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An Insight Representing a Scenario in Developing Nation

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Research Article

Investigating performance of a novel safety measure for assessing potential rear-end collisions: An insight representing a scenario in developing nation

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ABSTRACT

Road safety is one of the major concerns in the ever-growing traffic network. In addressing this, surrogate safety measures play a critical role in identifying collision instincts. Besides the added advantage of quantifying collision instincts in advance, surrogate safety measures have their limitations. For example, in some instances, those measures tend to show erroneous results. In this paper, a new surrogate safety measure Instant Heeding Time (IHT), is presented based on follower vehicle attention in the traffic streams. This new measure is integrated with a distance gap and the vehicles' speeds to assess probable rear-end collisions. Further, along with other safety measures, the developed safety framework is tested over a study section, with the help of trajectory datasets at three traffic flow conditions (free flow, capacity, and congested) under prevailing heterogeneous (mixed) traffic conditions. Based on the safety framework, it is observed that, in the case of free flow and capacity conditions, 23 and 55 probable rear-end collisions points are detected. At the congested conditions, no rear-end collision points are observed. Further, smaller vehicles in the traffic stream are associated with a higher number of rear-end collision instincts than other vehicle categories. The conceptualized safety framework can be applied on a real-time basis for monitoring the safety measures for vehicles in a mixed traffic stream.

1. Background

Since its inception, road collisions are one of the major problems in a transportation network. Various factors attributed to such scenarios are either due to erroneous driving behavior, faulty geometric design, or mismanagement. Despite the advances in automobile technology and the development of Intelligent Transportation Systems (ITS), road safety remains one of the major concerns. To address this problem, researchers initially used to analyze past collision records to identify the critical sections over a network. Such studies include techniques such as data aggregation [1], probabilistic collision determination [2,3], analysis from collision records [4–6], and type of collisions [7–9]. Based on such analysis, researchers used to map the critical spots on the road network and support decision-makers in allocating funds to improve the identified critical spots. Further, the development of the Next Generation SIMulation (NGSIM) trajectory datasets [10] and the Strategic Highway Research Program (SHRP) [11] boosted driving behavior studies in understanding the factors that affect safety. This includes safety performance through car-following models [12], driver attention [13] and speed choices of drivers [14].

Subsequently, researchers realized the importance of surrogate safety measures in assessing safety. Studies include the use of time gap for assessing collision chances [15,16], headway between vehicles [17], traffic simulation [18–20], gauging human behavior [21–23], collision avoidance studies [24,25], and safety from motion equations [26,27]. With similar studies in this direction, the following safety measures stood out: deceleration rate to avoid crash (DRAC) [28], potential index for collision with urgent deceleration (PICUD) [29,30], collision potential index (CPI) [31], time to collision (TTC) [32,33], and post encroachment time (PET) [34,35]. It is noted that the stated proactive measures have their advantages and disadvantages in evaluating road safety. For example, it can be noted that if the leader and follower vehicles tend to have the same speeds, say 10 km/h or 90 km/h, the DRAC and TTC will indicate zero collisions in both scenarios, irrespective of the distance gap between the leader and the follower vehicles. This would reflect ambiguity with these measures, and the predictions may

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deviate from the accurate collision instincts. Besides, assessing these safety measures further demands a high-quality vehicular trajectory dataset for the roadway sections.

On the other hand, in the case of mixed traffic conditions that prevail in India, given the data constraints, very few studies have been conducted on driving behavior and surrogate safety measures, including safety at midblock road sections due pedestrian traffic [36,37], distracted driving in mixed traffic [38], safety evaluation at unsignalized intersections [39], and safety analysis with TTC limits [40]. Further, other studies attempted to understand driving behavior, including vehicular lateral behavior [41], vehicle acceleration characteristics [42], and trajectory development [43,44].

Considering all these aspects, this study proposes new safety measures and a framework for safety evaluation of the traffic stream of mixed traffic. Video-graphic surveys were conducted over the study section. Later, using semi-automated image processing tools, trajectory data ware extracted over the study section at three different volume levels. Further, employing trajectory data, conventional surrogate safety measures were employed to understand probabilistic rear-end collisions. In this direction, using the hysteresis phenomenon between the following vehicle pairs, a new surrogate safety measure, named Instant Heeding Time (IHT) is proposed in evaluating rear-end collisions. Further, IHT was integrated with distance gap and vehicle speed, and a safety framework is conceptualized.

2. Methodology

The methodology is presented in Fig. 1, and involves four stages, as follows:

Stage 1: In this stage, data were collected, followed by vehicular trajectory data development for the three traffic flow conditions.

Stage 2: In this stage, probabilistic rear-end collisions were investigated based on the developed trajectory data.
Stage 3: At this stage, a new surrogate safety measure IHT was introduced based on the vehicles' hysteresis phenomenon.
Stage 4: A new safety framework for evaluating probable rear-end collisions instincts was conceptualized. Later, the framework was applied to the study section for evaluation.

3. Study section

In addressing the challenges under mixed traffic conditions, it was decided to design an experiment incorporating several roadway and traffic conditions. A segment on the western expressway in India was used for this purpose. A wide range of traffic flow variations was observed, including free-flow, near-capacity, and congested conditions. Video graphic surveys were conducted, and macroscopic plots were developed. Further, to analyze the driving behavior, high-quality trajectory data were collected at three traffic flow conditions for the section. Considering the ineptness of automated image processing tools under heterogeneous traffic conditions, a semi-automated image processing tool was used to develop trajectory data [45]. To improve upon the marginal noise in the developed trajectory data, smoothening techniques developed by researchers [46] were adopted. More details of the trajectory data are represented in Table 1. In Table 1, the details of the study section, which includes trap length, road width, traffic flow compositions, traffic volume, traffic flow parameters, and duration of the trajectory data. It can be noted that three flow conditions are observed from different flow regimes, which include free flow, medium flow, and near congested traffic conditions. in total, around 35 min of trajectory data is developed for around 3500 vehicles. The snapshots of the selected study sections followed by the developed time-space plots of the vehicles observed during real field conditions on the western expressway are depicted in Fig. 2. In the considered study section, six different types of vehicles are observed, which includes Motorized three-wheelers (MThW), Motorized two-wheelers (MTW), Buses, Cars, Trucks, and Light commercial vehicles (LCV). In that, MTW is a common vehicle in the south and east Asian countries. MTWs are often referred to in the literature as motorcycle, motorbike, bike, or cycle etc. similarly, Buses, Cars and Trucks are observed, but the vehicle physical properties can be different from other countries and will be in line with the vehicle standards for India. The light commercial vehicle (LCV) is a commercial carrier vehicle whose gross vehicle weight of no more than 3.5 metric tons (tonnes). The LCV designation is also occasionally used in European and some North American countries. The LCV type includes pickup trucks, vans etc., all commercially based goods or passenger carrier vehicles. Primarily the LCVs are used for intracity movement.

