lane-based” traffic, the lattice hydrodynamic (LH) model [22] facilitates the investigation of macroscopic traffic characteristics. Mohan et al. [23] expanded the LH model to incorporate overtaking in heterogeneous disordered traffic. Subsequently, Chattopadhyay et al. [24] used the model to compute statistical metrics, i.e., early warning signals, that indicate regime shifts in traffic flow, along with linear stability.

As mentioned above, it is evident that the sequence or order of vehicle types in heterogeneous traffic affects traffic characteristics. Our previous study [25] was the first to quantitatively clarify the combinations and chains of leader-follower relationships for all vehicle types in heterogeneous disordered traffic. In [25], we proposed viewing heterogeneous disordered traffic as a network of leader-follower relationships. This approach revealed a statistical bias in the leader-follower relationships formed by each vehicle type [25], and that certain vehicle types or their mixtures tend to frequently form and maintain leader-follower relationships over extended durations [26]. Such a vehicle set was referred to as “frequent subnetworks in standardized traffic (FSST)” in [26]; however, for clarity, we refer to it as a “group” in this study. A “group” refers to a set of vehicles that, considering the number of each vehicle type and structure of the leader-follower network, frequently form leader-follower relationships and maintain them for long periods. These groups primarily comprise vehicles that remain close to each other and continuously synchronize their velocities. By detecting such groups within heterogeneous disordered traffic, we have gained a new perspective: heterogeneous disordered traffic is composed of groups and remaining vehicles (referred to as “remains” in this study). Fig. 1 conceptualizes the definition of groups and remains. Vehicle combinations with certain leader-follower relationships that are frequently observed are defined as groups. Meanwhile, those not belonging to any group are classified as “remains.” The remains with mutual leader-follower relationships are classified into the same group of remains, whereas others are classified into a different group of remains.

Although we have discussed the characteristics of groups in our previous study [26],

Figure 1 Concept of groups and remains. Vehicle combinations of groups are frequently observed. Red solid arrows indicate leader-follower relationships within a group, and the blue solid arrows indicate those within a remain. Green dashed arrows indicate relationships wherein a vehicle belonging to a remain follows a vehicle belonging to a group and black dashed ones indicate those wherein a vehicle belonging to a group follows a vehicle belonging to a remain.

no study has addressed the relationship between groups and remains within traffic nor the characteristics of remains compared to groups. We aimed to clarify these aspects in this study by focusing on the following indicators:

- Whether each vehicle belonging to a group or a remain is more likely to form leader-follower relationships with those from groups or remains.
- The network indicators within groups and remains.

By clarifying these aspects, we anticipate the following outcomes: Improved evaluation of vehicle generators at the boundaries of microscopic traffic-simulation areas, ensuring that they reproduce the groups and remain observed in actual traffic. A vehicle generator should be able to (a) classify generating vehicles into groups and remains, (b) predict vehicle types within groups, and (c) reproduce the characteristics of remains in comparison to groups, including the relationships between groups and remains. Only when all of these elements are achieved can a simulation generate realistic mixed traffic characteristics without overfitting to actual vehicle platoons. Considering (a), generator development and performance evaluations have been conducted in [27], while for (b), similar efforts have been made in [28, 29] to reproduce groups. However, it is challenging to evaluate (c) because the fundamental characteristics of remains and their relationship with groups have not been clearly defined as evaluation metrics. In other words, even if a generator can predict and generate the vehicle types that form groups, no method exists to determine whether it can accurately reproduce remains and their interactions with groups. Consequently, without comprehensively addressing (a), (b), and (c), it is impossible to properly evaluate and refine the overall generation model. Furthermore, vehicles may be randomly generated at the simulation boundary based on the ratio of vehicle types and simulate their movement using a microscopic model, enabling groups and remains to emerge naturally and facilitating proper evaluation of traffic characteristics. However, the validity of the simulation cannot be ensured without evaluation metrics to verify whether the naturally emerged groups and remains exhibit characteristics consistent with real traffic. This is because real traffic undoubtedly comprises a mixture of groups, which exhibit a biased leader-follower combination, as shown in Fig. 1, and remains, which do not. It has been suggested that these structures potentially affect macroscopic traffic characteristics, such as flow and density [19–21].

Our investigation also provides insights into whether acceleration and deceleration waves are more likely to be amplified within groups or remains by examining the network-density and length of the leader-follower networks within groups and remains. A better understanding of the dynamics of leader-follower relationships among remains, which are typically considered to be configured randomly, can be gained by identifying the trends within them. A comprehensive understanding of the formation processes of groups and remains can be gained by investigating biases in leader-follower relationships between them.

The remainder of this paper is structured as follows. Sec. 2 introduces the traffic data used for the analysis as well as their preprocessing. Sec. 3 presents the analysis of the relationships between vehicles belonging to groups and remains and the internal characteristics within the two. Using the results, Sec. 4 provides examples of typical vehicle platoons in disordered heterogeneous traffic and discusses the relationship between the generation processes of remains and groups. Additionally, directions for future research are identified based on the present work. Finally, Sec. 5 concludes the paper.

