

Effect of Mixed Traffic Platooning by Commercial Vehicle Types on Traffic Flow Characteristics of Highways

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Abstract

The existence of different types of Commercial Vehicles (CVs) in the shared roadway affects traffic flow characteristics differently from other vehicles. Owing to the uncertain placement and movement of these CVs in both longitudinal and lateral directions, the opportunities for lane changing and overtaking by other vehicles with lower maneuverability decrease, resulting in the formation of platoons. The study's primary aim is to assess the effect of mixed traffic platoons formed by three different classes of CVs on highway traffic speed, flow, and density under two different traffic regimes (regimes A and B). In this study, regime A represents the non-platooning condition, and regime B represents the platooning condition. Bi-directional traffic data was collected from the highway sections in India using an Infra-Red sensor-based device. The critical leading time headway is determined for the different CVs (platoon leaders) based on the mean absolute relative speed of platoons. The speed-flow-density plots are established using the macroscopic fundamental diagrams for the highway sections under regimes A and B to quantify the platooning impacts of CVs on the traffic characteristics. The study findings reveal that the speed at capacity, density at capacity, and traffic capacity decreased significantly due to CVs' influence on the general traffic mix during the mixed traffic platooning conditions. However, this effect was found to be relatively higher during the Heavy Commercial Vehicle operation as a platoon leader compared to Medium Commercial Vehicle and Light Commercial Vehicle as a platoon leader.

Keywords

macroscopic traffic model, commercial vehicle, Infra-Red sensor, mixed traffic, platooning condition

1 Introduction

A number of different vehicles following a platoon leader keeping a constant speed and time headway is defined as a mixed traffic platoon. In this study, the combination of Light Commercial Vehicle (LCV), Medium Commercial Vehicle (MCV), and Heavy Commercial Vehicle (HCV) are collectively represented as "Commercial Vehicles (CVs)". The movement of these CVs in heterogeneous traffic is a common phenomenon on highways. Generally, CVs occupy any available space on the road, causing increased interaction among vehicles, thus impacting the traffic flow characteristics of the highway. The CVs are considered the most significant contributor to the negative impacts perceived by road transport. Under mixed traffic conditions, the composition of different CVs on the highways causes a significant effect on traffic flow. Unlike other vehicles, trucks significantly affect the highway capacity because of their physical and operational characteristics

(Sarvi, 2013). Due to the dominant presence of different CVs that follow weak lane discipline and block the following vehicles' sight distance, the platoons are formed (Zhou et al., 2018). The speed of the subject vehicle (platoon follower) is reduced to the speed of the lead vehicle (platoon leader) operating at a lower desired speed. This type of traffic operation forces the subject vehicle to follow the lead vehicle for a certain distance while maintaining a safe spacing. The effect of this phenomenon is reflected on the next nearest following vehicles also, thereby generating moving bottlenecks. Besides, it has been observed that the trucks affect the surrounding vehicles, which causes the driving activity of these vehicles to change (Kong and Gou, 2016).

Indian highways experience a significant presence of platoons due to CV activities. The complex and complicated platooning behavior of mixed traffic generated by

CVs and their interaction with other vehicles lead to traffic speed and flow rate disruption. This eventually decreases traffic capacity and highway performance. Therefore, the platooning phenomenon is vital in analyzing highway traffic characteristics. Additionally, the CV's platooning affects the traffic parameters, driver behavior, and service quality. It is essential to understand the platooning effect of CVs on macroscopic traffic flow characteristics in heterogeneous driving conditions. Hence, an attribute based on platooning parameters for different CV types should be considered to measure the traffic characteristics. We consider three different types of CVs, viz, LCV, MCV, and HCV, for identifying the platooning characteristics that may have a detrimental effect on traffic intensity, efficiency, and safety. The present research work aims to quantify the impact of the heterogeneity of CVs on the traffic speed, traffic density, and traffic capacity of Indian highways, considering the platooning phenomenon of CVs.

2 Background literature

Gattis et al. (1997) investigated the platooning behavior of vehicles in Northwest Arkansas (USA). They observed that the vehicle headway is shorter during high traffic volumes, and the number of platoons formed per hour is higher, and vice-versa. Moridpour et al. (2015) assessed the effect of HVs on the surrounding traffic characteristics. The analysis findings found that HVs had a significant negative impact on traffic speed and travel time. Zhou et al. (2018) quantified platoons' characteristics on four-lane level freeway segments in the Western U.S. The critical headway to identify the platoons was observed to be in the range of 3 seconds to 8 seconds, impeding almost 51 percent of vehicles. The analysis found that the truck-led platoons had the greatest effect on vehicular traffic.

Zheng et al. (2013) evaluated the impact of HVs on lane-changing decisions of passenger car drivers immediately following the HVs. They used trajectory data and conducted an analysis based on neural network techniques. Kong et al. (2016) used the cellular automaton model to analyze trucks' effects on traffic flow, considering the performance difference between passenger cars and trucks. The study shows that passenger car drivers are affected by trucks' percentage, and the space gap has increased. Leong and Shafie (2019) studied the effect of HVs and motorcycles on platooning based on headway and speed results. Deng and Burghout (2016) presented the platoon modeling of the traffic flow of passenger cars

and heavy-duty vehicles (HDV). The speed-density relationship was expressed using the traffic density function, HDV percentage, and HDV platoon spacing policy. The above research works focused primarily on the two types of vehicle classes, one of which included HVs. The other category of vehicles was the passenger car, which dominated the traffic stream.

Ahmed et al. (2013) conducted a study to determine the impact of Heavy Vehicles (HVs) on performance at different congestion levels. The study findings reveal that with an increase in the HVs percentage, the capacity and Level of Service (LoS) deteriorated. Roh et al. (2017) examined the reduction in highway speed due to the variance in the volume of HVs. They analyzed the effect of HVs on traffic flows using real-time data. The research results affirmed that the speed decreases with increased flow rate and HVs ratio. Wang et al. (2018) examined the impacts of overloaded HVs on freeway traffic conditions using a multi-class traffic flow model. Kong et al. (2019) analyzed the influence of HVs on the drivers of the rear vehicles using fuzzy logic techniques. Recently, Gao et al. (2020) predicted the impact of large-scale vehicles on the average speed under the various volume to capacity (v/C) ratios. They established a negative logarithmic linear relationship between average speed and large-vehicle mixing rates. Singh et al. (2020) assessed the effect of Heavy Transport Vehicles (HTVs) on speed-flow characteristics of Indian highway traffic. They found that the HTVs operation impacted the traffic speed and flow. Further, a comprehensive study by Singh and Santhakumar (in press) analyzed the impact of multi-class commercial vehicles on the traffic stream characteristics on national highways in India. All these studies focused on the impact of HVs under different traffic conditions, mainly under non-platooning traffic conditions. Hence, there is a void in terms of platoon characteristics analysis under mixed traffic conditions.

Additionally, these studies amply prove that little information is available on the effect of platoon formation caused by CVs on Indian highways. Comparatively, less research is available on the study of speed-flow-density models concerning the platooning phenomena of CVs on highways. As a result, CVs' effect on the traffic flow characteristics of highways is still uncertain and needs to be discussed in detail. Therefore, the present research was undertaken to examine the mixed traffic platooning impact of different CVs on the traffic speed, density, and capacity of the highways in the traffic mix.

