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Assessing the impacts of heavy vehicles on traffic characteristics of highways under mixed traffic platooning conditions

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Abstract

The study aims to investigate the impact of heavy vehicles (HVs) on traffic characteristics under platoon conditions on Indian highways. Traffic volume, speed, and time headway data were gathered from different highway sections using infra-red sensors. The mean relative speed criteria were used as an indicator of variability to estimate the critical time headway. The threshold value of a critical time headway of 4 sec was determined to represent vehicles into non-platoon followers and platoon followers. The speed-flow-density model curves were developed for two different traffic regimes, one without platoons and the other with platoons created by the HVs. The results show that under platoon conditions, the speed at capacity, density at capacity, and traffic capacity reduced by 11.2%, 12.5%, and 22.3%, respectively, compared to non-platoon conditions. Additionally, the average travel time and travel delay increased by 18.1 s/km and 12.7 s/km, respectively. The study's findings emphasize the importance of considering platoon dynamics under the influence of HVs to better understand their impact on traffic characteristics.

Keywords: Heavy Vehicle, Critical Time Headway, Platoon, Congestion, Highway, Mixed Traffic.

1. Introduction

Freight transportation is pivotal in logistical activities. With the increase in the population and land-use activities, traffic congestion on the highways has increased. Additionally, Heavy Vehicles (HVs) plying in the mixed traffic has caused variations in the traffic flow, resulting in unstable conditions. Thus, traffic congestion has a significant effect on individual users' journey speed and time. The HVs have several features that enable them to operate at various speed levels. The HVs' resistance impedes the following vehicles (Moridpour et al. 2010). Under such conditions, most vehicles chose to either pass by or lag in the adjacent lanes instead of making side-to-side movement. Therefore, the platoons are generated in the traffic stream. Highway traffic suffers from

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platoon driving because of the impedances caused by HVs. The platoon generated by the HVs affects several traffic parameters, which contributes to the incidence of congestion and severe traffic breakdowns. During critical driving conditions, truck platooning impacts traffic efficiency and safety (Faber et al. 2020, Hyun et al. 2021). The driver behavior and service quality are also affected by the complication of the HVs under platoon conditions (Sarvi, 2013). As a result, the vehicles operating under platoon conditions encountered severe traffic congestion and safety problems.

For efficient traffic operation under mixed traffic scenarios such as in India, analyzing the impact of the HVs platooning phenomenon is crucial. The first step in such an endeavor is to identify a congestion metric, which will aid in selecting appropriate mitigation action. For this purpose, the critical time headway was calculated based on the mean absolute relative speed and time headway. The critical time headway value representing the point of conjecture was used to define the platoon and non-platoon vehicles. Further, the traffic stream characteristics such as the speed, flow, and density were analyzed for the platoon and non-platoon conditions. The measures to quantify the congestion status of the traffic have been calculated based on congestion indices. The paper is organized as follows: literature review and data collection where the traffic data acquisition technique, study sections and field set up, data processing, and vehicle composition are explained. Later the estimation of critical time headway is carried out. The traffic data analysis presents the speed, flow, density estimation, speed, travel time, and delay calculation, then determines congestion indices and time headway and space headway under platoon and non-platoon conditions. Finally, the conclusion is given.

2. Literature review

Traffic congestion may be defined as the travel time or a delay that exceeds what would ordinarily be expected under free-flow conditions. Many studies used different metrics for describing congestion, such as traffic speed (Anjaneyulu and Nagaraj, (2009), Rao and Rao (2016), Quang and Bae (2021)), traffic delay (Anwar 2010), travel time (Samal et al. 2020), traffic density (Padiath et al. 2009) and traffic volume (Chalumuri et al. 2007). Some studies even developed indices like buffer time (BT) and planning time index (PTI) (Susilawati et al. (2010)), buffer time index (BTI) and PTI (Bharti et al. (2013)), travel time index (TTI) (Singh et al. 2019), speed performance index (He et al. 2016) and reliable buffer index (RBI) (Chepuri et al. 2018). Recently, Gore et al. (2021) identified the congestion thresholds based on vehicle Level of Service (LoS) criteria.

The high levels of congestion due to the HVs affect the accessibility and mobility of traffic. Surasak et al. (2001) emphasized the importance of platoon characteristics for determining the performance measure, i.e., LoS in terms of platoon rate, platoon size, percentage of following vehicles. The critical headways were identified as 3 s and 4 s for passenger cars and HVs as followers in a platoon, respectively. They observed that only the type of follower vehicle in a platoon influences relative speed while the kind of platoon leader has almost no effect. Gao et al. (2020) evaluated the impact of large vehicles on the expressway speeds. They found the relationship between average traffic speed and the mixing rate of large vehicles to be negative logarithmic linear. The results indicated that large vehicles reduce traffic flow speed. Singh and Santhakumar (2021a) investigated the impact of different HVs on traffic speed and flow of highways. The authors evaluated the traffic speed and flow characteristics under the influence of Medium Commercial Vehicle (MCV), Heavy Commercial Vehicle (HCV), Multi-Axle Vehicle (MAV) as platoon leaders. They found that the speed and flow decrease over time due to the different HVs' platoon and concluded that the MCV type of HV has a considerable effect on the median lane traffic while the MAV has a significant impact on the kerb lane traffic. Alecsandru et al. (2012) revealed that the percentage of HVs like trucks significantly impacts the Passenger Car Unit (PCU) of the HVs under different demand levels, traffic compositions, and compliance ratios.