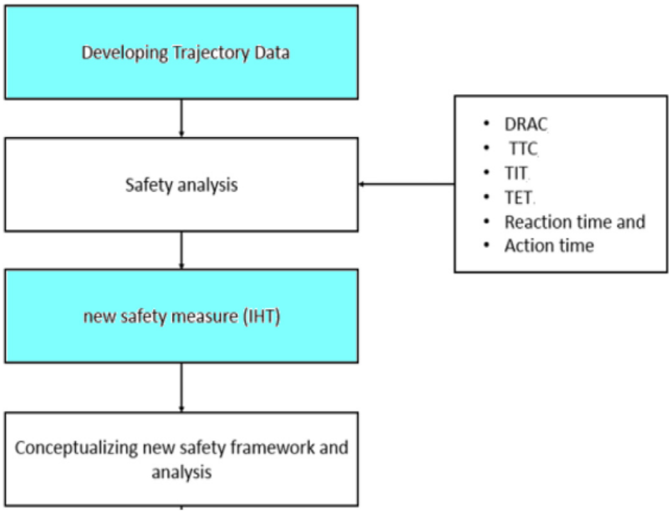


Fig. 1. Methodological framework adopted in the present study.

4. Existing safety measures

From the literature [47], it can be noted that numerous surrogative safety measures are conceptualized in assessing the probable rear-end collisions for midblock sections. These include deceleration rate to avoid crash (DRAC) [28], time to collision (TTC) [32], time integrated TTC (TIT) [48], time Exposed in TTC (TET) [49], reaction time [50], and attention time [51]. Based on the preceding safety measures, researchers analyzed probable rear-end collisions over midblock sections in combination with the leader-follower vehicles over the traffic stream, as explained next.

4.1. Deceleration rate to avoid crash (DRAC)

Let V_F and V_L be the speed (km/h) of the follower and leader vehicles, respectively, X_L and X_F be the longitudinal positions(m) over the road space, t be the time interval, and L_L and L_F be the length (m) of the leader and follower vehicles, respectively.

In general, DRAC evaluates the minimum deceleration requirement between the leader and follower, when the follower is closing on the leader to avoid a rear-end collision. DRAC (m/s^2) is given by

$$DRAC = \begin{cases} \dfrac{[0.278V_F(t) - 0.278V_L(t)]^2}{2\,(X_L - X_F - L_L)} & V_F(t) > V_L(t) \\ 0 & V_F(t) \le V_L(t) \end{cases} \tag{1}$$

Note that a higher value of DRAC indicates a higher chance of rear-end collision and vice versa.

Table 1
Details of the study section.

Study section	Trap length (m)	Road width (m)	Traffic flow classification	Traffic composition[b] (%)	Traffic flow parameters		V/C	No. of Vehicles tracked	Duration of trajectory data (minutes)
					Avg. speed (km/h)	Avg. flow PCU/h			
Western Expressway (Multilane Urban Roads)	100	17.5	F-1	15/35/5/40/2/3	65	4800	0.4	1080	15
			F-2	20/29/2/45/1/3	42	10,120	0.85	1715	15
			F-3[a]	17/25/5/45/3/4	20	3500	< 1	660	10

[a] Congested conditions.
[b] Traffic composition in order of MThW/MTW/Bus/Car/Truck/LCV.

4.2. Time to collisions (TTC)

TTC is given as the time gap between the leader and follower vehicles. This measure is defined as the ratio of the distance gap between the vehicles to the relative speed between them. TTC (s) *is givn by*

$$TTC = \begin{cases} \dfrac{X_L - X_F - L_L}{0.278 * [V_F(t) - V_L(t)]} & V_F(t) > V_L(t) \\ \infty & V_F(t) \leq V_L(t) \end{cases} \quad (2)$$

Note that a small value of TTC indicates a higher chance of rear-end collision and vice versa.

4.3. Time exposed in TTC (TET)

To quantify the rear-end collision instincts, TET is conceptualized. This measure is defined as the total time that a vehicle is exposed to risk situations. To better explain this, an example is presented, where TTC between the vehicles is plotted over time as shown in Fig. 3.