3 Research methodology

The platooning behavior of CVs on highways significantly affects the time headway and speed of the vehicles (Singh and Santhakumar, 2022a). Hence, a time headway analysis was carried out to determine the critical leading time headway value using the mean absolute relative speed of mixed traffic. The critical leading time headway value for different CVs as platoon leaders was estimated. This study considers two traffic regimes, viz regime A and regime B. The traffic recorded within a minute before the arrival of a CV type at the Infra-Red (IR) sensor detector is denoted as regime A. Regime A represents the non-platooning scenario. The traffic recorded after the arrival of a CV at the IR sensor detector for a certain time up to the platoon's existence is denoted as regime B. Regime B represents the platooning scenario. The CV type that creates the platoon is named the platoon leader, while the vehicles impeded by the platoon leader and are in the following condition are named the platoon followers.

Additionally, the study developed the speed-flow-density ($v-q-k$) characteristics plots for the highway section for these two regimes using the Macroscopic Fundamental Diagrams (MFDs). The MFDs are developed based on Greenshields Linear Model (GLM) (Greenshields et al., 1935) to estimate the reduction in the traffic parameters due to the influence of different types of CVs with due consideration of the platooning phenomenon. Comparing these two traffic regimes shows a significant difference in speed at capacity, density at capacity, and traffic capacity with respect to the type of CVs.

4 Field data collection strategy and technique

The field-related traffic data was acquired utilizing Transportable Infra-Red Traffic Logger (TIRTL), an IR sensor-based device setup across each direction of the National Highway (NH-83) in India. Using the TIRTL device, the traffic data such as vehicle class, vehicle speed, and time headway between vehicles were collected.

The traffic data for each traffic direction was collected for 20-hours on two separate days in each traffic direction. The traffic data include both weekday and weekend peak and non-peak hours traffic, including the variation of day-time, noon-time, evening-time, and night-time traffic characteristics. Since these conditions can be more accurately represented by a fictive traffic volume calculated based on 5-minute-long intervals, the traffic condition was characterized by a traffic volume of the 5-minute interval rather than the hourly traffic volume.

The mid-block portion of the four-lane divided highway was selected as the study site. The bi-directional highway sections are free from any kind of side friction in the vicinity of the data collection region, ensuring no effect of side friction on vehicular traffic flow other than the platoons formed by the CV types. Each directional section had two dedicated travel lanes (Median Lane-ML and Kerb Lane-KL) with a 3.5 m width and a median width of 1.2 m. The paved shoulder width in the West Bound (WB) direction and East Bound (EB) direction was 1.5 m and 2.5 m, respectively. Fig. 1 illustrates the roadway inventory details in NH-83-WB and NH-83-EB directions, including the placement of the TIRTL device across the highway sections for possible traffic data collection.

In India, highways bear mixed traffic, with various types of vehicles moving anywhere on the road without any lane control. Also, the intra-class heterogeneity of the CVs adds more complexity to the highway traffic flow. Thus, collecting and processing traffic data using the widely used videography technique becomes more challenging. Moreover, the traffic data collection using videography techniques during night-time is a complicated and costly task. This difficulty in traffic data collection is overcome by using the TIRTL device. It is a portable and automated IR sensor-based traffic recorder device. It can record traffic parameters like the vehicle class, vehicle dimensions, vehicle speed, vehicle headway (spatial and temporal), vehicle gap, vehicle clearance, and traffic volume on multi-lane divided highways. Fig. 2 illustrates the operation of the TIRTL device.

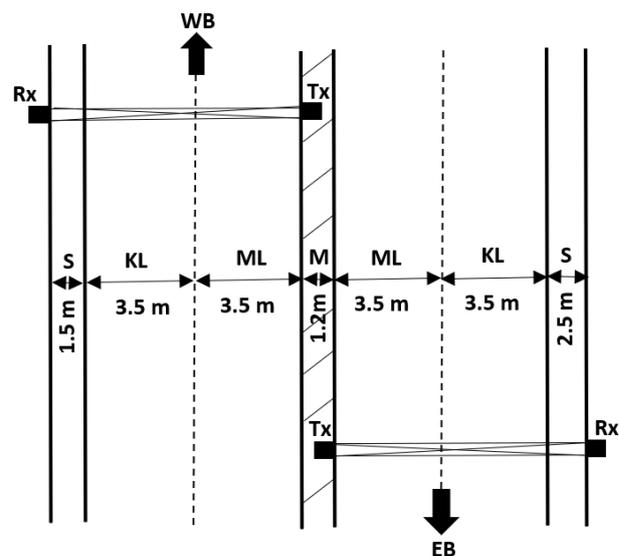


Fig. 1 Roadway inventory details of the highway, Note: S-Shoulder, KL-Kerb Lane, ML-Median Lane, M-Median, WB-West Bound, EB-East Bound, Tx-Transmitter, and Rx-Receiver

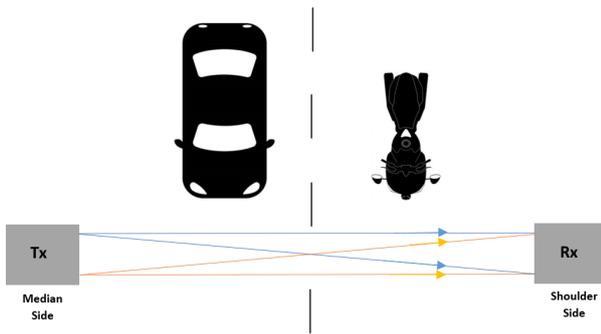


Fig. 2 Image showing the transmission of the Infra-Red beams of TIRTL device for vehicle detection

Fig. 3 illustrates the TIRTL device setup across one of the directions of the study section for acquiring traffic data. The main components of the IR sensor device are the transmitter unit (Tx) and a receiver unit (Rx) that are located on each side of the highway in a direction perpendicular to the traffic flow. The working power is supplied to Tx and Rx via an externally attached 12 Volt Direct Current (DC) battery (BT). The Tx is mounted on the median side and is the source of IR beams for traffic detection. The Tx unit forms two straight and two diagonal IR beam pathways. The Rx is mounted on the kerbside and connected to a laptop system through an RS232 serial port to access the system interface and store the data file in .csv format. The laptop system is also used to monitor on-site traffic detection. The Rx receives any disturbances in IR beam transmission caused by the moving vehicles.

