IMPACT OF FOG LEVELS ON FREE-FLOW SPEEDS IN MIXED TRAFFIC CONDITIONS

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Resume

The effect of fog levels on drivers' free-flow speeds for various vehicles in mixed traffic conditions is examined in this research. Visibility and free-flow speeds from eight highways are simultaneously collected and analyzed. The findings show distinct driver behavior patterns under different fog conditions. In dense fog, small visibility improvements lead to linear speed increases, while in light fog, speeds are mostly unchanged, though drivers maintain higher speeds than in clear conditions. Regardless of a vehicle type, driving patterns in fog are similar, though specific speeds differ. Cars tend to drive dangerously fast, while trucks remain slower due to limited manoeuvrability. This study offers insights for operational strategies in dense fog, supporting the use of dynamic warning systems and variable speed limits to reduce unsafe speed variations and potential crashes in low visibility.

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1 Introduction

Fog is a phenomenon that occurs when tiny water droplets, along with dust and other air particles, are suspended near the ground, scattering light in all directions. While driving in foggy weather, a driver's view is obstructed by fog particles, substantially affecting traffic operation and safety. Globally, millions of road crashes occur annually due to adverse weather conditions like fog [1].

Drivers in foggy conditions have a limited interaction range, as they cannot observe other vehicles' movements, road signs, or obstacles at longer distances. They may adapt to this low visibility by slowing down [2-5] or by following the taillights of a preceding vehicle [6]. However, some drivers may inadvertently increase their speed [7-8]. Studies show that as visibility decreases, drivers exhibit more erratic behavior in terms of acceleration, deceleration, and maintaining a consistent speed [5, 9-11].

Despite the drivers' efforts to anticipate and drive cautiously in reduced visibility, they may struggle to accurately judge safe stopping distances, leading to unsafe driving conditions. The impact of inadequate stopping sight distance is low on clear road segments [12], but it increases with denser fog levels. It is essential to understand how drivers adjust their speed according to varying visibility levels on long road stretches, as stated by McCann and Fontaine (2016) [13]. Therefore, the objective of this paper was to evaluate drivers' choice of free-flow speed under varying fog conditions on straight, unidirectional carriageways, urban and inter-urban highways, and mid-block sections with mixed traffic conditions.

2 Literature review

The literature in the context of present study is classified into effect of fog on traffic parameters, driver behaviour, and the psychological and physiological effects of fog.

2.1 Impact of fog on traffic parameters

Several researchers have studied the effect of fog on traffic parameters, including flow, speed, and headway.

NCHRP 95 [14] reported that the probability of speeding is most prominent in isolated vehicles, increasing from 55% to 69% in dense fog scenarios. Edwards (2002) [15] found that fog decreases the average peak-hour traffic volume by 9.2%. Trick et al. (2010) [16] suggested that the high-density traffic, combined with navigational challenges, adversely impacts older drivers more in clear conditions than in fog.

2.2 Driver behavior in fog

Studies have focused on driver behavior, examining speed, distance headway, and time headway [2, 5, 17]. Research indicates that foggy conditions lead to significantly lower average speeds, with passenger cars being more affected than trucks [4]. Additionally, the distance and time headways between vehicles decrease with reduced visibility [2, 18-22]. Drivers tend to overestimate vehicle spacing in fog, leading to closer following distances [2, 21].

Research shows that drivers' speed, reaction time, and steering vary depending on their experience, visibility, road type, and driving conditions [23-25]. Gao et al. (2020) [26] indicate that drivers in foggy conditions may accelerate earlier to follow leading vehicles closely, while Deng et al. (2019) [27] found that braking reaction time increases by 30% in fog. Furthermore, in mixed traffic scenarios, different categories of vehicles share the same roadway, frequently disregarding the assigned lanes. This situation complicates driving in foggy conditions. Consequently, it is essential to examine driving behavior in such mixed traffic environments.