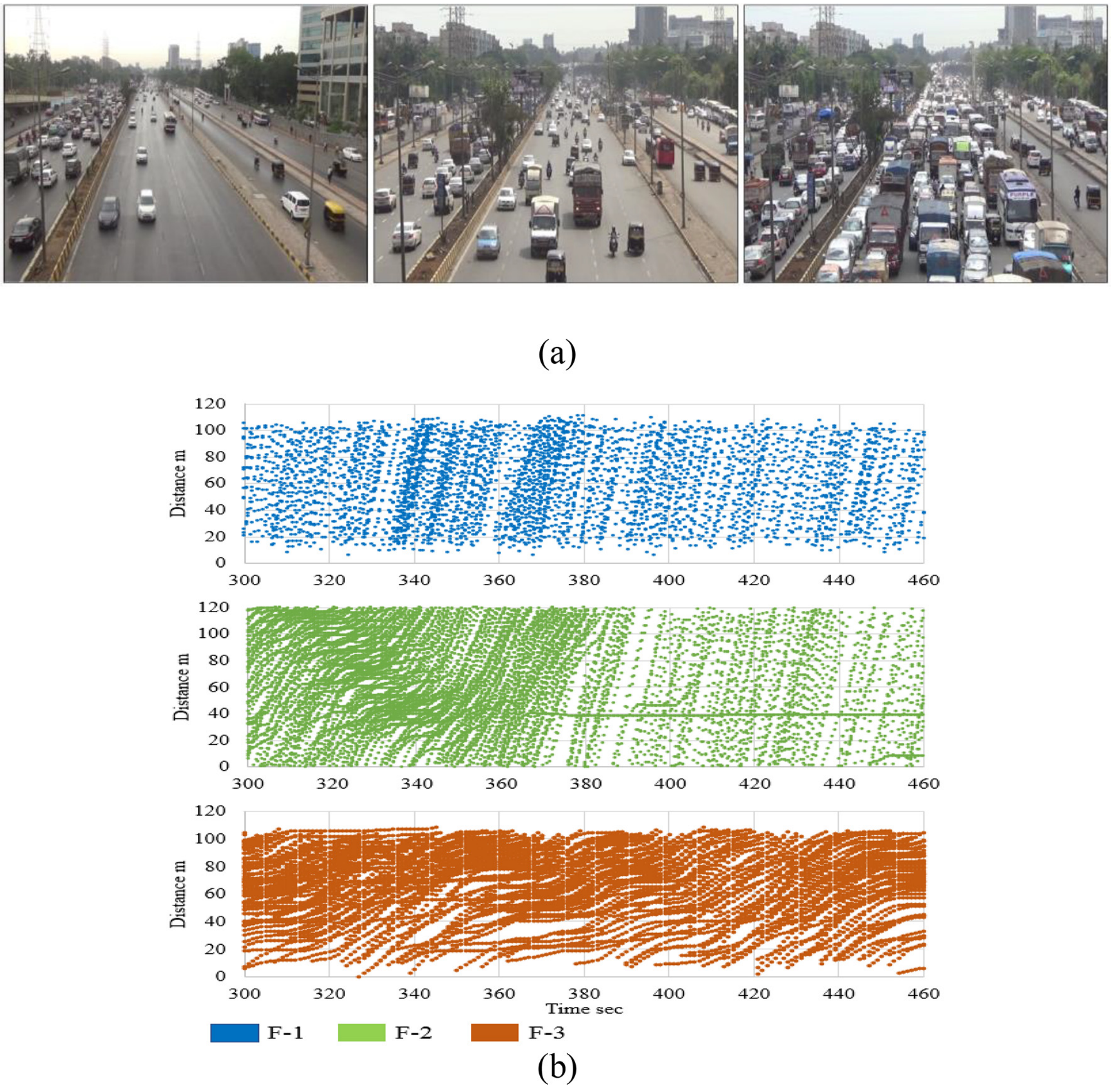


Fig. 2. (a) Snapshots from the study section (b) Time space plots of vehicles on western expressway at different flow levels.

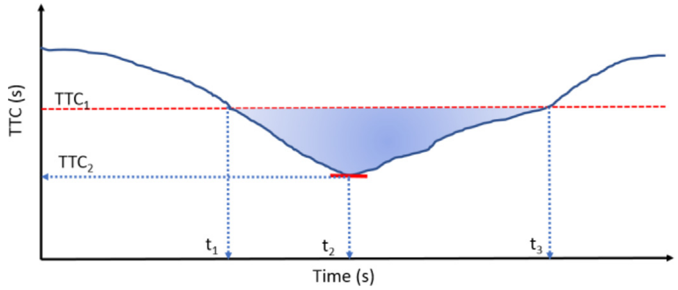


Fig. 3. TTC between the vehicles over time.

Let TTC_1 be the threshold limit and the risk situation is considered when $TTC < TTC_1$. From the Fig. 3 it is noted that from t_1 to t_3 the TTC between the vehicles is less that TTC_1. Further, TET (s) is given by

$$TET = \begin{cases} \sum_{t=t_1}^{t3} \varepsilon * \Delta t & TTC < TTC_1 \\ 0 & TTC \geq TTC_1 \end{cases} \tag{3}$$

where

$$\varepsilon = \begin{cases} 1 & TTC < TTC_1 \\ 0 & TTC \geq TTC_1 \end{cases} \tag{4}$$

Note that a higher TET value indicates a higher chance for rear-end collision and vice versa.

4.4. Time integrated TTC (TIT)

The TIT (s^2) considers the accumulated impact of risk behavior. This measure is defined as the area under the risk situation (area under the TTC_1 limit), as follows

$$TIT = \begin{cases} \int_{t_1}^{t_3} [TTC_1 - TTC(t)] * dt & TTC < TTC_1 \\ 0 & TTC \geq TTC_1 \end{cases} \tag{5}$$

Like TET, a higher value of TIT indicates a higher risk of collision and vice versa.

4.5. Reaction time

The reaction time of the follower vehicle is also considered as one of the safety measures in evaluating rear-end collisions. This measure is defined as the time taken by the subject vehicle to sense the risk time gap. From Fig. 3, the subject vehicle is at risk from $t_{1,}$ and at t_2 the subject vehicle sensed the severity and started its action. Therefore, the reaction time (s) is given as (t_2-t_1), is given by

$$Reaction\ time = \begin{cases} \sum_{t=t_1}^{Min(TTC)} \gamma * \Delta t & TTC < TTC_1 \\ 0 & TTC \geq TTC_1 \end{cases} \tag{6}$$

where

$$\gamma = \begin{cases} 1 & TTC < TTC_1 \\ 0 & TTC \geq TTC_1 \end{cases} \tag{7}$$

4.6. Action time

Along with the reaction time, the action time of is one of the parameters that gauges the action behavior of the vehicles. This measure is defined as the time taken by the subject vehicle to keep itself from the risk severity time gap and return to the normal time gap. From Fig. 3, the Action Time (s) (t_3-t_2) is given by

$$Action\ Time = \begin{cases} \sum_{t=Min(TTC)}^{t_3} \delta * \Delta t & TTC < TTC_1 \\ 0 & TTC \geq TTC_1 \end{cases} \tag{8}$$

where

$$\delta = \begin{cases} 1 & TTC < TTC_1 \\ 0 & TTC \geq TTC_1 \end{cases} \tag{9}$$

4.7. Analysis based on safety measures

An analysis was carried out using the other safety measures and with the help of the developed trajectory data. Initially, for the subsequent vehicles over the road space, the lateral overlaps among vehicles were computed, by programming in python. In general, the lateral overlap is defined as the overlying zone between the leader and the follower vehicles, concerning a lateral axis across the road section. If the vehicular pairs have a lateral overlap between themselves, the leading vehicle is later considered the leader, and the trailing vehicle is taken as the follower. On these lines, from the trajectory data, the leader-follower vehicles are mapped. Later, based on the leader-follower data, all the safety measures previously mentioned are evaluated.

Further, to identify the probable rear-end collisions, limits for DRAC and TTC are specified in analyzing potential rear-end collisions. In line with literature [52,53], the ranges DRAC ≥ 3.5 m/s2 and TTC ≤ 2.5 s are considered as probable rear-end collisions. On these lines, with the TTC threshold, other safety measures such as TET, TIT, Reaction Time, and Action Time are computed in assessing safety. Considering the vehicle compositions and the size of the vehicles to understand the trend of the safety analysis, specific vehicle categories are combined. In this direction, MThW, Car are combined as one, and Bus, Truck, and LCV are combined as single categories. The safety analysis presented in Tables 2 and 3 revealed that the smaller vehicles are more prone to rear-end collisions than larger vehicles. Further, with a rise in inflow conditions, the safety of the traffic stream deteriorated. All safety measures are computed with the help of trajectory datasets at the three traffic flow levels, and the results are presented in Table 2, where potential rear-end collisions are presented for DRAC and TTC based on the thresholds. On the other hand, for TET, TIT, the mean values of Reaction Time and Action Time are presented in Table 3 based on the vehicle class. From the analysis of DRAC and TTC, the number of rear-end collisions differ. For example, in the case of MTW at F-3, with DRAC 81 probable rear-end collision points are observed, with TTC 156 probable rear-end collision points are observed. Simultaneously, with the change in flow level, the probable rear-end collision points tend to rise with an increase in the flow level. Finally, the higher number of rear-end collision points are observed at the congested conditions. Even with the change in vehicle class, the rear-end collision points are varied at a given flow level. For example, the rear-end collision points are higher in MTW, followed by other vehicle classes. On the other hand, heavy vehicles such as Bus, Truck, and LCV tend to have fewer rear-end collisions as per DRAC and TTC. From the analysis, it is inferred that the smaller

Table 2
Potential rear-end collisions for different vehicle types.