Lu et al. (2020) analyzed the impact of trucks at different traffic volume levels by combining headway-based and delay-based algorithms. They indicated that the trucks have a significant effect on highway capacity under unbalanced conditions. Himes and Donnell (2010) developed speed models using the simultaneous equations for each traffic lane. The study results affirmed that the effect of HVs during congestion is more significant than its effect during free-flow conditions. Singh and Santhakumar (2021b) have also analyzed the impact of multi-class commercial vehicles on the traffic characteristics of multi-lane highways in India. The study found that the average flow rate decreased with an increase in the percentage of multi-class commercial vehicles. The traffic capacity decreased by 24.25% under the 30% penetration rate of multi-class commercial vehicles.

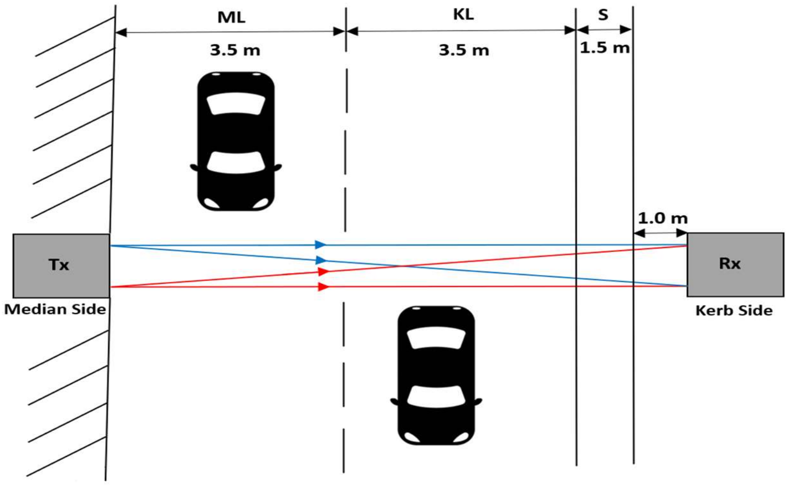
From the existing studies, we noticed that there had not been much emphasis on analyzing the effect of platoons on the traffic characteristics of multi-lane highways in the Indian context. In addition, there tends to be a gap of knowledge with a metric for defining highway traffic congestion under platooning conditions. With this motivation, this study aims to determine the congestion metrics and evaluate the traffic parameters that can be utilized to quantify platoon traffic under the influence of HVs.

3. Data Collection

Using high-resolution video cameras, collecting traffic data for long hours and throughout the day and night-time is challenging, tedious, and expensive. However, the advancement of modern technology has created new avenues and opportunities to address this issue. Especially, the Infra-Red (IR) sensor technologies have brought a significant change in the collection of traffic data (Singh et al. 2020b).

3.1 Traffic Data Acquisition Technique

The IR sensor device, named Transportable Infra-Red Traffic Logger (TIRTL), is a portable and automated vehicle detector device. It works on IR sensor-based technology to record various traffic-related parameters such as time headway, speed, vehicle count, classified traffic volume, and vehicle dimensions. Both transmitter (Tx) and receiver (Rx) are placed across the highway sections, as shown in Figure. 1. The 12.0 Volt batteries are the power source for Tx and Rx. The Tx generates the IR beams to detect the traffic. The Rx is used to detect the disturbance caused by the passing vehicle wheels. The Rx is connected to a laptop device through an RS232 serial port to access the system interface and store the data file in .csv format. The Tx and Rx are aligned to be less than 150 mm above the road surface, ensuring that the IR beams do not clip the vehicle bodies. Figure. 1 also illustrates the geometric features of the highway sections.



Note: ML-Median Lane, KL-Kerb Lane, S-Shoulder, Tx-Transmitter, and Rx-Receiver.
Figure 1: Schematic representation of the vehicle detection mechanism.

The IR sensor device records four beam events generating eight timestamps to derive the vehicle speed, time headway, spacing, clearance, and gap for any detection. Any vehicle crosses the IR sensor detection, the order of beam events determines the vehicle travel direction. The use of the "free-flowing" condition option optimizes vehicle detection for different traffic conditions (Singh et al. 2020a). The entry and exit of the vehicle make and break the beam events, which are measured as time intervals to determine vehicle positions. The speed and time headway are recorded when each vehicle crosses the IR sensor device.

3.2 Study Sections and Field Set up

The mid-block section of the National Highways (NH) in the southern part of India was chosen as the study section as per the Indian Highway Capacity Manual (Indo-HCM: 2017). These NH test sections did not have any crosswalks for pedestrians, median openings for making U-turning movement and were free from any other such side frictions. The data was collected by setting up the IR sensors across the traffic flow in one direction of the four-lane divided highway sections. This time set was adopted to collect a higher number of HVs in the traffic stream. Another primary motive for collecting the traffic data during the day and night-time was to capture maximum variation in vehicle and driver characteristics. Extraction of the traffic speed and volume data was carried at every 5-minute interval as it provides the realistic estimation of hourly traffic volume. Also, the disaggregated traffic speed has a large variance. Hence, the 5-minute intervals of the traffic data are used to express the speed-flow-density relationships. The field snapshot of the IR sensor device's setup across the NHs is depicted in Figure. 2.

3.3 Data Processing and Composition of Vehicles

The mid-block section of the NHs carried various types of vehicles. The traffic data was collected for 16 hours (between 15:00 h to 07:00 h) on each NH section. The idea behind choosing such time of data collection was to capture the mixed traffic platooning phenomenon created by the HVs.

(a) NH-32

(b) NH-38

(c) NH-48

(d) NH-83

Figure 2: Field snapshot of the IR sensor device set up across the NHs.