2.3 Psychological and physiological effects

Fog can lead to risky manoeuvres, physiological fluctuations, and psychological distress, impacting traffic safety [28]. It increases the risk [29] and severity [30] of crashes. Wu et al. (2018) [31] found that fog raised crash risk by 40% in Florida. Additionally, fog can greatly hinder drivers' capacity to identify and react to hazards on the road, thereby increasing the dangers associated with shorter following distances [32]. Incidents occurring in foggy conditions often involve several vehicles and can lead to collisions and pile-ups [33]. Lynn et al. (2002) [34] investigated multivehicle crashes in Virginia attributed to fog and recommended using variable speed limits (VSL) to alert drivers to potential hazards [35-37].

2.4 Insights from literature and objectives of the study

The literature reveals a significant influence of fog on traffic parameters like speed, flow, and headway. However, studies often involve multiple factors, obscuring the pure impact of fog. Investigations should consider solely the impact of fog, keeping other variables consistent. The need for further research is highlighted by inconsistent findings and incomplete mitigation strategies like VSLs. In this study, an attempt is made to provide a clearer understanding of how fog impacts driving behavior, helping to develop better traffic management and safety strategies for foggy conditions. This study addresses the gap in the literature by using the real-world data from various visibility levels to model how drivers choose their speeds under different fog conditions.

The objective of this study was to model drivers' choice of free-flow speed across a broad range of fog conditions on highways with mixed traffic, maintaining consistency in other influencing parameters. The scope of the study involves simultaneous data collection of fog and traffic on mid-block sections on highways during the daytime. In this study, we selected mid-block sections in plain terrain to collect data. This ensured consistency by minimizing external factors such as curves or gradients that could influence drivers' speeds. According to the Indian Highway Capacity Manual [38], vehicles traveling at free-flow speed are those maintaining a time headway of more than 8 seconds with any leading vehicle that shares a lateral overlap with them. We applied this definition to identify vehicles traveling at free-flow speed among all vehicles on the study sections.

3 Data collection

To address the research gap mentioned in the previous section, it was necessary to collect a large amount of traffic data for several traffic and fog conditions. Traffic was recorded using a camcorder with 90x zoom, 10 MP size and high-definition recording capability mounted by the authors at a suitable vantage point (tall tripod or foot over bridge). Data collection was conducted in several urban and inter-urban locations characterized by significant foggy weather. The overall methodology of this study is provided in Figure 1.

Mid-block road sections are meticulously chosen to eliminate external factors such as road geometry, curves, parked vehicles, or other land use that may obstruct vehicle movement, leaving only prevailing fog levels as the variable. The traffic video data was collected during winter mornings, repeatedly at the same locations, to capture a comprehensive range of fog conditions across most sites. Table 1 highlights the traffic data collection locations and their details. NH and SH indicate national highways and state highways in Table 1.

Non-car vehicles, including two-wheelers, three-wheelers, buses, trucks, and light commercial vehicles (LCVs), constituted between 11% and 88% of the total observed traffic across the studied sections, indicating a high level of vehicle heterogeneity.