2 Data and preprocessing

2.1 Observed data

We used the same dataset analyzed in our previous study [26], obtained through traffic observations in Mumbai, India, over four days, from January 18–21, 2017. Specifically, a segment of video recorded on January 19, between 11:34 AM and 2:34 PM, was selected for a detailed analysis. The video was captured using a Sony HDR-CX670 video camera positioned on the second-floor balcony of a shopping mall. A still from this video is depicted in Fig. 2. The section of the recorded road was 35-m long and is marked by a red dashed rectangle in the figure. Additionally, the area containing the traffic signals was situated just beyond this road section and is delineated with a black dashed rectangle.

This study focused on steady-flowing traffic, characterized by minimal changes in vehicle order owing to speed variations. The observation section was divided into three zones: A, B, and C (Fig. 3). The traffic flow within these zones was evaluated based on the density of these areas. Here, (ρ_A), (ρ_B), and (ρ_C) denote the density in Zones A, B, and C, respectively. Traffic was analyzed only when all densities were equal to or less than a threshold density ρ_{th}, which was set as 0.6 vehicles/m in this study.

The positions of the vehicles in the video image coordinate system were tracked semi-automatically using a multiple instance learning (MIL) tracker available in OpenCV [30], whereas the vehicle types were manually identified and recorded. The traffic was classified into motorcycles, auto-rickshaws (three-wheelers), passenger cars, and heavy vehicles, labeled as “m,” “r,” “c,” and “h,” respectively.

2.2 Detection of groups

To separate groups and remains, we first extracted groups from the traffic, similar to our previous study [26]. As the extraction method is described in detail in that study, we present a general overview here. Fig. 4 illustrates the flowchart of the process. First,

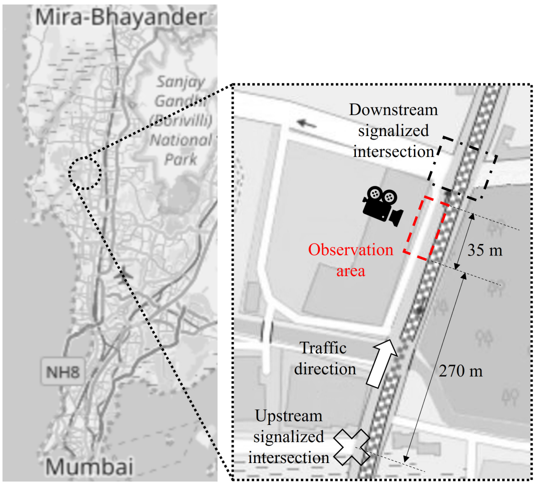

Figure 2 Traffic-observation location employed for data collection. The downstream intersection, upstream intersection, and the observation areas are marked using a black chained rectangle, black x mark, and red dashed rectangle, respectively. The map was sourced from OpenStreetMap under copyright.

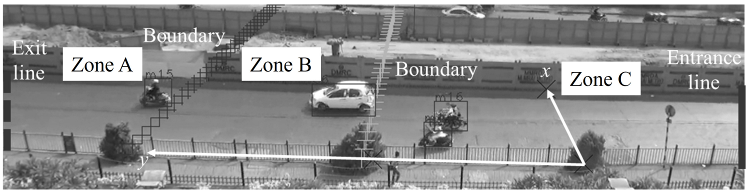

Figure 3 Division of the observation road. Zones A, B, and C are assigned downstream of the traffic.

we obtain the trajectory of each vehicle from the video and estimate the leader-follower relationship, which indicates that the acceleration/deceleration of one vehicle (leader) influences that of another (follower). In both this and our previous study [26], the leader-follower relationship was estimated based on whether the deviation of the lateral position of each vehicle was within a threshold and the Voronoi cells were adjacent. By representing the vehicles following a leader-follower relationship as nodes and the relationships themselves as directed edges, the traffic can be viewed as a directed graph network. Hereafter, this network is referred to as the "leader-follower network."

From this point, the process diverges into two branches. First, we focus on Branch A, marked with a shaded line in Fig. 4. First, the group candidates, i.e., the subnetworks that frequently appear in the leader-follower network at each moment are extracted. Subsequently, the average number of times that the candidate subnetwork i appears per unit time (λ_i^{O}) is determined by examining the number and duration of its appearance throughout the observation period. Subsequently, we focus on Branch B, marked with dots in Fig. 4. Moreover, we determine the average number of candidate subnetworks i that appears per unit time at the end of Branch B. However, this is achieved by repeatedly and randomly shuffling the nodes of the observed leader-follower network. As these nodes contain information regarding the vehicle types (m, r, c, and h), this randomized process enables us to determine the average number of occurrences per unit time (λ_i^{U}) after excluding the