Since the traffic data was collected on inter-city highways, the HVs traffic on the weekends would be more compared to normal day traffic. So, the traffic data was collected on starting of weekends (Friday and Saturday) and starting on weekdays (Sunday and Monday). Further, the data was processed and extracted at every 5-minute aggregation to minimize randomness in traffic and reduce errors in computations. The traffic composition is shown in Table 1.

Table 1: Traffic compositions at various NH sections.

Vehicle type	NH-32 (%)	NH-38 (%)	NH-48 (%)	NH-83 (%)
2-Wheeler (2W)	20.7	25.4	24.5	22.2
3-Wheeler (3W)	3.0	3.2	3.4	3.8
Small Car (CS)	25.7	30.2	26.3	24.1
Big Car (CB)	17.4	14.3	18.3	15.6
Light Commercial Vehicle (LCV)	5.6	3.2	6.8	7.5
Medium Commercial Vehicle (MCV)	15.4	14.1	10.2	12.3
Heavy Commercial Vehicle (HCV)	6.7	5.4	5.8	8.2
Multi-Axle Vehicle (MAV)	5.5	4.2	4.7	6.3

On average, the CSs held the highest traffic composition of 26.6%. The 2Ws had an average traffic composition of 23.2%, followed by CBs with 16.4%. The 3Ws held the lowest average traffic composition of 3.4%. It is to be noted that the LCVs include light-weight and small-sized commercial goods vehicles, which carried an average composition of 5.8%. The MCVs category included the two-axle trucks/buses, while the HCVs category included the three-axle trucks/buses. Other commercial vehicles with four-axles, five-axles, and six-axles or more are considered in one vehicle type category as MAVs. The MCVs, HCVs, and MAVs comprise the HVs class whose traffic composition varied from as low as 20.7% to as high as 27.6%. On average, the HVs were 24.7% of the total traffic. Further, the traffic volume across the NHs varied between 250 vph to 3000 vph.

4. Method: Estimation of Critical Time Headway

Time headway is defined as the time lapse between the front of the previous vehicle to the front of the present vehicle crossing the IR sensor beams. The usually assumed average time headway values for defining the critical time headway do not capture the complete traffic complexities of space-time. Using the same one with different traffic conditions would be unfair since the average time headway values are not susceptible to various traffic flow or traffic density conditions. The method to classify vehicles into non-following vehicles or following vehicles has a crucial effect on platoon analysis. Therefore, an accurate measure of traffic parameters is essential to deal effectively with any traffic problems associated with the influence of HVs (Singh and Santhakumar 2021c). The most accepted parameter is time headway, which is usually called critical time headway, used to identify platoon vehicles. The variation of the speed of the platoon was established at a rationale level to select the optimal value of the critical time headway so that traffic data provides adequate and exact platoon information. The criteria for classifying vehicles into non-following vehicles or following vehicles were based on the mean absolute relative speed and time headway criteria. This method was used as an Indicator of Variability (IoV) to estimate the critical time headway.

The IoV considers the effects of the variations of platoon speeds and the magnitude of the time headways. The adopted IoV method has the advantage of normalizing the data, thereby reducing the inherent variability in speeds and time headway deviations. This study mainly focuses on the impact assessment of the HVs on the traffic characteristics under platooning conditions; hence the HV types such as MCVs, HCVs, and MAVs are considered as the platoon leaders, and their following vehicles' mean absolute relative speed and time headway value is used to determine the critical time headway value. The HVs (as the platoon leaders) are taken into account based on the degree of impedance created by these vehicle types. The mean absolute relative speed is defined as the speed difference between the vehicles following each other, which is nothing but the relative speed of vehicles moving in the same direction. For ease in computations, absolute values of the mean speed are taken. The mean absolute relative speed and time headway were plotted at an interval of 1.0 seconds up to 15.0 seconds. Figure. 3. illustrates the mean absolute relative speed values corresponding to different time headway values for platoon identification.

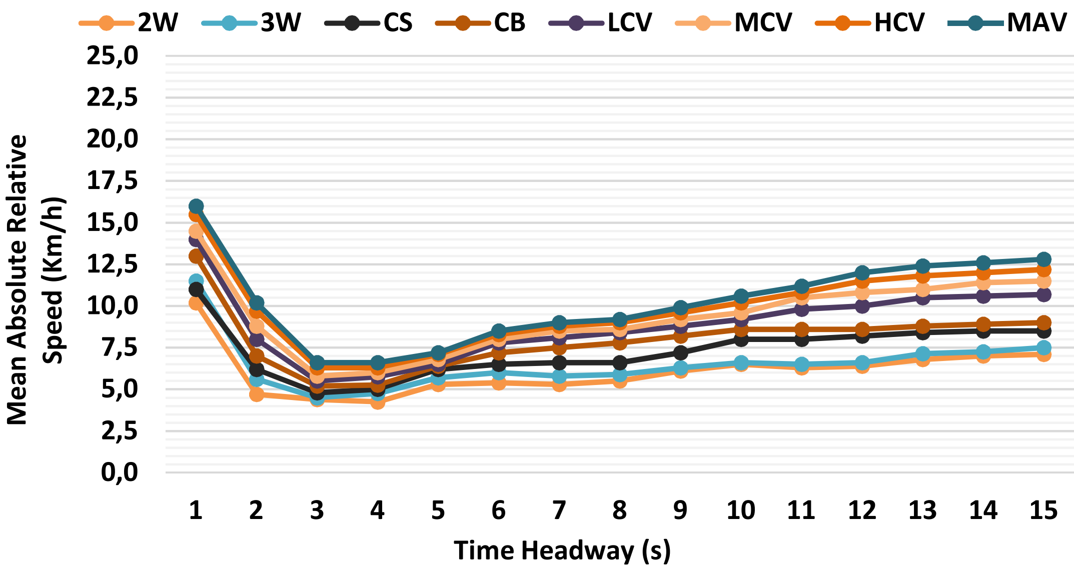


Figure 3: Identification of critical time headway for different vehicle types.