When a vehicle crosses the IR beam pathways, the vehicle speed is recorded from the timing of these IR beam events caused by the vehicles. The timestamp of the IR beam recorded for each vehicle crossing is used to determine the vehicle's time headway. The recorded inter-axle

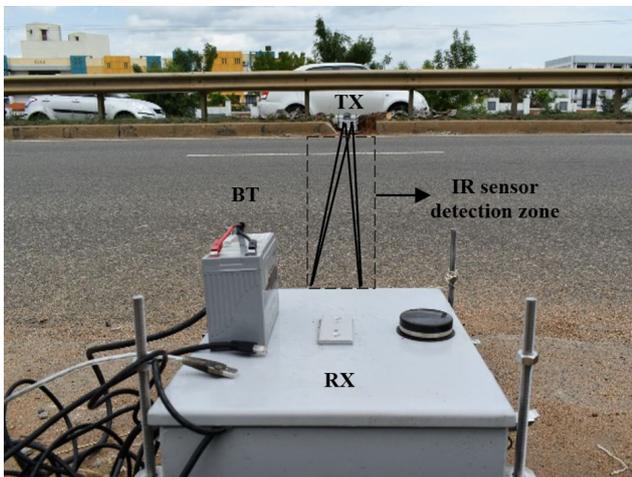


Fig. 3 Set up of TIRTL device on the highway, Note: Rx-Receiver, Tx-Transmitter, BT-Battery, and IR- Infra-Red

spacings and the number of vehicle axles are compared to a list of internally stored inter-axle spacing ranges to determine the exact vehicle classification. A further detailed explanation regarding the data collection using TIRTL can be referred to in the research by Singh and Santhakumar (2021a, 2021b).

4.1 Accuracy of the collected traffic data

The IR sensor device was calibrated prior to the proper data collection period to ensure the most accurate recording of vehicles. For this, the traffic passing through the IR detection zone of the TIRTL device is videotaped by positioning a video camera at a sufficiently high viewing point, covering a trap length of 50 m. The vehicle detection timings of the TIRTL are coordinated with that of the video camera, ensuring time synchronization between them. The traffic video captured was analyzed at the laboratory; the vehicle classification, vehicle speed, and time headway records between the vehicles from the test section (NH-83-WB) were manually taken for an hour to compare with the data obtained by the TIRTL device. A comparison of the extracted peak hour traffic data showed 97 percent accuracy with regard to the vehicle classification, 95 percent accuracy with regard to vehicle speed, and 96 percent accuracy with regard to the time headway. Another study by Minge et al. (2010), which used the same TIRTL device, reported that the vehicle speed accuracy was up to 98 percent and vehicle volume accuracy was also up to 98 percent.

5 Vehicle classification and composition

The vehicles are classified into the following seven classes: Two-Wheeler (TW), Three-Wheeler (ThW), Small Car (CS), Big Car (CB), Light Commercial Vehicle (LCV), Medium Commercial Vehicle (MCV), and Heavy Commercial Vehicle (HCV). The LCV includes light-weight commercial vehicles and small size commercial goods vehicles. The MCV includes the two-axle rigid trucks or buses, while the HCV includes the three-axle rigid trucks or buses. In this study, the combination of LCV, MCV, and HCV classes of vehicles are collectively represented as "Commercial Vehicles (CVs)". Also, the term CVs is interchangeably used to describe the "LCV, MCV, and HCV" class of vehicles.

The percentage composition of the Multi-Axle Vehicles (MAV) comprising 4-axle, 5-axle, 6-axle, and more than 6-axle vehicles was relatively lower, so these categories of vehicles were not considered in this study. Table 1 shows the recorded vehicular dimensions and composition in the NH-83-WB and NH-83-EB directions.

Table 1 Vehicular dimensions and composition at the highway sections

Vehicle Type	Vehicle Length (m)	Vehicle Width (m)	Vehicle Area (m ²)	NH-83-WB (%)	NH-83-EB (%)
TW	1.89	0.65	1.23	21.4	20.8
ThW	3.25	1.44	4.68	2.9	3.4
SC	3.65	1.50	5.48	26.2	23.7
BC	4.54	1.75	7.95	13.6	14.5
LCV	5.90	2.05	12.10	9.1	8.7
MCV	7.25	2.26	16.39	17.3	16.4
HCV	10.57	2.38	25.16	9.5	12.5

6 Analysis and results

6.1 Variation of the speed of vehicles over time

One of the prime traffic variables used to assess the effect of CVs on other vehicles is traffic speed. The relative vehicle speed depends upon the type of surrounding vehicles (Moridpour et al., 2010) and the proportion of other vehicles. The speed of vehicles in the traffic stream is affected by vehicular platoon characteristics, which cause frequent changes in the traffic speed leading to localized congestion. Therefore, speed could accurately represent the vehicles' overall interaction under mixed traffic conditions. As mentioned earlier, regime A represents the non-platooning scenario, regime B represents the platooning scenario, and post regime B represents the dispersion of the platoon and recovery of free-flow condition.

Each platoon has one or more platoon leaders and one or more followers. The platoon leader interacts with other vehicles in the traffic stream. Regime A represents the pre-platoon formation scenario, which is taken for the first 60 seconds (s) before the arrival of CV type at the IR sensor detector, while the regime B represents the platoon formation and platooning impact scenario, which is considered after the arrival of a CV type at the IR sensor detector, which lasts from the 61 s up to different times as per the CV type (platoon leader type). The platoon's disaggregation and the traffic recovery zone are represented by the post regime B scenario, which is considered to last from the end of regime B up to an additional 60 s (i.e., 180 s). The average vehicle speed variance in regime A, regime B, and post regime B, when LCV, MCV, and HCV, is a platoon leaders, is shown in Figs. 4–6, respectively.

In regime A, not much reduction in vehicles' average speed is seen, as this regime is the no platoon formation regime. In regime B, the number of vehicles joining the queue increases, and the average speed of vehicles decreases due to higher interaction among the vehicles. Specifically, the perturbation is amplified by the platoon formation of vehicles by the CV type. Figs. 5 and 6 show

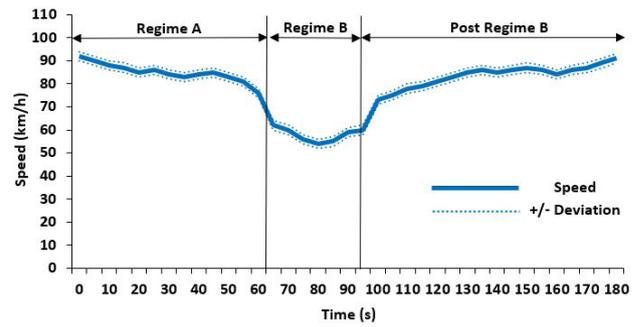


Fig. 4 Vehicle speed variance with time when LCV is a platoon leader

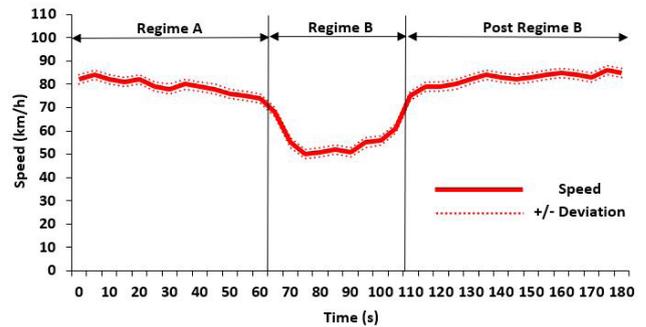


Fig. 5 Vehicle speed variance with time when MCV is a platoon leader

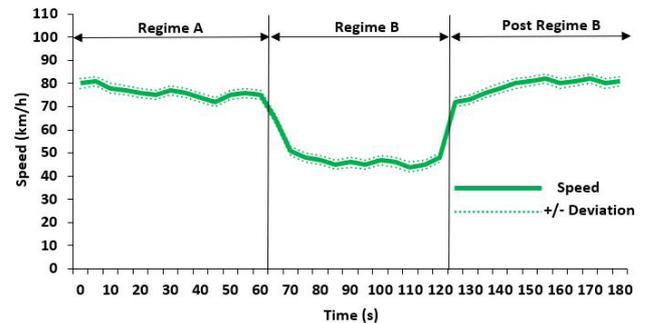


Fig. 6 Vehicle speed variance with time when HCV is a platoon leader

that the speed drop due to HCV and MCV, respectively, as a platoon leader, was more than when an LCV was a platoon leader, as shown in Fig. 4. Further, the speed drop was more when an HCV was a platoon leader than when an MCV was a platoon leader.