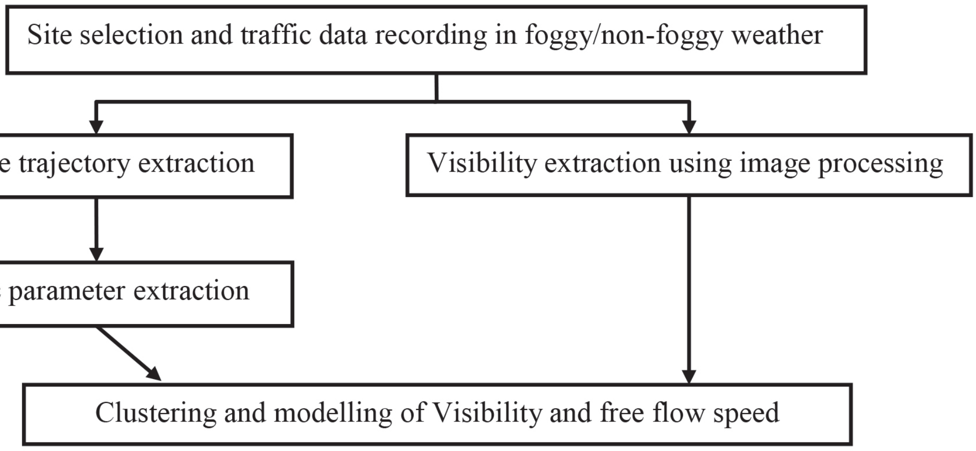


***Figure 1** Flowchart of the overall methodology*

***Table 1** Traffic and fog data collection locations*

S. No	Name of the road	Location of the road	Lanes per carriageway	Type of road
1	NH 16, (Chennai Kolkata Highway)	Salkia, dist Howrah West Bengal	3	Urban
2	West Bengal SH-13	Chandannagar, Dist. Hoogly, West Bengal	2	Inter-urban
3	NH-5	Knowledge City, Dist. SAS Nagar, Punjab	3	Urban
4	NH-7(Chandigarh Patiala Road)	Ramgarh, Dist. SAS Nagar, Punjab	2	Urban
5	NH-7 (Rajpura bypass)	Patiala Road, Dist. Patiala Punjab	2	Inter-urban
6	NH-8	Zirakpur, Dist, SAS Nagar, Punjab	2	Inter-urban
7	NH-44 (Grand Trunk Road)	Rajpura, dist. Patiala, Punjab	3	Inter-urban
8	NH 44, Jammu Delhi Road	Madhopur, Dist Fatehgarh Sahib, Punjab	3	Inter-urban

4 Data extraction

Two-fold data extraction of traffic and fog are conducted simultaneously from the selected traffic locations in Table 1 is presented below.

4.1 Traffic data extraction

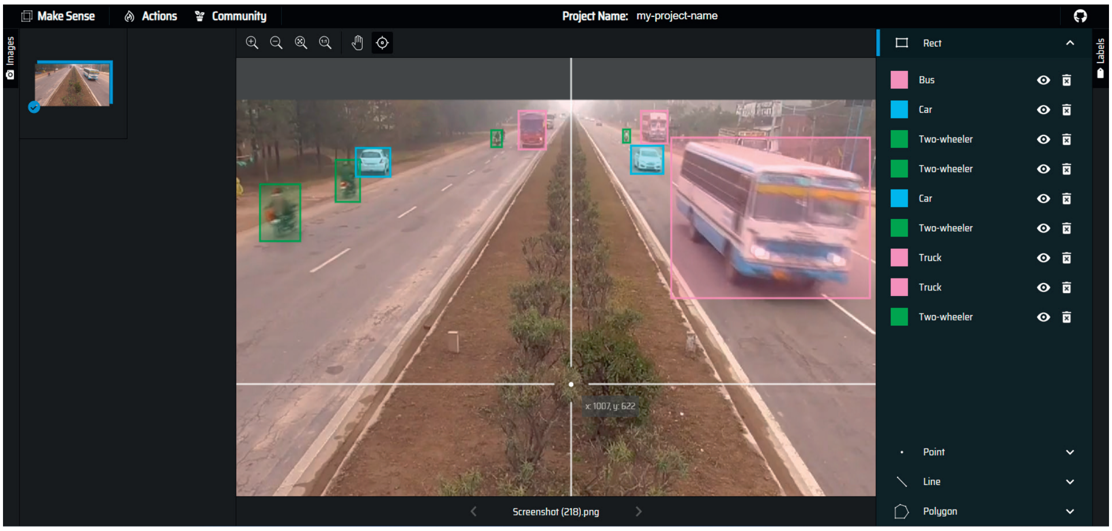
The present study uses the YOLOv8 detection algorithm [39] with the DeepSort tracking algorithm for vehicle detection [40]. Pre-training is conducted by manually drawing rectangular boundaries over vehicle images retrieved from the traffic videos, and classifying them into seven different vehicle classes (Figure 2). The algorithm is trained using vehicle image datasets from both foggy and non-foggy weather conditions. Accuracy of new vehicle detection by the trained YOLO model ranges from 50% to 97% with the vehicle types. Then, all the collected videos, totalling over 1900 minutes, underwent automatic vehicle detection by the YOLO (Figure 2). Image coordinates of the bounding box edges for each detected vehicle over every time frame are saved.

The image coordinates of the detected vehicles are then transformed into field coordinates using a camera calibration technique adopted from [41]. The converted field coordinate file contains the columns i, $X_{i,t}$, $Y_{i,t}$, t where i denotes the vehicle number, $X_{i,t}$ and $Y_{i,t}$ denote the longitudinal and lateral coordinates of the vehicle at time t, respectively. By knowing the time of travel of the vehicle over a large trap length (>100 m) for every section, individual vehicle speeds were calculated.