Figure 3 shows that the mean absolute relative speed values decrease as the time headway increases. The vehicles attain a clear minimum mean absolute relative speed when the time headway threshold is in the range of 3.0 s to 4.0 s for HVs as a platoon leader. This point range generally represents the restricted condition where all vehicles are forced to compromise their speed to follow the platoon leader (HV). It is also seen that most of the vehicles attain a constant mean absolute relative speed in the time headway range between 3.0 s and 4.0 s when HV is a platoon leader. Thus, a critical time headway of 4.0 s is adopted for defining the platoon criteria.

Beyond this time headway value, the vehicle's mean absolute relative speed is almost increasing and tends to be constant after a specific time headway value. This critical time headway seems logically plausible as it is within the range of the commonly assumed saturated time headway (3.0 s) and the ideal critical time headway (5.0 s). Consequently, 4.0 s is utilized as the critical time headway for platoon determination in the subsequent analysis. In fact, a convoy of vehicles traveling at a time headway less than the critical time headway is considered part of a platoon. The vehicles with time headway greater than the critical time headway were deemed to be free vehicles. As time headway value exceeds the threshold value, the interaction of vehicles decreases, and therefore, vehicles are free-flowing. This condition represents that the drivers do not tailgate the vehicles in front of them as they ride at their desired speed.

5. Traffic Data Analysis

5.1 Characterization of Mixed Traffic Platoon

Congestion can be related to the excess of vehicles on a highway pathway at a specific time, which results in speeds that are usually much slower than normal or free-flow speeds. In addition, platoon characteristics on a multi-lane highway vary significantly from those on a two-way two-lane highway for a variety of reasons. This includes the possibility of overtaking or shifting lanes and the influence of the opposite lane vehicles. In general, the driver of a trailing vehicle may feel more restricted than the driver of a leading vehicle (Surasak et al. 2001).

Under two different traffic regimes, viz. (a) non-platoon conditions and (b) platoon conditions, the traffic parameters were analyzed.

- A non-platoon condition is the traffic regime a minute before the HV arrives at an IR sensor detection point, implying that most vehicles are independent of this HV (platoon leader).
- On the other hand, a platoon condition is the traffic regime a minute after the HV arrives at an IR sensor detection point, implying that the following vehicles are impeded by the HV (platoon leader).
- The HVs are the major platoon leaders, and the following vehicles are vehicles of different categories. This type of platooning condition is referred to as mixed traffic platooning condition, prevalent in Indian traffic conditions.
- Further, in this analysis, the platooning characteristic is explained by assuming that the vehicles traveling ahead of an HV (platoon leader) are free-flowing vehicles unless they are part of the platoon. This traffic regime is referred to as a non-platoon condition.
- The vehicles which have the time headway of up to 4.0 s and follow any HV (platoon leader) are assumed to be part of the platoon. This traffic regime is referred to as a platoon condition.

The speed-flow-density model curves were developed for these two traffic regimes. Further, we consider speed, travel time, and travel delay as the performance indicators to compute the traffic efficiency under the non-platoon and platoon traffic conditions. Additionally, three types of indices, viz. speed index (I_S), travel time index (I_{TT}), and congestion index (I_C), are developed to evaluate the traffic conditions of the highways.

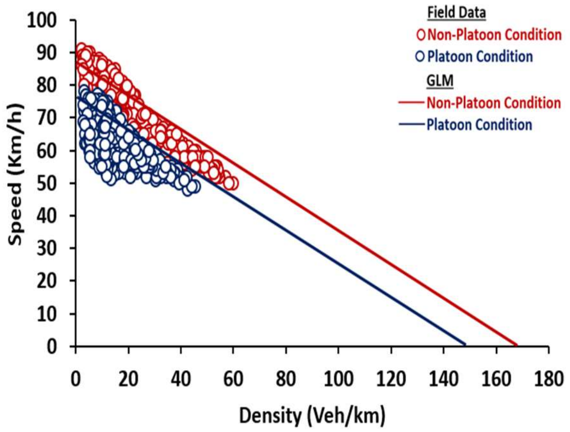
5.2 Analysis of Speed-Flow-Density

The speed, flow, and density are some characteristics with which the traffic behavior can be assessed. For the development of speed-flow-density plots under the non-platoon and platoon conditions, field data was used. Because the field observed data did not provide an elaborate and accurate pattern of the macroscopic fundamental relationship diagrams, three different single-regime traffic flow models, namely, Greenshields Linear Model (GLM) (Greenshields et al. 1935), Greenberg Model (GBM) (Greenberg, 1959), and Underwood Model (UWM) (Underwood, 1961) have been used. The model equations and the best-fitted models chosen based on the goodness-of-fitness value are presented in Table 2.