The time of platoon existence when the LCV was a platoon leader was lower than when an MCV and (or) HCV was the platoon leader. When LCV was a platoon leader, the platoon (regime B) existed from 60 s to 95 s, i.e., 35 s. In contrast, when MCV was a platoon leader, the platoon (regime B) existed from 60 s to 109 s, i.e., 49 s, and when HCV was a platoon leader, the platoon (regime B) existed from 60 s to 121 s, i.e., 61 s.

These traffic characteristics may be interpreted by the fact that it is more convenient for the vehicles to overtake and pass by a platoon formed by an LCV than to overtake and pass by a platoon formed by an MCV or HCV. It may take a substantial amount of time for the slower moving

vehicles in the platoon to pass other vehicles due to the delay caused by the localized congestion when the platooning condition is in existence. Additionally, the HCVs and the MCVs occupy more space than LCVs; hence, the average speed of vehicles decreases. The platoon lasts for a more extended period when MCV or HCV is a platoon leader. It is hypothesized that this event of MCV and HCV platooning increases with the increase in MCVs and HCVs in the traffic stream and leads to speed differentials. In fact, smaller inter-vehicle distances between CVs result in a higher speed drop due to leader-follower vehicle interactions.

Finally, after the dissipation of localized congestion, the regain in the speed of vehicles happens in the post regime B scenario. In the post regime B scenario, the beginning of platoon disintegration occurs due to the acceleration of platoon members. As a result, the following vehicles change lanes and successfully operate at a relatively high speed.

6.2 Critical leading time headway determination

The leading time headway is the time interval between the front bumper of the leader vehicle and the front bumper of the follower vehicle crossing the IR sensor detector. The threshold value for platoon identification is defined as the "critical leading time headway". In order to define a vehicle in the platoon, the critical leading time headway is used. The vehicles with time headway greater than the critical leading time headway were considered free vehicles.

The HVs operating on roadways lead to different and larger space and time headways (Aghabayk et al., 2012). Choosing the appropriate value of the critical leading time headway is crucial. A minor computational error in the critical leading time headway can lead to enormous differences in the resulting platoon characteristics. For example, using a large critical leading time headway would result in too large platoon sizes and too large variations in platoon characteristics. On the other hand, using a small critical leading time headway value would result in small platoon sizes and inadequate platoon details.

Many studies assume a single critical time headway value for different vehicle types in the platoon. Contrary to this, this study assumes that there is no single critical time headway value for all vehicle types. The static and dynamic features of the vehicle differ significantly in mixed traffic conditions. Additionally, since different vehicles with varying physical and operational capabilities ply on the highway, adopting a single critical time headway

value for the platoon formation may lead to biased or inconsistent results (Singh and Santhakumar, 2022b).

Since the critical leading time headway value is a function of interacting vehicles, it varies according to vehicle type. It is dependent on the relative speed of the interacting vehicles. It is identified for the mixed traffic platoon followers following the platoon leaders based on the platoon leader vehicle type. This study mainly focuses on the impact assessment of the CVs on the traffic characteristics under platooning conditions; hence the CV types such as LCV, MCV, and HCV are considered as the platoon leaders, and their following vehicles' mean absolute relative speed and time headway value is used to determine the critical leading time headway value. The LCV, MCV, and HCV, as the platoon leaders, are taken into account based on the degree of impedance created by these vehicle types.

It is to be noted that, since poor lane discipline is followed on Indian highways, so the analysis of the lane-based characteristics was not carried out. Even if the platoon leaders are separated based on lanes, the separation of platoon followers based on lanes is difficult. So, when two or more similar and dissimilar CVs (with the same speed and zero time headway) arrived on both the lanes at the IR sensor detector point, both were regarded as the platoon leaders, and the analysis was further carried out.

The vehicles on all lanes in one direction with leading time headways less than or equal to the critical leading time headway are considered to belong to the same platoon.

The mean absolute relative speed and time headway were plotted at an interval of 0.5 seconds for 8.0 seconds, considering different CVs as platoon leaders. Figs. 7–9 represent the critical leading time headway plot for platoon identification when LCV, MCV, and HCV are platoon

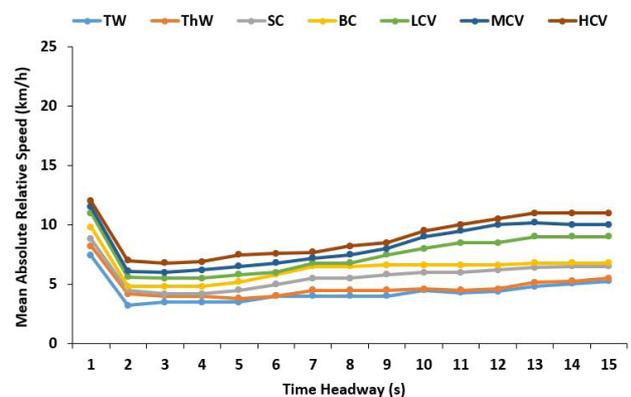


Fig. 7 Critical leading time headway identification plot for mixed traffic when the LCV is a platoon leader

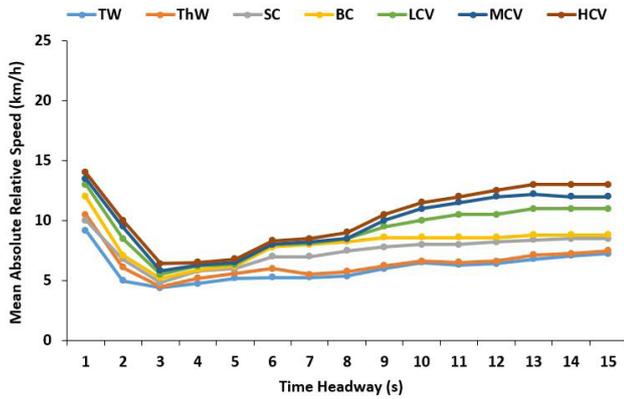


Fig. 8 Critical leading time headway identification plot for mixed traffic when the MCV is a platoon leader