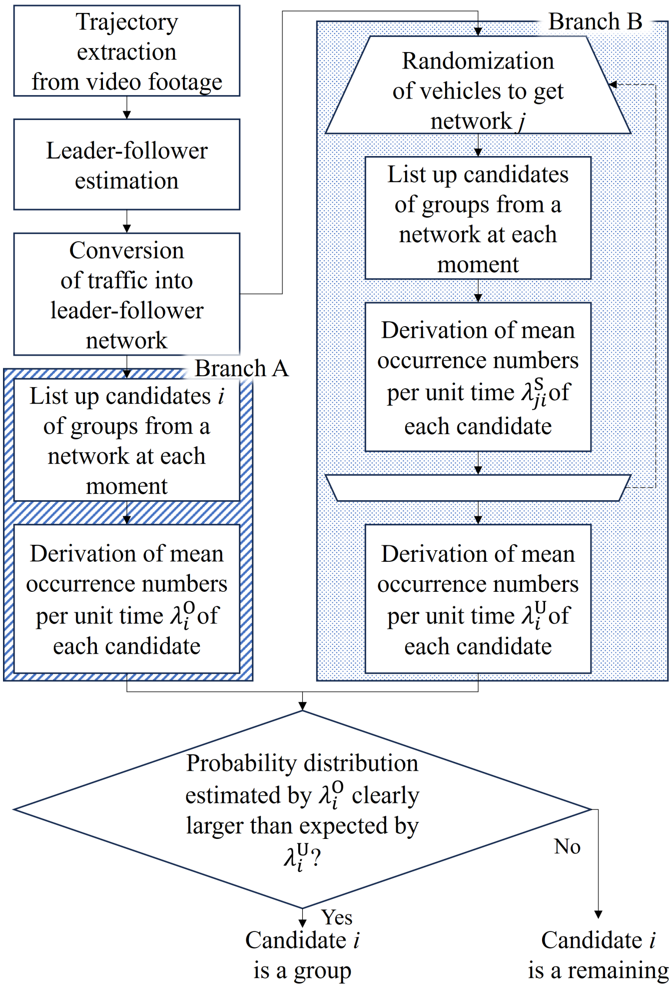

Figure 4 Flowchart for dividing vehicles into groups and remains.

inherent tendency of each vehicle type to form groups. In Fig. 4, $\lambda_{ji}^{\mathrm{S}}$ represents the average number of occurrences of i in the leader-follower network j, which is a randomized version of the observed network.

Using these two types of average number of occurrences per unit time λ_i^{U} and λ_i^{O}, we can obtain two Poisson distributions for the number of occurrences per unit time for subnetwork i. If the distribution based on λ_i^{O} (obtained from observation) is statistically larger than that based on λ_i^{U} (excluding the tendency to form groups), it can be concluded that subnetwork i exhibits a clear tendency to form groups. This subnetwork i is then identified as a group. Through this group-extraction process, the remaining vehicles in the leader-follower network can be classified as belonging to the remains.

Note that based on the definition of a group, groups are not static or indefinitely persistent. While differences exist in their existence duration, groups, like remains, are constantly subject to change.

3 Results

This section investigates whether each vehicle belonging to a group or a remain is more likely to form leader-follower relationships with those from groups or remains. To this end, we examine the in-degree and out-degree in the leader-follower network for each vehicle belonging to a group or remain, considering vehicles from both groups and remains. Additionally, to compare the network characteristics of remains with respect to groups, we analyze path length and network density, as well as the PageRank of each vehicle type within both groups and remains. These metrics help determine whether leader-follower structures exist within remains—despite the fact that remains are generally not expected to frequently form and maintain such relationships for long durations—which should be reproduced in microscopic simulations.

If we compare the characteristics of groups and remains using a certain metric and find differences, it is essential to clarify whether the differences stem from "the inherent tendency of groups to adopt a particular network structure based on the definition of the groups (i.e., subnetworks i for which $\lambda_i^{\mathrm{O}} > \lambda_i^{\mathrm{U}}$ are statistically significant)" or "fundamental differences between groups and remains that are independent of the definition." If this distinction cannot be made, the chosen metric would be considered inappropriate. When focusing on a single group, it is, of course, a cluster of vehicles that is naturally more likely to exhibit a certain network structure. However, all the extracted groups were identified solely based on whether their network structures exhibited statistically significant tendencies, rather than being selected for their inherent ability to adopt a specific network structure. Therefore, it is nontrivial whether the extracted groups exhibit a biased distribution in terms of the path length and density. Similarly, for remains, which are "vehicles that are not inherently inclined to adopt a particular network structure," it would not be surprising if all remains collectively exhibited a biased distribution in terms of specific path lengths or densities. Additionally, regarding the degree of distribution between groups and remains, the definition of a group does not inherently impose any obvious differences in the degree of distribution between vehicles that belong to groups and remains. Therefore, if differences emerge when the characteristics of groups, remains, and their relationships are compared using aforementioned metrics, the differences should not be attributed to the inherent tendency of groups to adopt a certain network structure. Instead, they should be interpreted as reflecting fundamental differences and intrinsic characteristics of groups, remains, and their relationships.