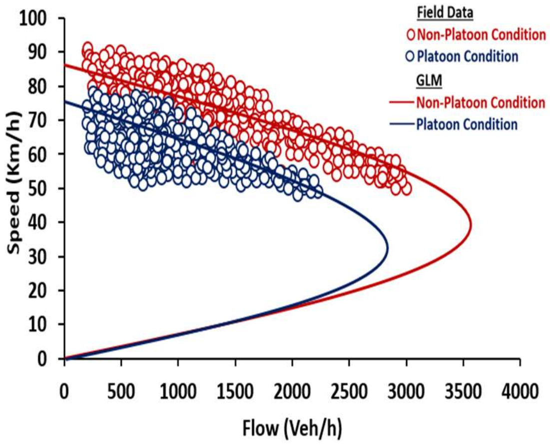
Table 2: Results of traffic stream models under non-platoon and platoon conditions.

Traffic condition	*Non-Platoon Condition*	*Platoon Condition*
GLM		
Model equation	$v = 85.1 - 0.5065 * k$	$v = 75.6 - 0.5143 * k$
R-Squared value	0.966	0.971
GBM		
Model equation	$v = 103.7 - 10.52 * \ln(k)$	$v = 92.4 - 11.56 * \ln(k)$
R-Squared value	0.902	0.916
UWM		
Model equation	$v = 86.3 * e^{-0.0079*k}$	$v = 76.4 * e^{-0.0085*k}$
R-Squared value	0.948	0.953

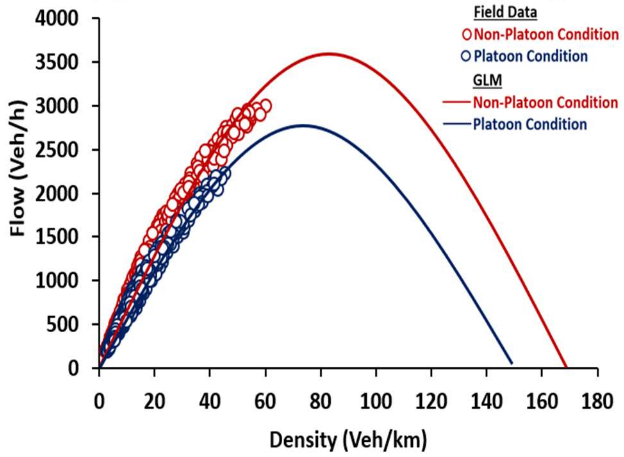
For selecting the best fit model, the coefficient of determination (R-Squared) value was used. The GLM was reported to be the most accurate in explaining the relationship between speed and density based on the outcome of the goodness-of-fitness test. As seen in Table 2, the fitted model achieved the highest R-Squared value of 0.966 and 0.971 under the non-platooning and platooning conditions, respectively. The outperformed models were adopted to develop the macroscopic fundamental diagrams. Figures. 4. (a), (b), and (c) illustrates the traffic characteristics through a macroscopic fundamental diagram under non-platooning and platooning conditions.



(a) Speed-Density plot



(b) Speed-Flow plot



(c) Flow-Density plot

Figure 4: Macroscopic fundamental diagrams under non-platooning and platooning conditions.

A platoon is made up of slow-moving vehicles. The platoon generating vehicle is called the platoon leader. The presence of slow-moving vehicles forms moving bottlenecks in the traffic stream. The measures non-platoon condition and platoon condition are used to comprehend the loss in the traffic maneuverability. Speed-flow-density characteristics are the essential traffic parameters in traffic analysis. Speed-flow-density plots provide an understanding of the vehicle's quality of service in the traffic stream. A decrease in the speed-flow-density characteristics directly indicates a decrease in the degree of freedom of vehicles. Table 3 summarizes the estimated traffic parameters under non-platooning and platooning conditions.

Table 3: Traffic parameters under non-platooning and platooning conditions.

Traffic Parameter	*Non-Platoon Condition*	*Platoon Condition*	*Difference*	*% Reduction*
Free Flow Speed (v_f) (Km/h)	85.1	75.6	9.5	11.2
Jam Density (k_j) (Veh/Km)	168	147	21	12.5
Speed at Capacity (v_c) (Km/h)	42.6	37.8	4.8	11.2
Density at Capacity (k_c) (Veh/Km)	84	73.5	10.5	12.5
Traffic Capacity (q_{max}) (Veh/h)	3574	2778	796	22.3

The analysis results showed a distinct difference between the non-platoon condition and platoon condition parameters. From Table 3, it can be observed that there is a significant difference in the estimated traffic parameters under the non-platooning and platooning conditions. This difference is due to the impedance generated by the HVs in the traffic mix. It can be seen that the speed is affected because of the interaction of various classes of vehicles impeded by the HVs. This led to the free-flow speed of the traffic under platooning conditions being reduced by 11.2% compared to the free-flow speed of the traffic under non-platooning conditions.

Meanwhile, the jam-density in the platoon condition reduced by 12.5% compared to that under non-platoon conditions. An increase in the number of HVs platoon causes obstacles to the other vehicles. Therefore, both free-flow speed and jam-density reduce. Additionally, the difference in the vehicles' mechanical performances and operational efficiency causes the platoons to sustain longer and cause frequent localized congestion to occur.

Increasing vehicle speed lowers the speed disparity between platoons and neighboring traffic. But this applies to a certain extent of traffic conditions such as free-flow conditions. Under capacity conditions, the traffic exhibits different scenarios. The speed at capacity and density at capacity under platoon conditions were estimated to be 11.2% and 12.5%, respectively, lower than the speed at capacity and density at capacity under non-platoon conditions.

Several platoons in the traffic stream cause more critical interactions with the surrounding vehicles and decrease the speed and flow rate in different lanes (Faber et al., 2020). The flow is mainly affected by the speed of the vehicles. The speed-flow reduction caused by the HVs platoons governs the traffic performance and operational quality. Eventually, under the platooning condition, we observed the traffic capacity to reduce from 3574 Veh/h to 2778 Veh/h, thereby showing a significantly higher percentage of capacity reduction of 22.3% compared to the non-platoon condition. This proves that the presence of HVs platoons hinders mainstream traffic.