To conduct the analysis on free-flow speed, the IDs (identification numbers) of vehicles travelling at free-flow speed are separated from the overall individual speed dataset, based on the criteria outlined in the Indian Highway Capacity Manual [38]. The term "free-flow condition" means that vehicles can move without being slowed down by prevailing traffic.

4.2 Measurement of visibility

In foggy weather conditions, road visibility can be quantified through the use of various devices such as a Visiometer, Photovoltaic cell [42], Optical sensor [43] etc. Hautiere et al. (2007) [44] have established a novel image-based method to estimate visibility, defining it as the distance at which the contrast threshold of a dark object decreases to 5% of its original value in fog. Say,
$BV_{f,w}$ = Brightness of white portion in foggy weather,



2(a) Manual detection for training

2(b) Automatic vehicle detection

Figure 2 *Vehicle trajectory extraction using YOLOv8*

$BV_{f,b}$ = Brightness of black portion in foggy weather,
$BV_{c,w}$ = Brightness of white portion in clear weather,
$BV_{c,b}$ = Brightness of black portion in clear weather.

The distance in a foggy weather when C_r (Contrast ratio) equals 0.05 is termed as visibility by Hautiere et al. (2007). So, at visibility,

$$C_r = \frac{BV_{f,w} - BV_{f,b}}{BV_{c,w} - BV_{c,b}}. \quad (1)$$

In the present paper, an umbrella was painted black and white and it was moved along the road at every site and every 10-15 min or whenever visibility has drastically changed. $BV_{f,w}$ and $BV_{f,b}$ are recorded using the brightness values of pixels (mouse clicked manually in the video frame), corresponding to the black and white portions of the umbrella at various distances from the camera. $BV_{c,w}$ and $BV_{c,b}$ are recorded earlier in clear weather conditions. The distance of the object from the camera is calculated using the camera calibration [41]. Figure 3 demonstrates the process.

A sample plot for one of the sites of C_r against various distances is shown in Figure 4. Negative exponential curve has the best fit (Equation (2)) $(R^2 = 0.79)$ for these plots. Based on the equation, the distance corresponding to C_r = 1 was calculated.

$$y = 2.68e^{-0.019x}, \quad (2)$$

where, $y = C_r$ and x = distance in m.x = distance.

This analysis of visibility calculation is conducted for visibility up to 800 m and verified with the meteorological data of the nearest weather station at the time of recording. For visibility more than 800 m, only meteorological visibility values are considered.