Measure	Flow conditions	MTW	MThW, car	Bus, truck, LCV
DRAC (m/s^2)	F-1	30	42	4
	F-2	56	65	19
	F-3	81	95	27
TTC (s)	F-1	13	3	–
	F-2	44	33	28
	F-3	156	110	34

Table 3
Mean values of safety measures for different vehicle types.

Measure	Flow conditions	MTW	MThW, Car	Bus, Truck, LCV
Mean TET (s)	F-1	0.17	0.06	0.04
	F-2	0.20	0.19	0.07
	F-3	0.6	0.12	0.15
Mean TIT (s^2)	F-1	0.26	0.08	0.11
	F-2	0.28	0.23	0.21
	F-3	1.24	0.29	0.27
Mean reaction time (s)	F-1	0.7	1.25	1.41
	F-2	1.44	1.5	1.82
	F-3	1.71	1.9	2.5
Mean action time (s)	F-1	0.56	0.94	1.44
	F-2	0.4	0.69	1.08
	F-3	0.15	0.47	0.61

vehicle MTWs tend to have good lateral maneuverability compared to other vehicle categories. Given this, whenever the MTWs longitudinal movement is constrained, the vehicles tend to maneuver laterally for a better movement. In doing so, the MTWs are exposed to other vehicles, resulting in short distance gaps and time gaps from their followers and new leaders. In combination with all the cases, the more MTW.

The mean values of TET, TIT, Reaction Time, and Action Time are evaluated to sense the intensity of severity over the traffic flow levels and vehicle classes. In the case of TET and TIT, similar inferences related to DRAC and TTC are observed. On the other hand, the mean values for smaller vehicles are less and increase with the size of vehicles from the reaction time analysis. Further, with the rise in the flow level, the Reaction Time of the vehicle increased. A similar kind of inferences is observed with Action Time.

Based on the analysis, it was found that smaller vehicles tend to have more chances of rear-end collisions, given their lesser reaction and action times. Further, with the rise in volume levels, the chances for rear-end collisions are found to increase.

Along with the added advantages, the mentioned safety measures also have limitations. Consider two scenarios: two vehicles with a distance gap of 30 m and a relative speed of 15 m/s and two vehicles with a distance gap of 10 m and a relative speed of 5 m/s. The TTC in both cases is 2 s, indicating similar probabilities of collision. However, in a realistic sense, the probabilities of collision in both scenarios are different, indicating erroneous definitions.

5. Safety measure

In understanding the leader-follower interactions, the distance gap vs. relative speed (follower speed minus leader speed) relation between the pairs is plotted, as shown in Fig. 4. The Fig. shows the hysteresis nature. In general, when a vehicle is following its leader vehicle, the follower tries to match the leader's speed and tends to maintain a constant distance gap from the leader vehicle. Further, the human sensory reaction can lead to fluctuations in distance gap and relative speed, under vehicle-following conditions. Nature is demonstrated by the arrows shown in the hysteresis diagrams that display the fluctuations in distance gap and relative speed between the leader-follower vehicles. Further, to show the trend clearly, the hysteresis plots are aggregated based on flow conditions, as shown in Fig. 4.

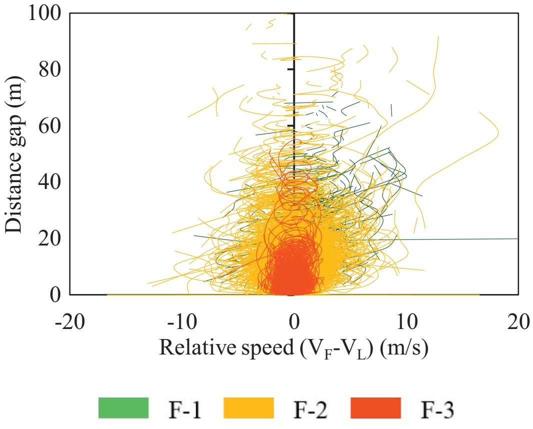


Fig. 4. Hysteresis plot between leader follower pairs.

From the aggregated hysteresis plots, in the case of free-flow condition (Flow 1), a partial hysteresis phenomenon is observed with a wide range of distance gaps and relative speeds. This indicates fewer following interactions between vehicles in the free-flow condition. On the other hand, in Flow 2 (near-capacity condition), a substantial hysteresis phenomenon between vehicles is observed. In contrast, in Flow 3 (congested condition), the variation in relative speed in the hysteresis plots is reduced, along with a decrease in the distance gap. The variation of the hysteresis phenomenon exemplifies the variation in driving behavior as traffic-flow level changes.

5.1. Instantaneous heeding time (IHT)

In explaining the hysteresis phenomenon, an example hysteresis plot is presented in Fig. 5(a). As noted, initially, the distance gap between the leader and the follower is around 25 m. Later, during the following process, the follower tends to move at high speed compared to its leader. Besides, the follower recognized that he/she is moving at high speed compared with that of the leader. Thus, from the point, *a*, onward, the follower vehicle tends to pay attention to the leader by dropping its speed and matching the leader's speed. In the present case, from a distance gap of around 20 m, the follower paid attention to the leader. The time gap between the leader and follower is computed between the pairs, as shown in Fig. 5(b).

Using the hysteresis phenomenon, the attention instincts of the follower towards its leader was evaluated. Let V_F be the speed of follower at which the follower has perceived its leader that is moving at V_L at a distance gap $(X_L - X_F - L_L)$. It is noted that, at the time of paying attention, the follower immediately starts dropping its speed, and at that time the follower has no acceleration. Further, in the case of hysteresis at heeding, the relative speed (V_F - V_L) is positive and is likely to experience a local-maxima as observed in real-field conditions. The time gap between vehicles is positive. In general, IHT is the time gap between the leader-follower pairs defined along with the associated conditions, as follows.