5.3 Analysis of Speed, Travel Time, Delay

The basic measurements used to quantify congestion are travel speed, travel time, and delay. Congestion in traffic leads to a loss of time. Delay in the traffic is caused due to the time difference. Under the platooning condition, the delay effect is due to the obstruction created by the large-sized HVs to other smaller vehicles. Hence these impeded vehicles tailgate the impeder vehicles till they find a sufficient gap to change lanes, overtake, and pass by. The average travel delay is estimated using Equation (1) shown below.

$$d_a = t_a - t_f = \left(\frac{3600}{v_a}\right) - \left(\frac{3600}{v_f}\right) \quad (1)$$

where,

d_a = average travel delay per unit distance (s/Km),
t_a = average travel time per unit distance at a given flow rate (s/Km),
t_f = free-flow travel time per unit distance (s/Km),
v_a = average speed at a given flow rate (Km/h), and
v_f = free-flow speed (Km/h)

The travel time-based measures are more adaptable in defining traffic conditions in both space and time. The travel time is an attribute of congestion that intuitively encapsulates road geometry, driving characteristics, and environmental factors. Therefore, congestion measurements derived from travel time data will aid in characterizing congestion levels and reliability. The average travel time (t_a) is the reciprocal of the average travel speed (v_a) at a given flow rate. The reciprocal of the free-flow travel speed (v_f) is the free-flow travel time (t_f). Table 4 represents the speed, travel time, and delay parameters under the two different traffic conditions.

Table 4: Speed, travel time, and delay under different traffic conditions.

Speed Parameter	*Non-Platoon Condition*	*Platoon Condition*	*Decrease by*	*% Decrease*
Free-Flow Speed (v_f) (Km/h)	85.1	75.6	9.5	11.2
Average Travel Speed (v_a) (Km/h)	50.2	40.1	10.1	20.1
Time Parameter	*Non-Platoon Condition*	*Platoon Condition*	*Increase by*	*% Increase*
Free-Flow Travel Time (t_f) (s/Km)	42.3	47.6	5.3	12.6
Average Travel Time (t_a) (s/Km)	71.7	89.8	18.1	25.2
Average Travel Delay (d_a) (s/Km)	29.4	42.2	12.7	43.3

The existence of HV platoons causes additional braking actions and increased vehicular engagement, resulting in significant speed reduction. Table 4 shows that the average speed decreases by 20.1% under the platoon condition compared to the non-platoon condition.

The speed of the platoon is related to the travel time and travel delay. Due to the speed reduction in the highway stream, the average travel time increased by 25.2%. The higher travel time spent by the vehicles under the platooning conditions indicates more chances to incur a larger impact of the HVs platoon on them. As a result, the average travel delay has increased by 43.3%. The increased effect of HVs on traffic deteriorates efficiency and safety, and often vehicles find themselves in risky situations under such platooning conditions. A breakdown at this point may lead to queuing of vehicles leading to stop and go state of traffic. Further, the impedance created by the HVs causes the increase in the free-flow travel time to increase by 12.6%. This confirms the fact that due to the interference of HVs, the speed reduces, which eventually causes an increase in travel time and travel delay. In addition, the formation of HVs platoons in the highways, especially during peak hour traffic conditions, limits the opportunities for the other vehicles, increasing the maneuvering complexity. Overall, HVs platoons in the traffic stream are adverse to traffic performance, efficiency, and safety.

5.4 Determination of Congestion Indices

Congestion is a function of a decrease in speed, which is the direct source of lost travel time. Therefore, the speed and travel time indices are necessary traffic measures that represent the state of traffic congestion which could be measured by speed and travel time. The traffic congestion index (I_C) reflects the congestion situation. It is the product of speed index (I_S) and travel time index (I_{TT}). The I_S and I_{TT} are given in Equations (2) and (3), respectively.

$$I_s = 1 - \left(\frac{v_a}{v_f}\right) \tag{2}$$

$$I_{TT} = \left(\frac{t_a - t_f}{t_f}\right) \tag{3}$$

Table 5: Index values under different traffic conditions.

Index	*Non-Platoon Condition*	*Platoon Condition*
Speed (I_S)	0.41	0.47
Travel Time (I_{TT})	0.70	0.89
Congestion (I_C)	0.29	0.42

The I_S and I_{TT} corresponding to the platoon condition is higher than that of the indices corresponding to the non-platoon condition. This denotes that the impedance of platoons on the traffic mix is higher during the platooning conditions. The I_C value of 0.42 in the platoon condition indicates severe traffic congestion ($0.40<I_C\leq 0.60$), compared to the I_C value of 0.29 in the non-platoon condition, which indicates the congestion status of traffic to be moderate ($0.20<I_C\leq 0.40$). The I_C value of ≤ 0.20 indicates mild traffic congestion. The I_C value between 0.60 to 0.80 indicates heavy traffic congestion, while I_C value >0.80 indicates very heavy traffic congestion.

5.5 Analysis of Time Headway and Spacing of Vehicles

The time headway and spacing of the vehicles are the basis for analyzing the traffic stream characteristics at a microscopic level. Vehicle time headway (h_c) is the time gap between the passage of the front ends of two successive vehicles across the IR sensor detector. Vehicle spacing (s_c) is the distance between the passage of the front ends of two successive vehicles across the IR sensor detector. The h_c and s_c at capacity conditions are determined from Equations (4) and (5), respectively.

$$h_c = \left(\frac{3600}{q_{max}}\right) \tag{4}$$

$$s_c = \left(\frac{1000}{k_c}\right) \tag{5}$$

where

h_c = Vehicle time headway at capacity (s/Veh)
s_c = Vehicle spacing at capacity (m/Veh)
k_c = Traffic density at capacity (Veh/Km) and
q_{max} = Traffic capacity (Veh/h).