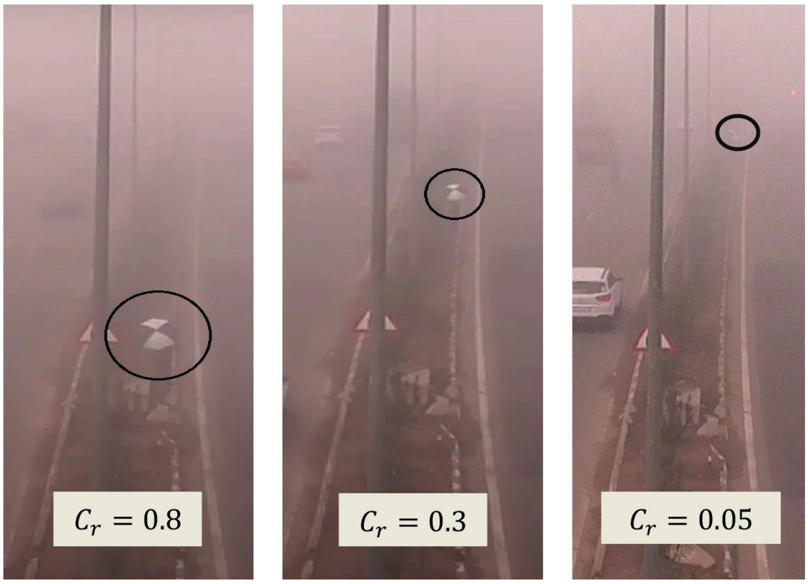


***Figure 3** Estimation of visibility using black and white object*

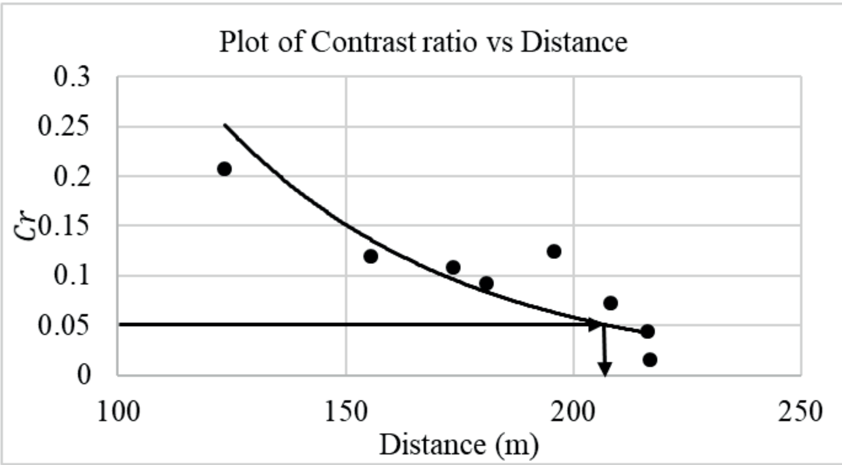


***Figure 4** Contrast ratio vs distance plot for visibility estimation*

5 Data analysis

Out of the entire vehicle dataset, 3,945 vehicles operated in free-flow conditions. The composition included 2,258 cars (57.2%), 627 two-wheelers (15.9%), 276 LCVs (7.0%), 633 trucks (16.0%), 49 buses (1.2%), and 102 three-wheelers (2.6%). Further analysis focused on cars, trucks, LCVs, and two-wheelers, and excluded buses and three-wheelers due to their limited sample sizes. Visibility values during the travel were recorded for these vehicles, as well and plotted against free-flow speed on a logarithmic graph (Figure 5).

Figure 5 shows an initial increase in the free-flow speed with visibility up to a certain limit, then a reduction with further visibility improvement. Further, contour maps were generated to display the distribution of the dataset, including percentage frequency and cumulative frequency (Figure 6). These maps reveal three distinct sections, prompting further investigation into potential differences in driver behavior across these regions.

5.1 Clustering of visibility

A box-and-whisker plot is shown in Figure 7 for separate vehicle types for the same visibility grouping of 100 m intervals each. From the box-and-whisker plot, one can make the following observations:

- At lower visibility levels, free-flow speed increases with visibility.
- Median value of the free-flow speed has increased for visibility 0 to 300 m after which there has been a decrease in the free-flow speed for visibility 300 m to 500 m. Thereafter free-flow speed has remained consistent.
- Contrary to the larger spread of the dataset in Figure 5, vehicle type-wise free-flow speed is not observed to have a large variation (Figure 7).
- All the vehicle types have similar speed-visibility plot patterns. Cars have a higher mean free-flow speed in every visibility range as compared to other vehicle types.