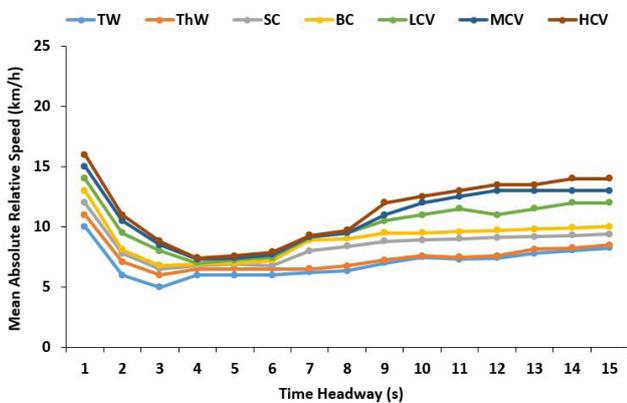


Fig. 9 Critical leading time headway identification plot for mixed traffic when the HCV is a platoon leader

leaders. Figs. 7–9 show that the vehicles attain a minimum mean absolute relative speed when the time headway threshold is in the range of 1.5 s to 2.5 s for LCV as a platoon leader, 1.5 s to 3.0 s for MCV as a platoon leader, and 1.5 s to 4.0 s for HCV as a platoon leader, respectively. This range generally represents the restricted condition where all vehicles are forced to compromise their speed to follow the platoon leader. It is also seen that most of the vehicles attain a constant mean absolute relative speed in the time headway range between 2.0 s and 2.5 s when LCV is a platoon leader, 1.5 s to 3.0 s when MCV is a platoon leader, and 2.5 s to 4.0 s when HCV is a platoon leader. Thus, a critical leading time headway of 2.5 s for LCV as a platoon leader, 3.0 s for MCV as a platoon leader, and 4.0 s for HCV as a platoon leader is adopted for defining the platoon criteria. Beyond this, the mean absolute relative speed for the vehicles is almost constant.

As time headway value exceeds the threshold value, the interaction of vehicles decreases, and therefore, vehicles are considered free-flowing. This means that the drivers are not tailgating the vehicles in front of them and ride at their desired speed.

It can be seen from Figs. 7–9 that the critical leading time headway is not the same for the different types of CVs viz LCV, MCV, and HCV as platoon leaders. The following vehicles choose to change lanes and overtake at times when an LCV is a platoon leader because of its lower impact on the mixed traffic. So, the time headway of the following vehicles is less in this case. When the vehicles follow the MCV, the following vehicles tend to decelerate and maintain higher time headway to avoid rear-end collision. The following vehicles move smoothly despite occasional disturbances (local congestion). However, when HCV is a platoon leader, the impact is higher; therefore, the lane-changing and overtaking is restricted, and the time headway of the following vehicles increases.

Consequently, a higher time headway was seen to be maintained by the following vehicles tailgating the HCV or MCV compared to that when tailgating an LCV. The time headway of vehicles following the platoon leader increases as the CV category varies from LCV to MCV and HCV. The variation in the critical leading time headway of the CVs is observed due to the CVs' physical and operational characteristics as perceived by the following vehicles. The larger the physical size of the vehicle, the higher is the time headway maintained by the following vehicles. Most of the following vehicles held higher time headway to mitigate the impact resulting from interaction with the MCV or HCV. This means that the vehicles are greatly influenced by the movement of MCV and HCV and thus cannot keep their own desired time headway. Thus, the impeded vehicles adopt higher time headway values to ensure safer driving.

6.3 Frequency of platoon size for different CV types

The frequency of the platoon size with respect to the critical leading time headway of the platooned vehicles was determined. Figs. 10–12 depict the platoon size-frequency plots when LCV, MCV, and HCV, respectively, is a platoon leader.

When LCV is a platoon leader, the two-vehicle platoon size frequency is higher, as illustrated in Fig. 10. Since the critical leading time headway for LCV as a platoon leader is less, the small platoon size is higher. Also, small time headways indicate dense platoons. The platoon size frequency suggests that the traffic stream experience a lower platoon-size formation when the LCV is a platoon leader. The following vehicles find a sufficient gap and overtake the LCV; however, this is not the case when the MCV or HCV is a platoon leader, which obstructs the movement of the following vehicles.

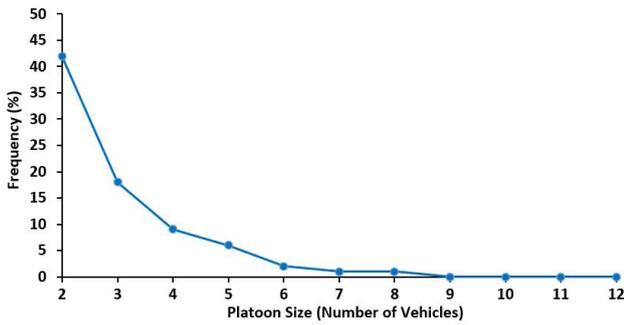


Fig. 10 Frequency of platoon size when the LCV is a platoon leader

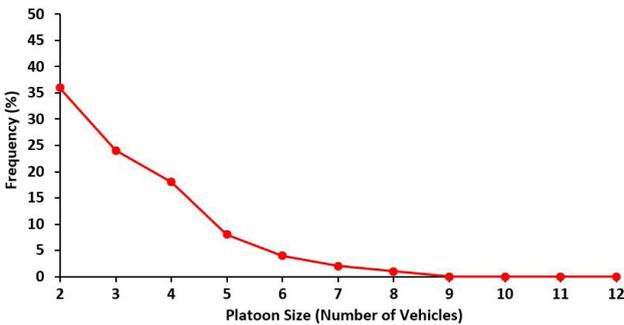


Fig. 11 Frequency of platoon size when the MCV is a platoon leader

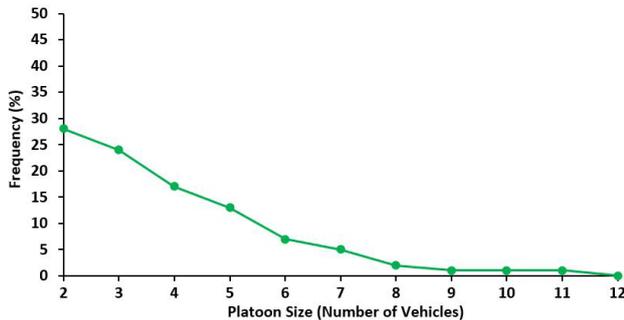


Fig. 12 Frequency of platoon size when the HCV is a platoon leader

As the CV's size increases, the critical leading time headway increases, and as the leading time headway increases, more vehicles will be included in platoons, increasing the platoon size. Hence the platoon size of the traffic with MCV as a platoon leader is more than LCV as a platoon leader, as illustrated in Fig. 11.

The small platoon formation frequency is noted to be less when the HCV is the platoon leader, as illustrated in Fig. 12. In comparison, the platoon size is larger when the HCV is a platoon leader due to their higher impedance. Also, the interactions between the follower vehicles with respect to the HCV are much influenced compared to MCV or LCV.