3.1 Relationship between vehicles belonging to groups and remains

First, we investigated whether vehicles that belong to groups or remains were more likely to establish leader-follower relationships with others in the groups or remains. Fig. 5 and Fig. 6 show the relative frequency, i.e., proportion of the number of vehicles in groups and remains, respectively, that follow or lead a single vehicle belonging to remains. The vertical axes in the figures represent the frequency of the number of vehicles that follow or lead a single vehicle in remains, displayed on a logarithmic scale. "G" within circles and "R" within triangles represent vehicles that belong to groups and remains, respectively.

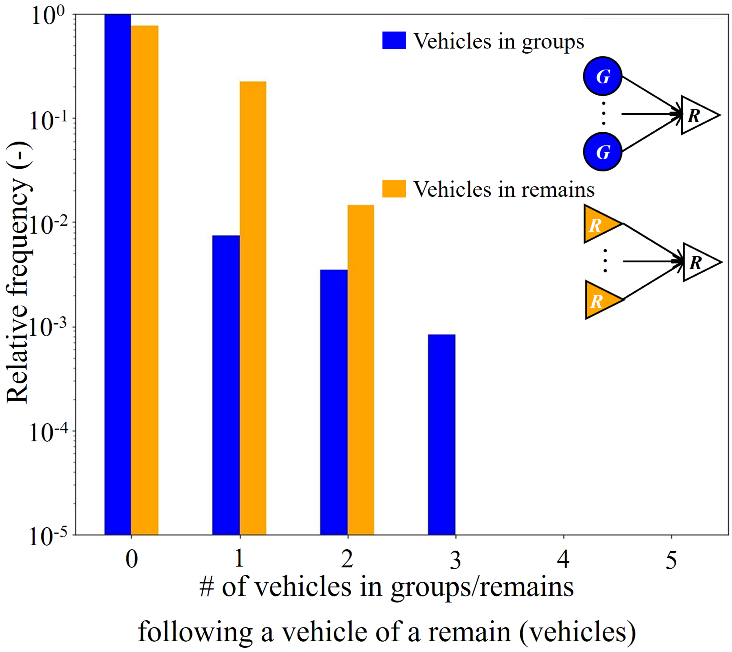

Figure 5 Relative frequencies of vehicles following a vehicle belonging to remains. The blue bars indicate the numbers of group vehicles, while the orange bars indicate those from remains.

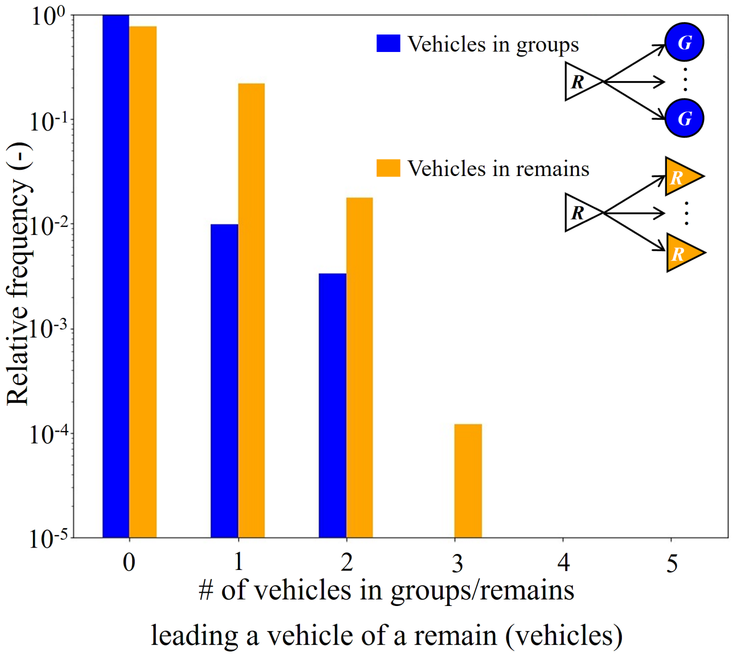

Figure 6 Relative frequencies leading a vehicle belonging to remains. The blue bars indicate the numbers of group vehicles, whereas the orange bars indicate those from remains.