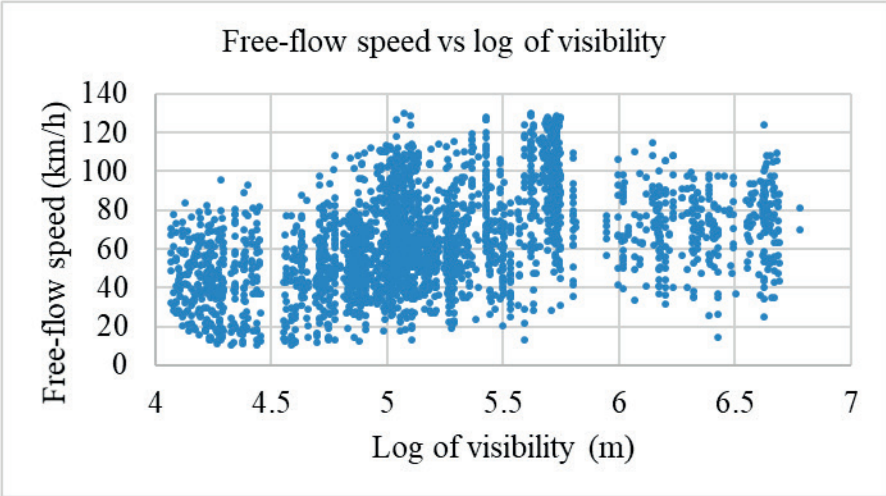
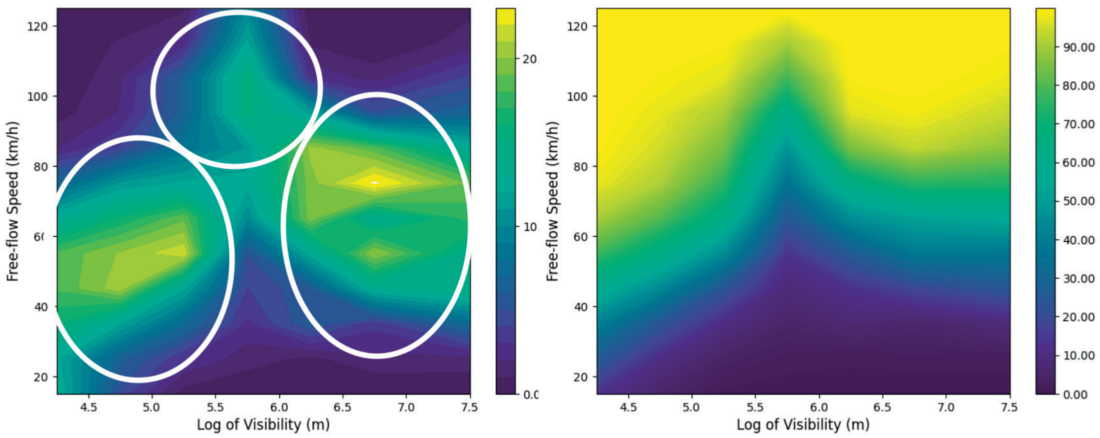


Figure 5 *Free-flow speed vs log of visibility*



a) Contour map of percentage frequency *b) Contour map of cumulative percentage frequency*

Figure 6 *Contour plot of percentage frequency and cumulative percentage frequency of free-flow speed vs visibility*