Table 5 represents the h_c and s_c at capacity under the non-platoon and platoon conditions.

Table 5 Time headway and spacing under different traffic conditions.

Traffic Parameter	*Non-Platoon Condition*	*Platoon Condition*	*Increase by*	*% Increase*
Vehicle Headway at Capacity (h_c) (s/Veh)	1.0	1.3	0.3	30.0
Vehicle Spacing at Capacity (s_c) (m/Veh)	11.9	13.6	1.7	14.3

From Table 5, it can be observed that the time headway varies with changes in the traffic condition, and the percentage increment in vehicle headway obtained was 30.0%. On the other hand, the percentage increment in vehicle spacing was obtained to be 14.3%. It can be inferred that the variation in the traffic conditions significantly influences the h_c and s_c of vehicles. In general, the h_c and s_c of vehicles increased with an increase in the traffic flow and density caused by the HVs' impedance. When compared to the base condition, platoon conditions triggered by HVs have a pessimistic effect on traffic operation and safety (non-platoon condition). A larger number of such incidents may result in traffic instabilities, which could lead to dangerous situations.

6 Conclusions

This research work provides an in-depth analysis of traffic parameters considering platoon characteristics on multi-lane highways. The various traffic parameters under platoon conditions were analyzed to assess the influence of HVs on the traffic stream characteristics. Some noteworthy variations with regard to the traffic characteristics under the platoon condition compared to the non-platoon condition were also observed. Our key observation is that HVs platooning can be detrimental to operating traffic quality, safety, and mobility. The data examined from the field study revealed that there exists a more significant influence of the HVs on traffic speed, flow, and density. This impact has ultimately resulted in the increase in the travel time and delay leading to the increase in the time headway and spacing of vehicles. The traffic congestion index was estimated to be 0.42, denoting severe traffic congestion under the platooning condition. Eventually, it can be concluded that the presence and interaction of HVs platoons lower the operating characteristics and efficiency of the highways.

The present study is one of the first studies in this direction that can better evaluate platoon-based traffic flow characteristics under mixed traffic conditions. The results might help to identify strategies to reduce congestion due to HVs on the highways. For example, implementing a dedicated highway lane for the HVs to separate them from the mainstream traffic. The scope of this research is limited to four-lane divided national highways. Future research will explore other types of facilities such as six-lane or eight-lane highways, urban arterials, and sub-arterials. Additionally, the attributes of platoons will be extended to assess the impact of unexpected events on multi-lane highway networks based on simulation techniques.

References

Alecsandru, C., Ishak, S., Qi, Y. (2012) "Passenger Car Equivalents of Trucks on Four-Lane Rural Freeways Under Lane Restriction and Different Traffic Conditions", *Canadian Journal of Civil Engineering,* 39, pp. 1145-1155.

Anjaneyulu, M., Nagaraj, B. (2009) "Modelling Congestion on Urban Roads Using Speed Profile Data", *Journal of Indian Road Congress,* 70, pp. 65-74.

Anwar A. (2010) "A Study on Factors for Travel Time Variability in Dhaka City Corporation Area," *Journal of Bangladesh Institute of Planners,* 3, pp. 53-64.

Bharti, A.K., Satish, C., Chalumuri, R.S. (2013) "Performance Evaluation of Urban Arterial in Delhi Using Travel Time Reliability", *Proceedings of the Eastern Asia Society for Transportation Studies,* Taipei, Taiwan.

Chalumuri, R.S., Kitazawa, T., Tanabe, J., Suga, Y., Asakura, Y. (2007) "Examining Travel Time Reliability on Han-Shin Expressway Network", *Journal of the Eastern Asia Society for Transportation Studies,* 7, pp. 2274-2288,

Chepuri, A., Borakanavar, M., Amrutsamanvar, R., Arkatkar, S., Joshi, G. (2018) "Examining Travel Time Reliability Under Mixed Traffic Conditions: A Case Study of Urban Arterial Roads in Indian Cities", *Asian Transport Studies*, 5 (1), pp. 30-46.

Faber, T., Sharma, S., Snelder, M., Klunder, G., Tavasszy, L., Lint, L.V. (2020) "Evaluating traffic efficiency and safety by varying truck platoon characteristics in a critical traffic situation", *Transportation Research Record,* pp. 1-23.

Gao, C., Xu, J., Jia, X., Dong, Y., Ru, H. (2020) "Influence of Large Vehicles on the Speed of Expressway Traffic Flow", *Advances in Civil Engineering,* 2020, pp. 1-9.

Gore, N., Pulugurta, S.S., Arkatkar, S., Joshi, G. (2021) "Congestion Index and Reliability-Based Freeway Level of Service", *Journal of Transportation Engineering, Part A: Systems,* 147 (6): 04021027. https://doi.org/10.1061/JTEPBS.0000531

Greenberg, H. (1959) "An analysis of traffic flow", *Operation Research* 7(1), pp. 79-85.

Greenshields, B.D., Channing, W.S., Miller, H. H. (1935) "A study of traffic capacity", Proceedings of the Highway Research Board, National Research Council (USA), Highway Research Board, pp. 448-477.