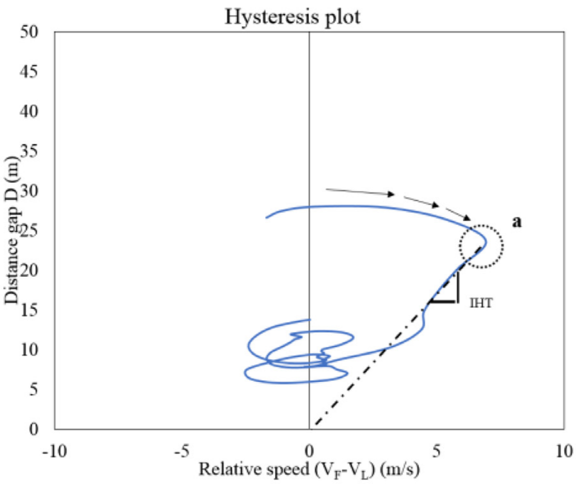
$$IHT = \frac{(X_L - X_F - L_L)}{0.278 * (V_F - V_L)}; \text{when} \begin{cases} (t_n) > V_F(t_{n+1}); \\ \frac{\partial(V_F)}{\partial(t)} = 0; \\ V_F - V_L > 0; \\ \frac{\partial(t_g)}{\partial(t)} = 0 \\ t_g > 0; \end{cases} \tag{10}$$

where *IHT* = instantaneous heeding time (s), t_g = time gap (s), V_F = speed of the follower (km/h), V_L = speed of the leader (km/h), D = distance gap (m), $V_F(t_n)$ = speed of the follower at time t_n, and $V_F(t_{n+1})$ = speed of the follower at time t_{n+1}.

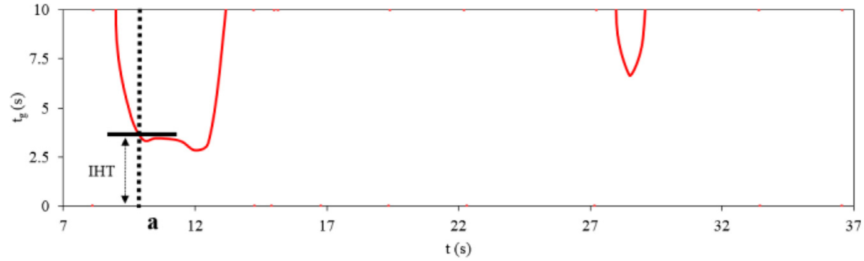
Using Eq. (10) as a criterion, with the help of python code, the values of IHT between vehicles are computed. Further, along with the follower instincts' attention, the state at which the follower perceived its leader plays a crucial role in defining the probability of rear-end collisions.

For example, for Scenario 1 the follower sensed it leader at VF = 20 km/h, VL = 10 km/h and distance gap = 20 m. Thus,

$$\text{IHT} = \frac{(X_L - X_F - L_L)}{0.278\ (V_F - V_L)} = \frac{(20)}{0.278\ (20 - 10)} = 7.2\ s$$



(a) Definition of IHT from hysteresis phenomenon



(b) Time gap between the leader and follower over the time.

Fig. 5. Fundamental relation of *IHT* and Time gap at the instant of paying attention. (a) Definition of IHT from hysteresis phenomenon. (b) Time gap between the leader and follower over the time.

Scenario 2, the follower sensed it leader at $V_F = 40$ km/h, $V_L = 20$ km/h and distance gap = 40 m. Thus,

$$\text{IHT} = \frac{(X_L - X_F - L_L)}{0.278\,(V_F - V_L)} = \frac{(40)}{0.278(40-20)} = 7.2\ s$$

Further, it can be noted that in both scenarios, the IHT between the vehicles is the same with 7.2 s and depicting similar chances for rear-end collisions. However, in a realistic sense, with the variation in distance gap and speed, the chances for rear-end collisions are different in both scenarios.

However, the driving behavior of the road section is one of the complex phenomena. At the same time, for a given subject follower vehicle, it is up to the driver who can maintain his/her desired speed at any given relative distance gap from his/her leader vehicle. Given this, both the follower speed and distance gap will be independent. Further it can be noted that, in most of the established car-following models consider both the distance gap and the speed of the subject vehicle as independent variables for modeling the dependent variable. The conceptualized IHT is a time gap that marks the attentiveness of the subject vehicle. It is up to the subject vehicle to act and avoid a collision with its leader. For example, if the driver is aggressive, he/she can mark a less IHT value with more speed and distance gap and vice versa. In this regard, the authors treated the three variables as independent and conceptualized the conditional probability.

Therefore, it can be concluded that in addition to the *IHT*, the follower speed and distance gap play a vital role and forms a robust probability scheme among the three variables in assessing rear-end collisions. Such a scheme should generate a high probability for rear-end collisions between the follower and the leader when all variables are at their extreme limits.

Let $P(V_F)$ be the probability that the follower speed is greater than the critical speed, $P(IHT)$ be the probability that *IHT* is greater than its critical limit, and $P(D)$ be the probability that the distance gap is less than the critical distance gap for rear-end collisions. Given this, all three parameters are dependent on the following behavior and are mutually exclusive events. Based on this, a rear-end collision will occur when all the parameters cross their critical limits. Thus, the probability of a rear-end collision, $P(\text{rear}-\text{end collision})$, is given by

$$P(\text{rear}-\text{end collision}) = P(V_F)*P(IHT)*P(D) \tag{11}$$

6. Analysis of safety concept

A conceptualized safety framework is tested on the study section to estimate rear-end collisions instincts. From the literature, it is noted that there are no clear findings related to the critical limits of V_F, *IHT*, and critical *D* with respect to rear-end collisions. Therefore, according to Shi et al. [47] $TTC = 2.5$ s was regarded as a critical value, and therefore this limit was considered as the critical limit for IHT. Also, based on driving behavior studies [54,55], a follower speed of 30 km/h [56] and a distance gap of 10 m were taken as the critical limits. Thus, in this study for a given leader-follower interaction, $IHT \leq 2.5$ s, $D \leq 10$ m, and $V_F \geq 20$ km/h were considered for estimating the probability of rear-end collisions. Based on these critical limits, the developed framework was tested

Table 4
Number of potential rear-end collisions for different vehicle types as followers.

Flow conditions	MTW	MThW, Car	Bus, Truck, LCV	Total
F-1	13	9	1	23
F-2	32	20	3	55
F-3	7	–	–	7

over the study section, as shown in Table 4. From the results presented in Table 4, it is noted that, compared to other measures, fewer collision points are observed with IHT. Concerning traffic flow conditions, the congested stage F-3 tends to have fewer collision points. Like the other measures, smaller vehicles tend to have more collision points than larger vehicles. Further, the nature of interactions is marked over the geometry of the road section at all three flow levels, as shown in Fig. 6.