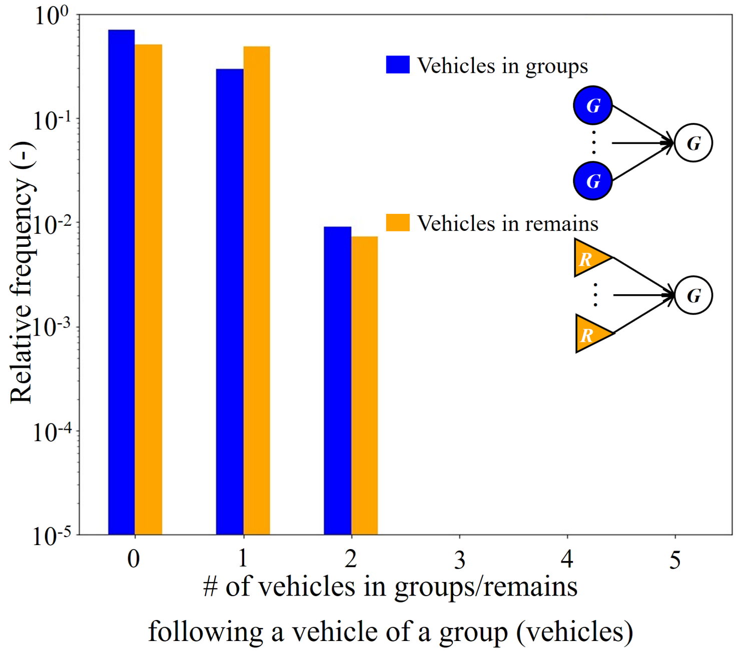

Figure 7 Number of vehicles following a group vehicle. The blue bars indicate the number of group vehicles, and the orange bars indicate those belonging to remains.

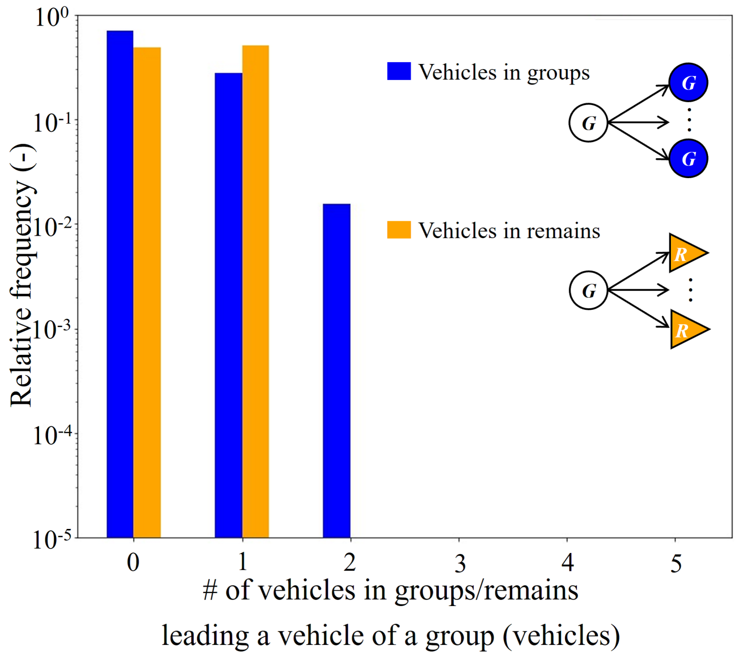

Figure 8 Number of vehicles leading a group vehicle. The blue bars indicate the number of group vehicles, and the orange bars indicate those belonging to remains.

In Fig. 5, the number of vehicles in groups and remains that follow a vehicle belonging to the remains decreases exponentially or more quickly. Similarly, Fig. 6 shows that the number of vehicles in groups and remains leading a vehicle belonging to the remains decreases exponentially or more quickly.

Additionally, on the one hand, the frequencies for up to two vehicles in Fig. 5 and Fig. 6 clearly show that those belonging to the remains tend to have stronger relationships with others belonging to the remains. On the other hand, when three vehicles follow a remain vehicle, they are more often group vehicles, whereas when three vehicles lead a remain vehicle, they are more often remain vehicles.

Fig. 7 and Fig. 8 show the relative frequency of the number of vehicles from groups and remains that follow or lead a single vehicle that belongs to a group. The number of group vehicles that follow or are followed by a single group vehicle decreases exponentially, with a maximum of two vehicles. By contrast, the number of remain vehicles that follow or are followed by a single group vehicle decreases at a rate faster than an exponential decrease. In particular, a remain vehicle leading a group vehicle is at most one.

Additionally, Fig. 5 and Fig. 6 show that remains are often positioned in front or behind a single remains vehicle. However, from Fig. 7 and Fig. 8, it can be observed that if a single vehicle is attached to a group vehicle, the remain tends to be positioned either in front or behind (slightly more often behind). If two vehicles are attached, the group vehicle is slightly more likely to be positioned front. It can be stated that, among group vehicles, there exists a tendency for the number of leaders to increase, whereas usually only a single leader-follower relationship exists between group and remain vehicles.

A comparison of Fig. 7 and Fig. 8 with Fig. 5 and Fig. 6 reveals that the proportion of one remain vehicle without a leader-follower relationship is higher than that of one group vehicle without such a relationship. This indicates that leader-follower relationships involving a single remain vehicle are sparse.