In summary, it can be inferred that the vehicles joining the platoon are higher when the HCV is a platoon leader. Hence, the HCV type of platoon leader had a relatively significant impact on the traffic environment. Moreover, the

use of a large critical leading time headway resulted in large platoon sizes. However, the frequency of the large platoon size was noticed to be low. At the same time, the large platoon size diminished for the LCV type of CV as a platoon leader. Because, as the critical leading time headway decrease, fewer vehicles will be included in platoons. Hence the small vehicle platoons increase as the critical leading time headway decrease. Conversely, the large critical leading time headway value resulted in large platoon sizes.

6.4 Platoon speed and platoon size for different CV types

Figs. 13–15 illustrate the platoon speed with respect to the platoon size in mixed traffic when the LCV, MCV, and HCV are platoon leaders.

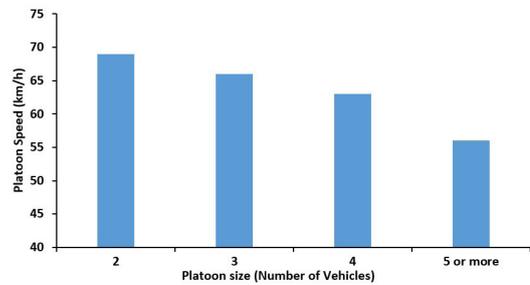


Fig. 13 Platoon speed for various platoon sizes when LCV is a platoon leader

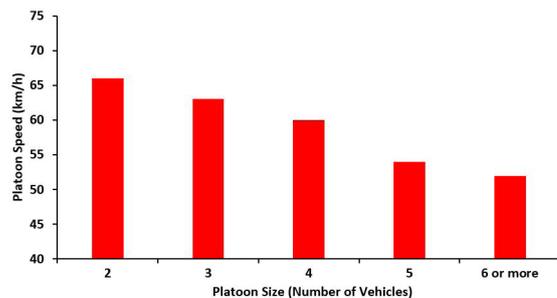


Fig. 14 Platoon speed for various platoon sizes when MCV is a platoon leader

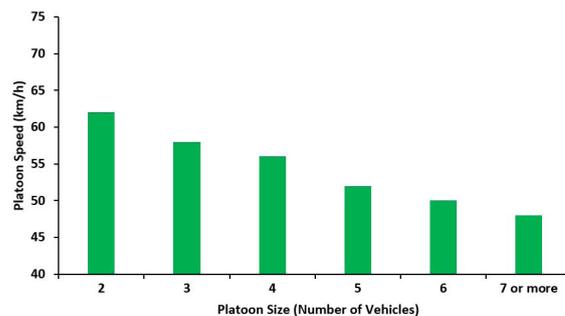


Fig. 15 Platoon speed for various platoon sizes when HCV is a platoon leader

The platoon speed for the small platoon size is higher than that for the large platoon size when LCV, MCV, and HCV are platoon leaders. However, the platoon speed at a small platoon size was found to be lower for MCV and HCV type of CV as a platoon leader compared to LCV type of CV as a platoon leader. This may be attributed to being due to the speed characteristics of the MCV and HCV and their impedance on the following vehicles in the mixed traffic platoon. The MCV or HCV usually travel at a slower speed due to their self-weight and heavier loads. Further, due to inter-vehicular interactions of vehicles within the platoon, the speed of the platoon decreases, leading to an increase in the size of the platoon.

From this analysis, it can be inferred that if the platoon leader is a large-sized slow-moving vehicle, the following vehicles in the platoon will be traveling at a much slower speed than their desired speeds. The effect of a large-sized slow-moving platoon leader intensifies the following vehicles to join the platoon. Hence, the lower the platoon leader's speed, the lower is the entire platoon speed, and the larger the platoon size.

6.5 Traffic flow characteristics analysis under mixed traffic platooning conditions

Platooning occurs primarily because of the disparity in vehicle speed. There is an adverse effect of the CV types on the traffic performance, which affects the speed-flow-density ($v-q-k$) characteristics of the mixed traffic stream. A CV traveling at an undesired lower speed relative to the ideal free-flow speed forms a queue that will back up the other vehicles behind it and gradually congest the highway to a certain distance. As a result, the truck behaves as a platoon leader and limits the opportunities to switch between the lanes to gain speed for other vehicles (Roh et al., 2017). This condition gets severe when two-truck-led platoons occupy each lane during a high traffic volume and when the percentage of the truck is higher (Zhou et al. 2018).

In our case, it is the movement of a CV type operating at a speed slower than the desired traffic speed. The operation of LCV, MCV, and HCV (as leader vehicles) at speeds below the desired speeds on the traffic lanes often leads to platoons' formation and disrupts the regular traffic flow. Due to this form of obstruction, the steady-state traffic characteristics change, and a new traffic regime is formed. The traffic regime with no platoon formation is referred to as regime A and the traffic regime with platoon formation is referred to as regime B. To understand the effect of CVs on the traffic stream characteristics,

the vehicle-type-specific (based on CV platoon leader) speed-flow-density characteristic analysis was carried out using the GLM, which is discussed in the subsequent sub-subsections.

The development of speed-flow-density plots for different CV types as platoon leaders under platoon characteristics was carried out using GLM equations as shown in Eq. (1). The speed at capacity, density at capacity, and the maximum traffic flow (capacity) were estimated using Eqs. (2)–(4).

$$V = V_f \times [1 - (K/K_j)] \tag{1}$$

$$V_o = V_f / 2 \tag{2}$$

$$K_o = K_j / 2 \tag{3}$$

$$Q_{max} = (V_f \times K_j / 4), \tag{4}$$

where

V = traffic speed in km/h

V_f = free-flow speed in km/h

V_o = speed at capacity in km/h

K = traffic density in vehicle/km

K_j = jam density in vehicle/km

K_o = density at capacity in vehicle/km

Q_{max} = maximum traffic flow in vehicle/h.

The GLM is used in this study as it considers the cumulative behavior of traffic, including speed, flow, and density characteristics. The GLM provides a more realistic characterization of traffic behavior as it represents the local conditions and situations in a more accurate manner. Besides, the GLM is used due to its low computational complexity and simplicity.

6.5.1 Macroscopic traffic flow characteristics under regime A and regime B with LCV as a platoon leader

To measure the impact of a CV type on the traffic flow, the traffic characteristics of regimes A and B are compared. Regime A represents the traffic characteristics of the non-platoon vehicles moving ahead of an LCV. Regime B represents the traffic characteristics of the platoon vehicles moving behind the LCV (platoon leader) with critical leading time headway less than or equal to 2.5 s. The speed-flow-density ($v-q-k$) characteristics plots are developed, representing regime A and regime B. The speed-density ($v-k$) plot was represented by a linear function, while a parabolic function represented the speed-flow ($v-q$) plot and flow-density ($q-k$) plot. The speed-flow-density plots

under regime A and regime B and the respective threshold drop in the speed at capacity, density at capacity, and traffic capacity are illustrated in Fig. 16.