The analysis shows that in the case of F-1 (free flow), a total of 23 probable rear-end collisions are observed, where MTW dominates with 13 probable rear-end collisions. In the case of F-2 (near capacity), 55-rear-end collision points are observed, where smaller vehicles tend to have a higher number of rear-end collisions. Interestingly in the case of F-3 (congested), 7-rear-end collision points are observed. At the same time, al the points belong to MTW as followers. Further examination of the results at F-3 showed that vehicles at congested conditions tend to follow one another with lesser speeds and distance gaps. As a result, vehicles tend to have higher time gaps, other than MTWs as follower in few instincts, Due to this phenomenon, probable rear-end collisions are less observed at the congested conditions, a finding that is also supported by the literature [57].

Further, to depict the importance of the threshold values, to be adopted, in understanding the potential rear-end collisions, a sensitivity analysis was performed, results for which are reported in Table 5. It can be noted that the safety analysis was performed taking a threshold combination of $V_F \geq 20$ km/h, $D \leq 10$ m, and $IHT \leq 2.5\ s$. As a part of the sensitivity analysis, the threshold value of speed was increased to 30 km/h, while other thresholds were retained constant. The collision instincts were evaluated over the three considered flow conditions *(F-1: free flow, F2: near-capacity flow and F-3: stop-and-go flow)*. In the case of F-1 and F-2, it was found that the number of collisions were found to be dropped from 23 to 19 and 55 to 42, indicating a percentage change of 17% and 23%, respectively. On the other hand, with the rise in speed threshold ($V_F \geq 30$ km/h), the earlier 7 rear-end number of collisions at flow level, F-3 was found to change to a scenario of non-collision, depicting zero collision chances at the F-3 flow conditions.

Table 5
Sensitivity of probable rear-end collisions to changes in threshold values.

Flow conditions	$V_F \geq 20$ km/h, $D \leq 10$ m, $IHT \leq 2.5\ s$	$V_F \geq 30$ km/h, $D \leq 10$ m, $IHT \leq 2.5\ s$	Change (%)
F-1	23	19	17
F-2	55	42	23
F-3	7	0	100

This supports that the along with the adopted conceptualized methodology, the threshold values of the respective parameters, in grading the safety play a significant role in sorting the instincts (number of possible collisions). Further, using this developed framework, more studies are required to be accomplished, to identify the critical values of thresholds of important variables (*follower-vehicle speed, Distance gap and IHT*) by incorporating the effect of variation in roadway conditions, vehicle type and traffic composition in the traffic stream.

7. Summary and conclusions

From the study, it was observed that safety over the traffic stream is one of the most sensitive parameters of a road network, which can be affected by any means and decisively can influence the road network performance. However, at the same time, frameworks related to quantifying the traffic stream's safety are lacking. Given this, the study had formulated a structure in monitoring the safety in the traffic stream and advocated the importance of trajectory data in understanding the traffic at its best. Interestingly, it uncovered mixed traffic behavior and exposed the smaller vehicles' major share in rear-end collisions. Further, the study strongly advocated the state of vehicles in assessing probable rear-end collisions. This study is the first of its kind in this direction and bridges the gap in monitoring the safety of a traffic stream at a microscopic scale. Based on this study, the following comments are offered:

- To assess the rear-end collisions, initially, conventional safety measures are adopted. Based on the analysis, it is observed that as the flow level increases, the number of rear-end collisions increases. However, in congested conditions, the conventional measures tend to show higher rear-end collisions than at free flow and capacity conditions.
- Based on the follower vehicle's attention towards the leader vehicle in the following process, a safety measure IHT is proposed in the present

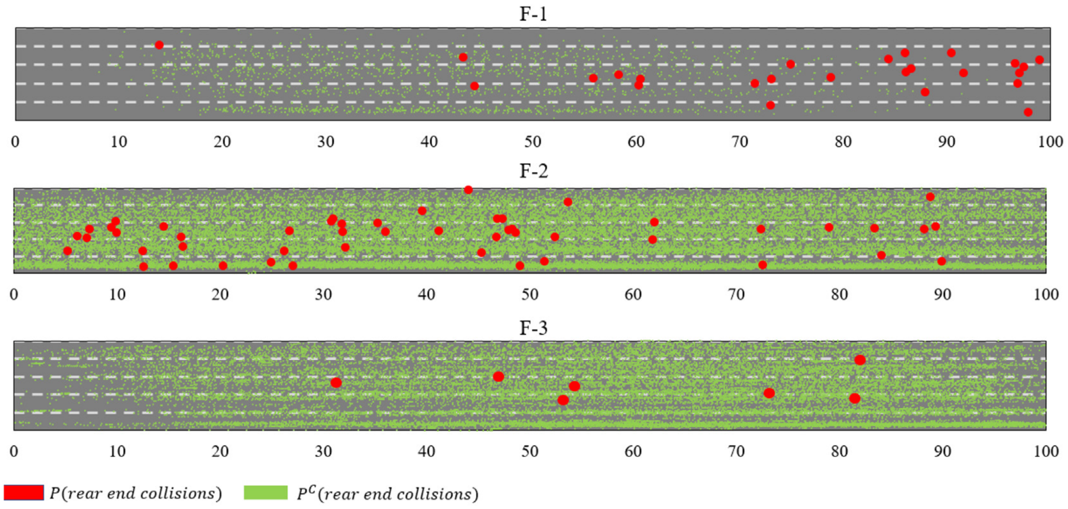


Fig. 6. Leader-follower instincts over the geometry of the road section.

study. This measure is the time gap between the leader and follower vehicles at the time of attention. Along with that, the study reasoned the importance of vehicle state in evaluating rear-end collisions. On these lines, the distance gap and speed of the follower vehicle is integrated with IHT to develop a safety framework for assessing rear-end collisions.

- By adopting the conceptualized safety framework over the study section, at flow levels F-1 and F-2, around 23 and 55 rear-end collision points were observed. Further, the study revealed that at F-3 congested conditions, no rear-end collision points were observed. This exemplifies conventional traffic theory that the traffic stream's safety and efficiency are inversely related to one another.
- From the safety analysis based on vehicle category, it is observed that smaller vehicles (due to their size and a high degree of maneuverability) tend to have a higher number of rear-end collisions in the traffic stream. At the same time, those vehicles were found to have less reaction and action times, due to this heterogeneity among the vehicles. This has resulted in higher numbers of rear-end collisions for those smaller vehicles.
- The critical limits for IHT, distance gap, and speed of the follower are adopted from the literature. This may be considered as a limitation in the present study. A few more studies are required in this direction to assess the critical limits for those parameters.
- With the possibility of using trajectory data on a real-time basis, the conceptualized methodology can be applied on a real-time basis, for safety surveillance over the road networks. Based on the density of the rear-end collision points, critical black spots can be mapped well in advance.