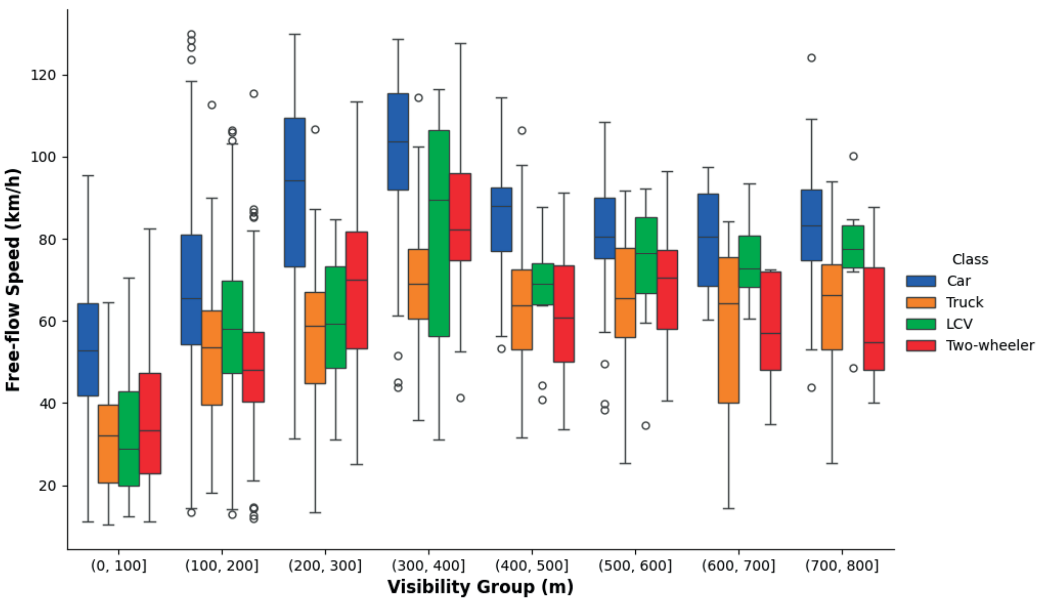


Figure 7 *Box and whisker plot of Free-flow speed vs Visibility groups*

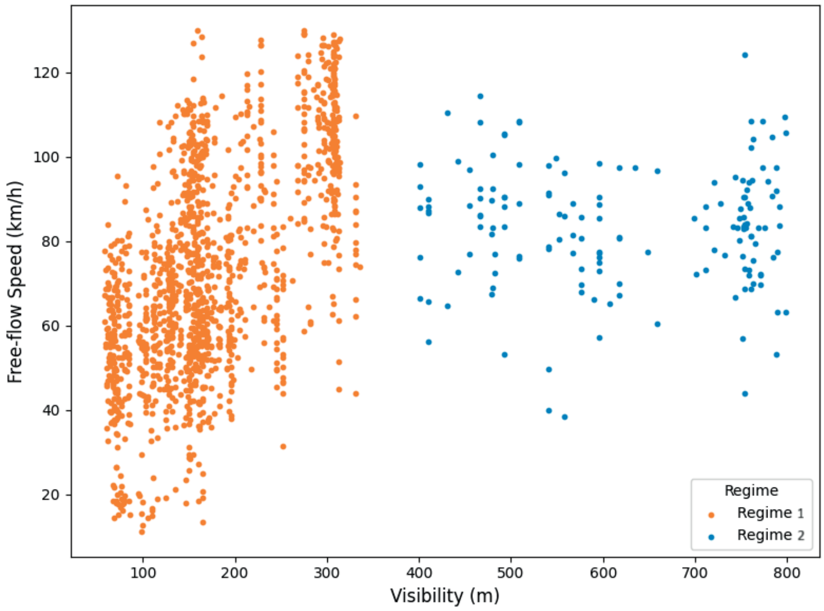


***Figure 8** Clustering of visibility with free flow speed for cars showing two distinct clusters*

The one-way ANOVA indicates a significant overall difference in means across the visibility groups 1-8 ($p < 0.05$). Pairwise ANOVA reveals statistically different free-flow speeds at most group levels ($p < 0.05$), except for groups 2 and 6 ($p = 0.07$), groups 3 and 7 ($p = 0.59$), and groups 5, 6, and 7. From the ANOVA test and box-and-whisker plot, it is evident that drivers reduce speed in visibility up to 200 m, then increase speeds between 200 m and 400 m, albeit higher than in clearer conditions (> 400 m visibility). Authors of [7-8] also observed this counterintuitive result, suggesting that drivers may increase speed at medium or shallow visibility levels due to a perceived decrease in visible information in the peripheral field of view.

It is essential to determine if the speed changes continuously with visibility or if there are specific fog levels where it changes abruptly, which can be confirmed by identifying distinct clusters. To advance in this direction, K-means clustering has been opted for the foggy dataset (up to 800 m) only. By performing a hard clustering analysis, one can distinctively identify the fog level where the driver behaviour changes. The optimum number of clusters is identified by the Silhouette score [45]. The Silhouette score values for 2, 3, 4, and 5 numbers of clusters are 0.75, 0.59, 0.59, and 0.50 respectively. Thus, the optimum number of clusters in foggy weather is two. The clustering of free-flow speed data of cars in foggy weather is shown in Figure 8, other vehicle type datasets can be clustered similarly. Considering a separate regime for clear weather conditions, the entire dataset is now clustered into three regimes as mentioned below. The regimes are shown for cars and similar regime boundaries are observed for other vehicle types.

(1) Regime 1: Visibility values less than 382 m. (speed increases with visibility)
(2) Regime 2: Visibility values 382 m to 800 m. (higher speeds and shallow fog)
(3) Regime 3: Non-foggy data (clear weather conditions).

The clustering analysis reveals three distinct ways in which the drivers perceive fog. We checked the regime 1-regime 2 boundary for different vehicle types and found it lying at almost the same range (< 382 m for cars, < 382 m for trucks, < 390 m for LCVs, and < 400 m for two-wheelers). This suggests that driver behavior patterns with fog remain consistent across vehicle types. Thus, drivers assess fog levels independent of their vehicle type.