Compared to regime A, the regime B traffic characteristics indicate a substantial decrease in the speed-flow-density values. The summary of the results is presented in Table 2,

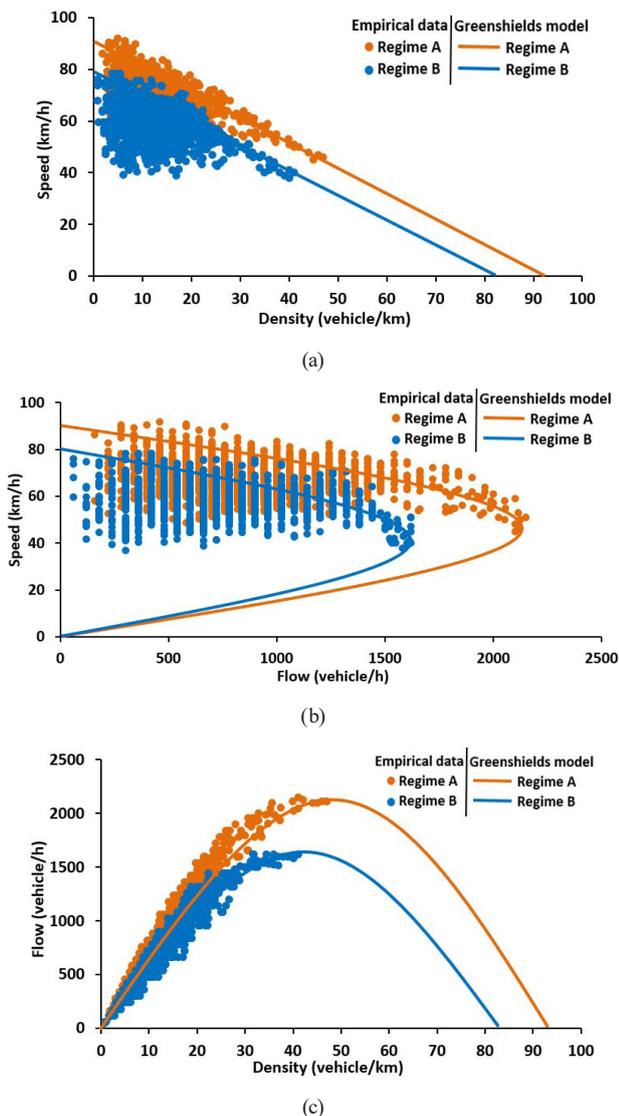


Fig. 16 Speed-Flow-Density relationship diagrams under regime A and regime B with LCV as a platoon leader, (a) $v-k$ plot, (b) $v-q$ plot, (c) $q-k$ plot

which reveals that the speed at capacity decreases from 46 km/h to 40 km/h, resulting in a 12.1 percent reduction when LCV was a platoon leader. Meanwhile, the density at capacity decreases from 47 vehicle/km to 41 vehicle/km, resulting in an 11.8 percent reduction. Eventually, the traffic capacity decreases from 2116 vehicle/h to 1640 vehicle/h resulting in a 22.5 percent reduction. This effect occurs maybe because of the movement of the LCVs in the high-speed lane at a speed slower than the desired stream speed. The LCV (platoon leader) operates at a speed slower than the desired highway speed due to their inferior operational characteristics. This causes difficulties in the maneuverability of the vehicles behind the LCV, leading to a reduction in the stream speed, flow rate, and traffic density.

6.5.2 Macroscopic traffic flow characteristics under regime A and regime B with MCV as a platoon leader

The speed-flow-density relationship plots are developed for the same proposed concept of platooning phenomena with MCV operating as a platoon leader in regime B, which is illustrated in Fig. 17.

It can be seen from Table 2 that the speed at capacity drops from 45 km/h to 36 km/h, resulting in a 15.3 percent of speed reduction. Meanwhile, the density at capacity drops from 43 vehicle/km to 37 vehicle/km resulting in a 15.1 percent density reduction. This is because some of the vehicles behind the MCV (platoon leader) have trouble identifying gaps to change to another lane, resulting in a decrease in speed before the entire platoon has dispersed on the highway. Subsequently, the traffic capacity drops from 1828 vehicle/h to 1314 vehicle/h resulted in a 28.1 percent reduction in traffic capacity. A distinctly higher percentage decrease in speed at capacity, density at capacity, and traffic capacity are observed when the MCV operates as a platoon leader compared to when the LCV operates as a platoon leader. The results show that MCVs' movement disrupts the speed and flow of all other vehicles driving on the highway. This is attributed to being due to the frequent formations of the platoons by the MCVs while

Table 2 Traffic flow parameters under regime A and regime B

Traffic Parameter	LCV as a platoon leader			MCV as a platoon leader			HCV as a platoon leader		
	Regime A	Regime B	Percentage Reduction (%)	Regime A	Regime B	Percentage Reduction (%)	Regime A	Regime B	Percentage Reduction (%)
Speed at capacity (V_o) (km/h)	46	40	12.1	45	36	15.3	41	33	19.3
Density at capacity (K_o) (vehicle/km)	47	41	11.8	43	37	15.1	42	34	19.0
Traffic capacity (Q_{max}) (vehicle/h)	2116	1640	22.5	1828	1314	28.1	1743	1139	34.7

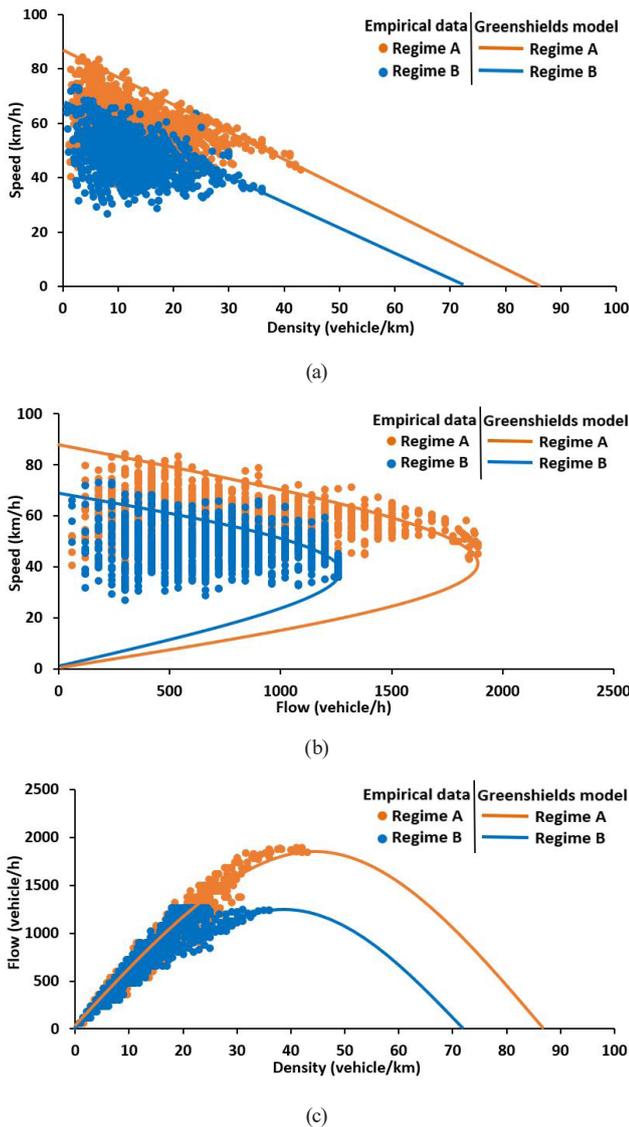


Fig. 17 Speed-Flow-Density relationship diagrams under regime A and regime B with MCV as a platoon leader, (a) $v-k$ plot, (b) $v-q$ plot, (c) $q-k$ plot

acting as platoon leaders due to their relatively higher composition among the CV types. Additionally, the impact of MCV on traffic characteristics is due to the larger size and differences in vehicle performance and driving nature.