Declaration of Competing Interest

None.

References

[1] G. Koorey, Road data aggregation and sectioning considerations for crash analysis, Transp. Res. Rec. J. Transp. Res. Board. (2009) https://doi.org/10.3141/2103-08.

[2] A.P. Tarko, J. Thomaz, D. Grant, Probabilistic determination of crash locations in a road network with imperfect data, Transp. Res. Rec. J. Transp. Res. Board. (2009) https://doi.org/10.3141/2102-10.

[3] P. Chen, Y. Huang, J. Mou, P.H.A.J.M. van Gelder, Probabilistic risk analysis for ship-ship collision: state-of-the-art, Saf. Sci. (2019) https://doi.org/10.1016/j.ssci.2019.04.014.

[4] R. Harb, E. Radwan, X. Yan, A. Pande, M. Abdel-Aty, Freeway work-zone crash analysis and risk identification using multiple and conditional logistic regression, J. Transp. Eng. (2008) https://doi.org/10.1061/(ASCE)0733-947X(2008)134:5(203).

[5] A. Abadi, T. Rajabioun, P.A. Ioannou, Traffic flow prediction for road transportation networks with limited traffic data, IEEE Trans. Intell. Transp. Syst. (2015) https://doi.org/10.1109/TITS.2014.2337238.

[6] S. Ukkusuri, L.F. Miranda-Moreno, G. Ramadurai, J. Isa-Tavarez, The role of built environment on pedestrian crash frequency, Saf. Sci. (2012) https://doi.org/10.1016/j.ssci.2011.09.012.

[7] G. McGwin, C. Owsley, K. Ball, Identifying crash involvement among older drivers: agreement between self-report and state records, Accid. Anal. Prev. (1998) https://doi.org/10.1016/S0001-4575(98)00031-1.

[8] M.A. Quddus, C. Wang, S.G. Ison, Road traffic congestion and crash severity: econometric analysis using ordered response models, J. Transp. Eng. (2010) https://doi.org/10.1061/(ASCE)TE.1943-5436.0000044.

[9] K. El-Basyouny, T. Sayed, Safety performance functions using traffic conflicts, Saf. Sci. (2013) https://doi.org/10.1016/j.ssci.2012.04.015.

[10] NGSIM, Next Genaration Simultaion, FHWA, 2007 https://ops.fhwa.dot.gov/trafficanalysistools/ngsim.htm.

[11] L. Precht, A. Keinath, J.F. Krems, Effects of driving anger on driver behavior – results from naturalistic driving data, Transp. Res. Part F Traffic Psychol. Behav. (2017) https://doi.org/10.1016/j.trf.2016.10.019.

[12] A.H. Ghods, F.F. Saccomanno, Comparison of car-following models for safety performance analysis using vehicle trajectory data, Proceedings, Annu. Conf. - Can. Soc. Civ. Eng, 2010.

[13] T. Victor, Analysis of Naturalistic Driving Study Data: Safer Glances, Driver Inattention, and Crash Risk, 2016 https://doi.org/10.17226/22297.

[14] T. Schneidereit, T. Petzoldt, A. Keinath, J.F. Krems, Using SHRP 2 naturalistic driving data to assess drivers' speed choice while being engaged in different secondary tasks, J. Saf. Res. (2017) https://doi.org/10.1016/j.jsr.2017.04.004.

[15] M.M. Minderhoud, P.H.L. Bovy, Extended time-to-collision measures for road traffic safety assessment, Accid. Anal. Prev. (2001) https://doi.org/10.1016/S0001-4575(00)00019-1.

[16] C. Caliendo, M. Guida, Microsimulation approach for predicting crashes at unsignalized intersections using traffic conflicts, J. Transp. Eng. (2012) https://doi.org/10.1061/(ASCE)TE.1943-5436.0000473.

[17] A. Al-Kaisy, S. Karjala, Car-following interaction and the definition of free-moving vehicles on two-lane rural highways, J. Transp. Eng. (2010) https://doi.org/10.1061/(ASCE)TE.1943-5436.0000148.

[18] D. Gettman, L. Head, Surrogate safety measures from traffic simulation models, Transp. Res. Rec. (2003) https://doi.org/10.3141/1840-12.

[19] A. Al-Kaisy, Y. Jung, H. Rakha, Developing passenger car equivalency factors for heavy vehicles during congestion, J. Transp. Eng. (2005) https://doi.org/10.1061/(ASCE)0733-947X(2005)131:7(514).

[20] S.H. Stroeve, H.A.P. Blom, G.J. Bert Bakker, Systemic accident risk assessment in air traffic by Monte Carlo simulation, Saf. Sci. (2009) https://doi.org/10.1016/j.ssci.2008.04.003.

[21] D. Shinar, Traffic Safety and Human Behavior, 2017 https://doi.org/10.1108/9781786352217.

[22] G. Yannis, C. Antoniou, S. Vardaki, G. Kanellaidis, Older drivers' perception and acceptance of in-vehicle devices for traffic safety and traffic efficiency, J. Transp. Eng. (2010) https://doi.org/10.1061/(ASCE)TE.1943-5436.0000063.

[23] G. Agamennoni, J.I. Nieto, E.M. Nebot, A Bayesian approach for driving behavior inference, IEEE Intell. Veh. Symp. Proc, 2011 https://doi.org/10.1109/IVS.2011.5940407.

[24] S.B. Liu, S.M. Lo, K.L. Tsui, W.L. Wang, Modeling movement direction choice and collision avoidance in agent-based model for pedestrian flow, J. Transp. Eng. (2015) https://doi.org/10.1061/(ASCE)TE.1943-5436.0000762.

[25] A. Mukhtar, L. Xia, T.B. Tang, Vehicle detection techniques for collision avoidance systems: a review, IEEE Trans. Intell. Transp. Syst. (2015) https://doi.org/10.1109/TITS.2015.2409109.

[26] H. Behbahani, N. Nadimi, H. Alnoori, M. Sayadi, Developing a New Surrogate Safety indicator Based on Motion Equations, Promet - Traffic - Traffico, 2014 https://doi.org/10.7307/ptt.v26i5.1388.

[27] A. Vahidi, A. Eskandarian, Research advances in intelligent collision avoidance and adaptive cruise control, IEEE Trans. Intell. Transp. Syst. 1318 (2003) 34–39 https://doi.org/10.1109/TITS.2003.821294.

[28] S. Almqvist, C. Hyden, R. Risser, Use of speed limiters in cars for increased safety and a better environment, Transp. Res. Rec. (1991).