3.2 Internal characteristics within groups and remains

Fig. 9 shows the distribution of the mean path length for groups and remains. The mean path length (l) is calculated as follows:

$$l = \frac{1}{N(N-1)} \sum_{i \neq j} d_{ij}. \tag{1}$$

where d_{ij} is one when a leader-follower relationship exists from vehicle i–j; otherwise, it is zero. N indicates the number of vehicles within the group or remains being analyzed. In Fig. 9, the green bars indicate vehicles that belong to groups, whereas the pink bars indicate those belonging to remains. From Fig. 9, it can be observed that group vehicles have a more diverse range of path lengths compared to remains and can also form longer leader-follower networks.

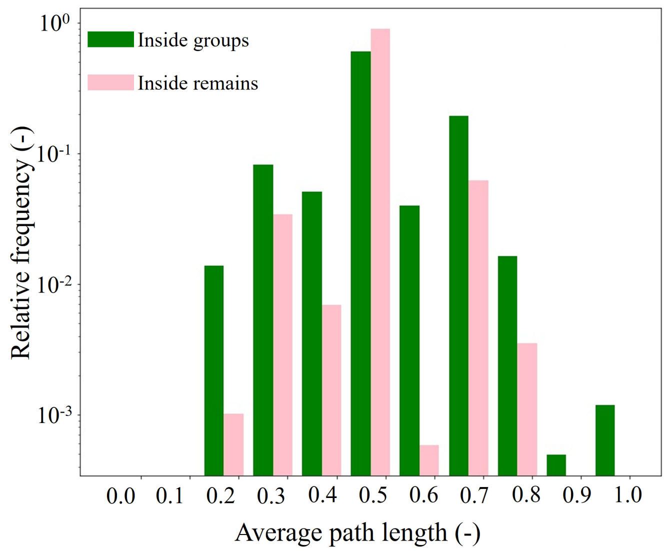

Figure 9 Relative frequency of mean path lengths for groups and remains.

Fig. 10 shows the frequency distribution of the network density for both groups and remains. Network density is defined as the ratio of the actual number of edges to the total number of possible edges between the nodes in a network. The green bars represent the densities of the groups, whereas the pink bars represent those of the remains. In Fig. 10, the density of remains is relatively heavily skewed toward 0.5, whereas group vehicles exhibit high frequencies across various densities, including 0.5, 0.3, and 0.2. This suggests that when acceleration or deceleration occurs within each group or remains, the paths through which these changes propagate in a group vary more widely than those in remains.

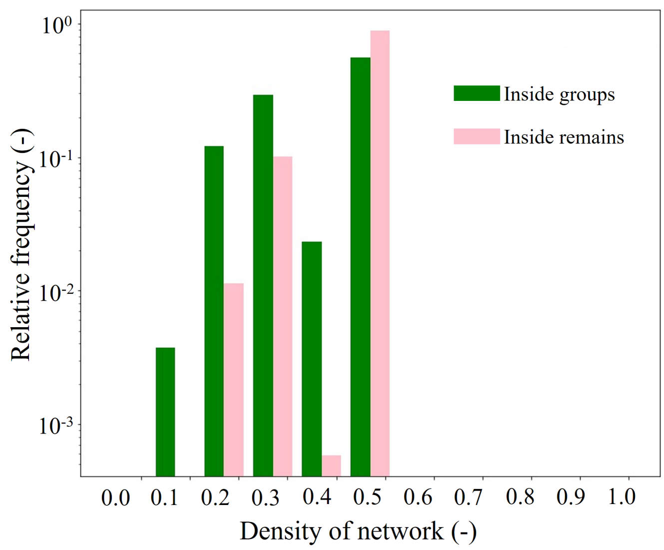

Figure 10 Network density within groups and remains.

Fig. 11 shows the average PageRank [31, 32] for each vehicle type within groups and remains. PageRank, originally an algorithm designed to rank web pages by their importance, can also be understood as a random walk model, wherein the importance of a webpage is determined by the probability that a user will reach it via random clicks, assigning higher ranks to pages that are frequently visited during the process. Interpreting the frequency distribution of PageRank within the leader–follower relationship network, it represents the vehicle that was most likely to receive acceleration or deceleration initiated elsewhere, even in a dynamically changing network. From Fig. 11, in groups, the PageRank of each vehicle type gradually increases with the vehicle size (from m to h). Contrastingly, for remains, in addition to this trend, the PageRank of cars is noticeably larger. This suggests that within groups, acceleration and deceleration occurring internally tend to have a greater impact on larger vehicle types. However, in remains, in addition to this tendency, the structure of the leader-follower network particularly amplifies the influence of acceleration and deceleration on cars. Such a structure can arise when cars are positioned relatively upstream of the remains.