He, F., Yan, X., Liu, Y., Ma, Lu. (2016) "A Traffic Congestion Assessment Method for Urban Road Networks Based on Speed Performance Index", *Procedia Engineering,* 137, pp. 425-433. https://doi.org/10.1016/j.proeng.2016.01.277

Himes, S.C., Donnell, E.T. (2010) "Speed Prediction Models for Multi-Lane Highways: A Simultaneous Equations Approach," *Journal of Transportation Engineering,* 16 (10), pp. 855-862.

Hyun, K. K., Mitra, S. K., Jeong, K., & Tok, A. (2021) "Understanding the Effects of Vehicle Platoons on Crash Type and Severity. *Accident Analysis and Prevention,* 149, 105858, pp. 1-12. https://doi.org/10.1016/j.aap.2020.105858

Indian Highway Capacity Manual (Indo-HCM). (2017). Central Road Research Institute (CRRI), New Delhi, India.

Lu, P., Zheng, Z., Tolliver, D., Pan, D. (2020) "Measuring Passenger Car Equivalents (PCE) for Heavy Vehicle on Two Lane Highway Segments Operating Under Various Traffic Conditions", *Journal of Advanced Transportation,* 2020 pp. 1-9.

Moridpour, S., Rose, G., Sarvi, M. (2010) "Effect of Surrounding Traffic Characteristics on Lane Changing Behavior", *Journal of Transportation Engineering,* 136 (11), pp. 973-985.

Padiath, A., Vanajakshi, L., Subramanian, S.C., Manda, H. (2009) "Prediction of Traffic Density for Congestion Analysis Under Indian Traffic Conditions", 12th International IEEE Conference on Intelligent Transportation Systems. St. Louis, MO, USA.

Quang, D.T., Bae, S.H. (2021) "A Hybrid Deep Convolutional Neural Network Approach for Predicting the Traffic Congestion Index", *Promet – Traffic & Transportation*, 33 (3), pp. 373-385. https://doi.org/10.7307/ptt.v33i3.3657

Rao, A.M., Rao, K.R. (2016) "Identification of Traffic Congestion on Urban Arterials for Heterogeneous Traffic", *Transport Problems,* 11 (3), pp. 131-142.

Samal, S.R., Kumar, P.G., Santhosh, J.C., Santhakumar, S.M. (2020) "Analysis of Traffic Congestion Impacts of Urban Road Network under Indian Condition", *IOP Conf. Ser.: Mat. Sci. Eng.* Proceedings of the Sustainable Construction Technologies & Advancements in Civil Engineering (ScTACE-2020) 2020, Bhimavaram, India.

Sarvi, M. (2013) "Heavy commercial vehicles-following behavior and interactions with different vehicle classes", *Journal of Advanced Transportation,* 47 (6), pp. 572-580.

Singh, S., Panda, R.K., Saw, D.K., Santhakumar, S.M. (2020a) "Effect of Heavy Transport Vehicles on Speed-Flow Characteristics of Mixed Traffic on Multi Lane Divided Intercity Highways", *Resilience and Sustainable Transportation Systems-ASCE,* Proceedings of the 13th Asia Pacific Transportation Development Conference, Shanghai, China. https://doi.org/10.1061/9780784482902.021

Singh, S., Santhakumar, S.M. (2021a) "Platoon-Based Impact Assessment of Heavy-Duty Vehicles on Traffic Stream Characteristics of Highway Lanes Under Mixed Traffic Environment", *International Journal of Intelligent Transportation Systems Research*. https://doi.org/10.1007/s13177-021-00268-z

Singh, S., Santhakumar, S.M. (2021b) "Empirical Analysis of Impact of Multi-Class Commercial Vehicles on Multi-Lane Highway Traffic Characteristics under Mixed Traffic Conditions", *International Journal of Transportation Science and Technology.* https://doi.org/10.1016/j.ijtst.2021.07.005

Singh, S., Santhakumar, S.M. (2021c) "Evaluation of Lane-Based Traffic Characteristics of Highways Under Mixed Traffic Conditions by Different Methods", *Journal of the Institution of Engineers India (Series A),* 102(3), pp. 719–735. https://doi.org/10.1007/s40030-021-00549-6

Singh, S., Shukla, B.K., Santhakumar, S.M. (2020b) "Infra-Red Sensor-Based Technology for Collecting Speed and Headway Data on Highways Under Mixed Traffic Conditions," *Institute of Electrical and Electronics Engineers (IEEE),* Proceedings of the 7th International Conference on Signal Processing and Integrated Networks (SPIN), Amity University, Noida, India. https://doi.org/10.1109/SPIN48934.2020.9070829

Singh, V., Gore, N., Chepuri, A., Arkatkar, S., Joshi, G, Pulugurtha, S. (2019) "Examining Travel Time Variability and Reliability on an Urban Arterial Road Using Wi-Fi Detections- A Case Study", *Journal of the Eastern Asia Society for Transportation Studies,* 13, pp. 2390-2411. https://doi.org/10.11175/easts.13.2390

Surasak, T., Okura, I., Nakamura, F. (2001) "Study of Platoon Characteristics on a Multi-Lane Expressway", *Journal of Infrastructure Planning Review* 18(5), 909-918.

Susilawati, S., Michael, A.P., Sekhar, V.C. (2010) "Travel Time Reliability Measurement for Selected Corridors in the Adelaide Metropolitan Area", *Journal of the Eastern Asia Society for Transportation Studies,* 8, pp. 86-102.

Underwood, R. T. (1961) "Speed, volume, and density relationship in quality and theory of traffic flow", Bureau of Highway Traffic, Yale University, 141-188.