6.5.3 Macroscopic traffic flow characteristics under regime A and regime B with HCV as a platoon leader

The speed-flow-density characteristic with the HCV as a platoon leader in regime B indicates a significant drop compared to the speed-flow-density values in regime A as illustrated in Fig. 18.

Table 2 shows that when the HCV operates as a platoon leader, the speed at density drops from 41 km/h to 33 km/h, resulting in a 19.3 percent reduction. Meanwhile, the density

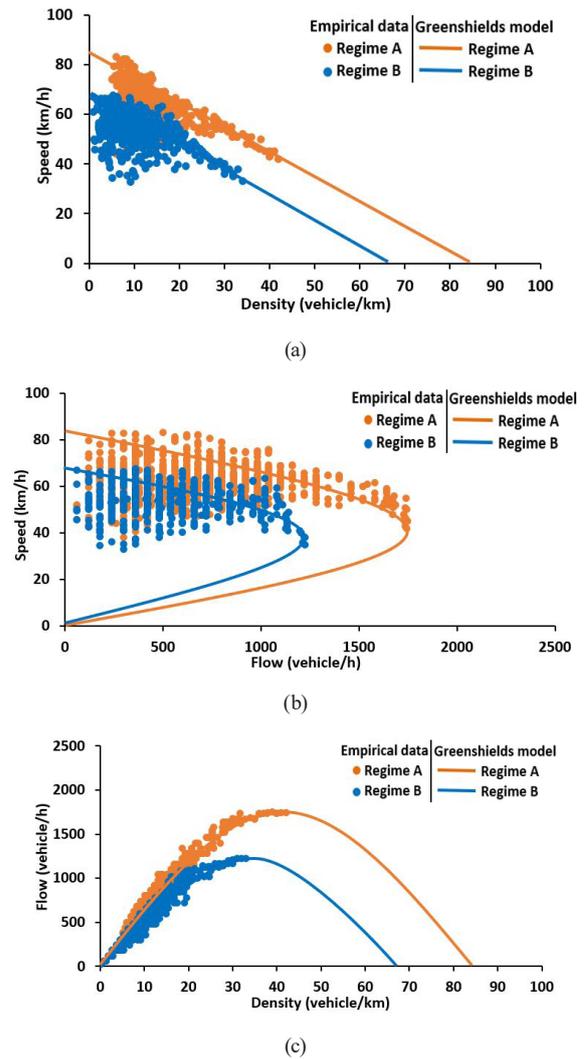


Fig. 18 Speed-Flow-Density relationship diagrams under regime A and regime B with HCV as a platoon leader, (a) $v-k$ plot, (b) $v-q$ plot, (c) $q-k$ plot

at capacity decreases from 42 vehicle/km to 34 vehicle/km resulting in a 19.0 percent reduction. Eventually, the traffic capacity drops from 1743 vehicle/h to 1139 vehicle/h resulting in a 34.7 percent traffic capacity reduction.

The characteristics of this regime (regime B) may be attributed to being due to the difficulties faced by the following vehicles in overtaking HCVs because these HCVs are larger and longer compared to other classes of vehicles. Subsequently, from an operational point of view, a vehicle that is blocked by slow-moving HCVs follows the latter for a certain distance until it finds an opportunity to pass through. Hence, the platoon is formed in case of inadequate overtaking opportunities, and the vehicles travel in the platoon with speed impedance. Eventually, these regime characteristics reduce the speed and flow rate, reducing highway capacity. Therefore, it can be inferred

that HCVs have a greater impact on the speed-flow-density characteristics of the traffic due to their lower maneuverability and acceleration/deceleration characteristics compared to other classes of CVs.

7 Discussions

As can be observed, the impact of the CVs on the speed and flow of traffic is substantially high. Consequently, density reduction is also seen in the traffic environment due to the less access control to the vehicles, which in turn has led to the conditions of reduction in highway capacity. However, when comparing the different CVs classes, the impact of HCVs was found to be higher than the impact of any other type of CV, such as LCVs and MCVs. The speed-flow-density characteristic metrics showed that the vehicles impeded by HCVs experienced the highest reduction in speed, density, and capacity. Nevertheless, irrespective of the type of CV, the effect of CVs has caused localized congestions that are hard to vanish. Additionally, the platoon formation by the CVs affects the driving behavior of other vehicles due to their physical dimensions, speed variation, differential inter-vehicular distance and timing, and lower operating capabilities. Thus, without any doubt, it can be said that the presence of these different types of CVs and their mixed traffic platoon formation has a significant impact on the traffic flow characteristics of highways.

8 Summary and conclusions

The present study demonstrates the effect of different CVs on the traffic speed, density, and capacity of Indian highways from a macroscopic point of view. Based on the analysis, the use of 2.5 s, 3.0 s, and 4.0 s as the critical leading time headway values when the LCV, MCV, and HCV, was platoon leader, respectively, was deemed appropriate to ensure that most of the vehicles detected were in the platoon. The variation of speed and time headway was found to be proportional to the impact of CVs on four-lane level divided Indian highways. In particular, this paper has developed the speed-flow-density characteristics plots under heterogeneous traffic conditions prevailing on multi-lane divided highways. The highway capacity was estimated using the MFDs based on the GLM for each CV type as a platoon leader. This study proposed a

methodology that compares the traffic parameters under two different traffic regimes. The effects of CVs under these two traffic regimes (regime A and regime B) were examined. The platooning phenomena caused by three different CV types for conditions with localized congestion are also analyzed. The percent reduction in the traffic speed at capacity and density at capacity ranged from 12.1 to 19.3 percent and 11.8 to 19.0 percent, respectively. This reduction was associated with a traffic capacity drop ranging from 22.5 to 34.7 percent.

The analysis shows that the movement of CVs significantly influences speed, density, and capacity. The findings produced from this study put forward the results that with the change in the CV's static and dynamic characteristics, the speed, density, and capacity of the highway change and even worsen. The impact of CVs makes local congestion difficult to disappear, and traffic flow becomes more congested as the impact of CV increases. The present platooning concept reveals more comprehensively the severity of the effect of CVs on traffic flow characteristics. This methodology is extremely valuable in improving the accuracy of many traffic models for analysis and other traffic studies when a higher proportion of different CVs are present. Besides, this study's findings provide a basis for the practical development and implementation of future traffic control measures. The identified MFD patterns can help develop efficient traffic regulation and management strategies to enhance transport efficacy. These insights will be useful to traffic engineers and practitioners in studying traffic impacts due to the dominance of different CVs types. Meanwhile, the present study can be extended to a lane-based traffic characteristics analysis, including the investigations of the vehicle-to-vehicle interaction during the car-following process. The possible future work would also include the analysis of mixed traffic platoon characteristics under congested traffic conditions, especially near on and off-ramps.

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