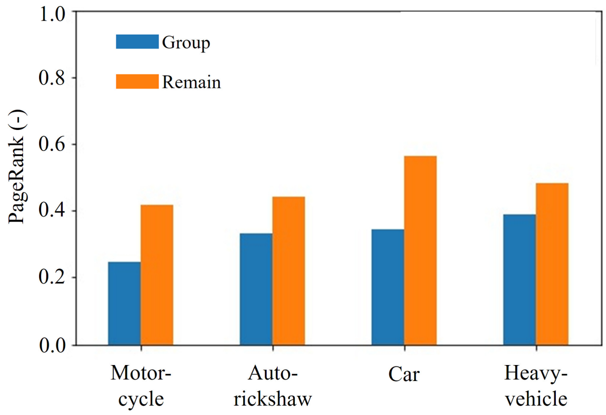

Figure 11 PageRank values for groups and remains.

4 Discussion

Based on the results, the relationships between remains and groups, including their internal characteristics, can be summarized as follows:

- Leader-follower relationships involving remains are sparse, whereas relationships with group vehicles are more common in both groups and remains.
- There exists a tendency for the number of leaders to increase within groups.
- The group-remain relationship tends to only have a single leader-follower connection.
- Groups can form longer leader-follower networks than remains.

- Groups exhibit more varied pathways than remains for the propagation of acceleration and deceleration waves.

- Remains often exhibit a structure wherein acceleration and deceleration effects are more likely to impact normal passenger cars.

Ideally, vehicle generators used in microscopic traffic simulations, which generates vehicles at the boundaries of the simulation area, should reproduce these characteristics to ensure realistic traffic-flow modeling.

These findings suggest that vehicle platoons resembling those shown in Fig. 12 are more common in traffic. "G" in circles and "R" in triangles represent vehicles in groups and remains, respectively. In Fig. 12, a "set" is formed with a sparse distribution of remains around a longer group, creating a leader-follower network composed of both group and remains vehicles. Additionally, the chain of vehicles appears to be interrupted by the remains. Moreover, there exists a higher possibility of a normal passenger car being positioned upstream of a remain.

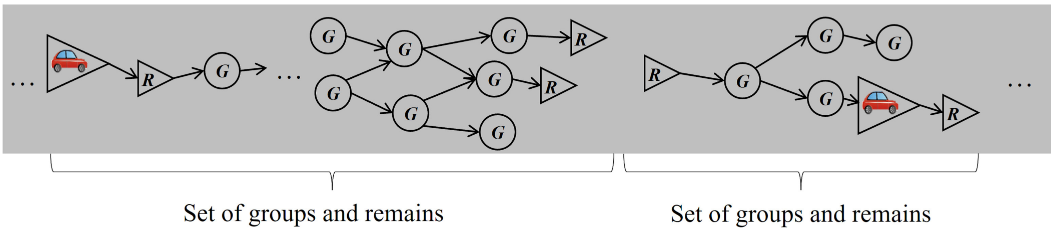

Figure 12 Image of a typical heterogeneous disordered traffic structure.

Subsequently, we investigated where acceleration and deceleration waves are most likely to be amplified: within groups or remains. Considering groups occasionally have longer network lengths, it is expected that in unstable conditions, acceleration and deceleration waves will be further intensified within the group. Conversely, portions of remains may gradually disperse, as suggested in the previous paragraph. In this case, acceleration and deceleration waves are unlikely to propagate backward. This implies that the internal structure of heterogeneous disordered traffic may be divided into sections wherein acceleration and deceleration waves are amplified and propagated, and those wherein they are interrupted.

Based on this, we predict that acceleration and deceleration waves amplify when they propagate through a group, which decreases the speed of the group, potentially obstructing the traffic flow. Studies on pedestrian traffic have been reported that social groups either obstruct speed [33], enhance it [34], or have no impact on the speed-density relationship [35]. However, further research using real data and models are required to clarify the effects of groups, collections, and other components in the remains that affect vehicular traffic flow. Specifically, when investigating the stability of traffic and propagation of acceleration and deceleration waves within groups through model-based approaches, it is essential to employ mathematical models that consider weak lane discipline [9,24]. This is because, groups feature a more diverse network density than remains, enabling various wave-propagation pathways.

Finally, we discuss the generation process of remains. Here, we attempt to infer the generation process by dividing it into two cases: the set of remains and the leading group, and the set of groups and the leading remain. Notably, based on the previous results, the former occurs slightly more frequently. In our previous study [36], we thoroughly examined the factors that contribute to the formation of groups. The results suggested that some groups are formed when highly agile vehicles move ahead of others when the traffic density is decreasing. The remains located upstream of the groups in Fig. 12, which are slightly major, are possibly clusters of vehicles left behind by the advancing group. Conversely, the same study [36] identified another factor that contributes to the formation of groups: vehicles being hindered by the surrounding space. If this results in the formation of a group, it is natural for unhindered vehicles to appear in front. These vehicles may be categorized as remains if they exhibit the following behaviors. Within remains, the behavior of two types of vehicles can be considered. Vehicle clusters formed in front of or behind the group have adequate space to freely rearrange their leader-follower relationships, continuously driving close to each other while changing these relationships. This scenario was referred to as a "collection" in [36]. The behavioral characteristics (such as speed and acceleration) of the vehicle types forming these clusters differ significantly. In this case, the remains gradually disperse. Any remain, based on the situation, may possibly merge with a faster-moving remain or group coming from upstream or with a slower remain or group downstream.