[29] N. Uno, Y. Iida, S. Yasuhara, M. Suganuma, Objective analysis of traffic conflict and modeling of vehicular speed adjustment at weaving section, Infrastruct. Plan. Rev. (2011) https://doi.org/10.2208/journalip.20.989.

[30] G. Guido, F. Saccomanno, A. Vitale, V. Astarita, D. Festa, Comparing safety performance measures obtained from video capture data, J. Transp. Eng. (2011) https://doi.org/10.1061/(ASCE)TE.1943-5436.0000230.

[31] F. Cunto, F.F. Saccomanno, Calibration and validation of simulated vehicle safety performance at signalized intersections, Accid. Anal. Prev. (2008) https://doi.org/10.1016/j.aap.2008.01.003.

[32] R. Van Der Horst, J. Hogema, Time-to-collision and collision avoidance systems, Proc. 6th Work. Int 1993, pp. 1–12, (doi:10.1.1.511.3548).

[33] M. Althoff, O. Stursberg, M. Buss, Model-based probabilistic collision detection in autonomous driving, IEEE Trans. Intell. Transp. Syst. (2009) https://doi.org/10.1109/TITS.2009.2018966.

[34] D. Gettman, L. Head, Surrogate safety measures from traffic simulation models, Transp. Res. Rec. J. Transp. Res. Board. (2003) https://doi.org/10.3141/1840-12.

[35] J.S. Oh, C. Oh, S.G. Ritchie, M. Chang, Real-time estimation of accident likelihood for safety enhancement, J. Transp. Eng. (2005) https://doi.org/10.1061/(ASCE)0733-947X(2005)131:5(358).

[36] B. Raghuram Kadali, V. Perumal, Pedestrians' gap acceptance behavior at mid block location, Int. J. Eng. Technol. (2012) https://doi.org/10.7763/ijet.2012.v4.339.

[37] C. Avinash, S. Jiten, S. Arkatkar, J. Gaurang, P. Manoranjan, Evaluation of pedestrian safety margin at mid-block crosswalks in India, Saf. Sci. (2019) https://doi.org/10.1016/j.ssci.2018.12.009.

[38] P. Choudhary, N.R. Velaga, Effects of phone use on driving performance: a comparative analysis of young and professional drivers, Saf. Sci. (2019) https://doi.org/10.1016/j.ssci.2018.07.009.

[39] A. Kathuria, P. Vedagiri, Evaluating pedestrian vehicle interaction dynamics at unsignalized intersections: a proactive approach for safety analysis, Accid. Anal. Prev. (2020) https://doi.org/10.1016/j.aap.2019.105316.

[40] S. Das, A.K. Maurya, Defining time-to-collision thresholds by the type of lead vehicle in non-lane-based traffic environments, IEEE Trans. Intell. Transp. Syst. (2019) https://doi.org/10.1109/tits.2019.2946001.

[41] V. Kanagaraj, G. Asaithambi, T. Toledo, T.-C. Lee, Trajectory data and flow characteristics of mixed traffic, Transp. Res. Rec. J. Transp. Res. Board. 2491 (2015) 1–11 https://doi.org/10.3141/2491-01.

[42] A.K. Maurya, P.S. Bokare, Study of deceleration behaviour of different vehicle types, Int. J. Traffic Transp. Eng. (2012) https://doi.org/10.7708/ijtte.2012.2(3).07.

[43] N. Raju, S. Arkatkar, G. Joshi, Experiences of supervised machine learning to replicate driving behavior under traffic environment, Transp. Res. Board 98th Annu. Meet. Res. Board, Washington DC, 2019 https://trid.trb.org/view/1601033.

[44] C. Munigety, V. Vicraman, T. Mathew, Semiautomated tool for extraction of microlevel traffic data from videographic survey, Transp. Res. Rec. J. Transp. Res. Board. (2014) https://doi.org/10.3141/2443-10.

[45] V. Vicraman, C. Ronald, T. Mathew, K.V. Rao, Traffic Data Extractor, http://www.civil.iitb.ac.in/tvm/tde2 2014.

[46] N. Raju, P. Kumar, C. Reddy, S. Arkatkar, G. Joshi, Examining smoothening techniques for developing vehicular trajectory data under heterogeneous conditions, J. East. Asia Soc. Transp. Stud. 12 (2017) 1549–1568.

[47] X. Shi, Y.D. Wong, M.Z.F. Li, C. Chai, Key risk indicators for accident assessment conditioned on pre-crash vehicle trajectory, Accid. Anal. Prev. 117 (2018) 346–356 https://doi.org/10.1016/j.aap.2018.05.007.

[48] C. Schwarz, On computing time-to-collision for automation scenarios, Transp. Res. Part F Traffic Psychol. Behav. (2014) https://doi.org/10.1016/j.trf.2014.06.015.

[49] Q. Meng, X. Qu, Estimation of rear-end vehicle crash frequencies in urban road tunnels, Accid. Anal. Prev. (2012) https://doi.org/10.1016/j.aap.2012.01.025.

[50] A. Tordeux, S. Lassarre, M. Roussignol, An adaptive time gap car-following model, Transp. Res. Part B Methodol. (2010) https://doi.org/10.1016/j.trb.2009.12.018.

[51] K.A. Brookhuis, D. de Waard, Monitoring drivers' mental workload in driving simulators using physiological measures, Accid. Anal. Prev. 42 (2010) 898–903 https://doi.org/10.1016/j.aap.2009.06.001.

[52] B.R. Fajen, Calibration, information, and control strategies for braking to avoid a collision, J. Exp. Psychol. Hum. Percept. Perform. (2005) https://doi.org/10.1037/0096-1523.31.3.480.

[53] Q. Meng, J. Weng, Evaluation of rear-end crash risk at work zone using work zone traffic data, Accid. Anal. Prev. (2011) https://doi.org/10.1016/j.aap.2011.01.011.

[54] E. Polders, J. Cornu, T. De Ceunynck, S. Daniels, K. Brijs, T. Brijs, E. Hermans, G. Wets, Drivers' behavioral responses to combined speed and red light cameras, Accid. Anal. Prev. (2015) https://doi.org/10.1016/j.aap.2015.05.006.

[55] Z. Li, P. Liu, W. Wang, C. Xu, Development of a control strategy of variable speed limits to reduce rear-end collision risks near freeway recurrent bottlenecks, IEEE Trans. Intell. Transp. Syst. (2014) https://doi.org/10.1109/TITS.2013.2293199.

[56] C. Hydén, The development of a method for traffic safety evaluation: the Swedish traffic conflict technique, Bull. Lund Univ. Technol. (1987) https://doi.org/10.1002/2016GC006399.

[57] P. Marchesini, W. Weijermars, The relationship between road safety and congestion on motorways, SWOV Inst. Road Saf. Res. 28 (2010).