5 Conclusion

This study aimed to clarify the relationships between groups and remains within heterogeneous disordered traffic and characterize remains compared to groups. Our investigation yielded several key findings:

- Leader-follower relationships involving remains are sparse, whereas relationships with group vehicles are more common in both groups and remains.
- There exists a tendency for the number of leaders to increase within groups.
- The group-remain relationship tends to only have a single leader-follower connection.
- Groups can form longer leader-follower networks than remains.
- Groups exhibit more varied pathways than remains for the propagation of acceleration and deceleration waves.
- Remains often exhibit a structure wherein acceleration and deceleration effects are more likely to impact normal passenger cars.

The main conclusion of this study is that these characteristics should be incorporated into vehicle generators used in microscopic traffic simulations. In other words, the vehicle generator should not generate groups at the simulation boundary while randomly generating other vehicles. Instead, a simulator that accurately replicates the characteristics of real traffic can be developed by reproducing the generation of groups and the characteristics of remains and group-remain interactions. Furthermore, these findings suggest a typical vehicle platoon comprises a sparse distribution of remains around longer groups.

From our results, we obtained these implications: acceleration and deceleration waves are more likely to be amplified within groups than in remains. This is primarily because groups tend to feature longer networks, which can result in a greater amplification of waves under unstable conditions. Contrastingly, portions of the remains outside the collections may gradually disperse, making it less likely for acceleration and deceleration waves to propagate backward. This suggests that the internal structure of heterogeneous disordered traffic can be divided into sections wherein waves are amplified and propagated and those wherein they are interrupted.

We predict that when acceleration and deceleration waves amplify when they pass through a group, decreasing the group speed and potentially obstructing traffic flow. Similar dynamics have been reported in pedestrian traffic, wherein social groups can either hinder traffic speed, enhance it, or have no impact on the speed-density relationship. Therefore, further research using both real-data and model-based approaches are necessary to understand the effects of groups, collections, and other components within remains that affect vehicular traffic flow.

Regarding the generation processes of groups and remains, we can infer that several factors contribute to their formation. For instance, some groups may form when highly agile vehicles move ahead of others as traffic density decreases, leaving behind a cluster of remains. Conversely, groups may also form owing to hindrance of some vehicles by the surrounding space, causing them to cluster together. In such cases, it is natural for a cluster of unhindered vehicles to appear in front, potentially forming a set that is recognized as a remains.

A "group" is defined as a "set of vehicles that, considering the imbalance in the number of different vehicle types constituting the traffic, statistically and significantly form a leader-follower formation more frequently and for a longer duration than what would be expected from their numerical distribution." Under this distinct quantitative definition, the study conducted by the authors [26, 36] was the first to enumerate groups. Since then, no research has examined the relationships of quantitatively defined vehicle groups with other vehicle clusters (remains) or compared their characteristics, based on the detection of such quantitatively defined emergent vehicle groups. More specifically, in traffic with a high proportion of motorcycles, a study that qualitatively defines groups as clusters of motorcycles traveling together and investigates trends within such groups differs fundamentally from the scope of the "groups" addressed in this study. In this study, we analyzed "the relationships between vehicles that have a tendency to maintain a leader-follower formation for extended periods (groups) and other vehicles (remains), which included comparing their characteristics." More precisely, we examined "the relationships and characteristic comparisons between inherently emergent vehicle groups and other remaining vehicle clusters within traffic." Therefore, our findings are neither previously known nor trivial.

Based on the analysis of the characteristics of groups and remains and their interrelationships, the findings provide insights into wave propagation in relation to groups, remains, and their interactions. However, directly verifying or validating these insights was challenging owing to the limited length of the observation area. A validation study on the differences in wave propagation between groups and remains is necessary for future research. As another direction of future work, comprehensive evaluation of vehicle generators from the perspectives of (a) classifying generating vehicles into groups and remains, (b) predicting vehicle types within groups, and (c) reproducing the characteristics of remains in comparison to groups, including the relationships between groups and remains, is expected. The propagation of acceleration and deceleration waves are likely to significantly vary in magnitude or speed based on the vehicle type on the propagation path. Considering this impact and our PageRank analysis, further determining which vehicle types are particularly prone to accumulating acceleration and deceleration waves within dynamically changing networks remains a topic for future research.

Finally, the relationship between the accuracy of reproducing groups and remains in microscopic simulations and the accuracy of reproducing macroscopic traffic characteristics, such as flow and density, remains a crucial topic for future research.

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