5.2 Modelling of free-flow speed vs visibility

Distinct regime-wise models are necessary to illustrate how visibility affects the free-flow speed across different fog levels. In this regard, regression curves are plotted for all the vehicle classes in regime 1. In regime 2, there is no significant relationship between visibility and free-flow speed, but mean speed is notably higher than in regime 3. A linear relationship between free-flow speed and visibility levels can accurately represent the trend of visibility versus speed across all the vehicle types for regime 1. Increasing the degree of the equation does not significantly enhance the goodness of fit of the regression curve. Consequently, the entire dataset is modelled as regression lines, (Equation (3)) differently for different vehicle types.

$$u = av + b + R \tag{3}$$

where u = free-flow speed in km/h, v = visibility in m, a = slope and b = intercept of the regression line, R = Residual of the corresponding regime. Table 2 shows the regression parameters for all vehicle types. The mean and standard deviation values against the corresponding regime and vehicle type are also expressed in Table 2. Overall, the residuals (R) are observed to statistically best follow Gamma (3P) distribution as ascertained by the Kolmogorov-Smirnov test, but they do closely follow normal distribution as well. We assess the consistency of residual spread about the regression curve with changes in visibility. Initially, the Goldfeld-Quandt (G-Q) test is conducted on regime 1 dataset for each vehicle type. The resulting p-values for cars, trucks, LCVs, and two-wheelers are 0.01, 0.85, 0.71, and 0.80, respectively, indicating heteroscedastic residuals in the cars' dataset. To address this, residuals are modified (R_m) linearly with visibility. Subsequent G-Q tests on the modified residuals confirm homoscedasticity, allowing them to be modelled as a single distribution. The equation of Gamma (3P) distribution is given as,

$$f(x) = \frac{\alpha}{\beta}\left(\frac{\beta}{x-\gamma}\right)^{(\alpha-1)} \exp\left(-\left(\frac{\beta}{x-\gamma}\right)^{\alpha}\right), \quad \gamma \le x < \infty, \tag{4}$$

where, α = shape parameter, β = scale parameter and γ = location parameter.

All distribution parameters and p-values are shown in Table 2.

Table 2 shows that the standard deviation of free-flow speed is higher in regime 1 (dense fog) than in regime 2 (shallow fog) for all vehicle types, indicating greater speed variability and potentially higher crash risk [46]. An F-test reveals f-values of 25.47, 35.19, 27.89, and 9.12 for cars, trucks, LCVs, and two-wheelers, respectively, indicating significant variance differences in free-flow speeds between the two regimes for each vehicle type. We use the linear regression values from Table 2 in Equation (3) and plot them in Figure 9, along with the corresponding safe stopping sight distance (SSD) curves for comparison. The SSD calculations consider deceleration, road friction (0.35), and reaction time (2.5 sec) as per AASHTO (2018) [47]. Vehicles travelling below the safe SSD curve are considered safe, whereas those with free-flow speeds above the curve may pose a risk during the emergency braking.

Cars generally maintain higher free-flow speeds in foggy conditions compared to other vehicle types, with trucks having the lowest speeds, perhaps due to their limited manoeuvrability. Regression curves show that at visibilities below 60 m, the safe speed for cars determined by SSD criteria is higher than the modelled speed. In regime 1, 14.85% of cars exceed the safe SSD speed, while less than 1% of other vehicles do. This indicates a higher risk of collisions for cars in dense fog if they do not adhere to safe SSD. This result can help

***Table 2** Linear regression parameters of free flow speed-visibility models*

Vehicle type	a	b	Mean free-flow speed		Standard deviation of free-flow speed		Parameters of Gamma (3P) distribution			
			Regime 1	Regime 2	Regime 1	Regime 2	α	β	γ	p-value of residuals with observed distribution
Car	0.21	37.12	72.82	83.22	25.43	14.48	220.48	0.03	-5.7	0.24
Truck	0.13	29.79	52.31	63.41	18.54	17.37	117.48	1.49	-175.6	0.62
LCV	0.18	25.7	47.49	70.72	22.32	13.95	41.8	2.96	-124.2	0.99
Two-wheeler	0.2	20.41	52.62	62.01	20.65	15.84	108.52	1.5	-163.4	0.71

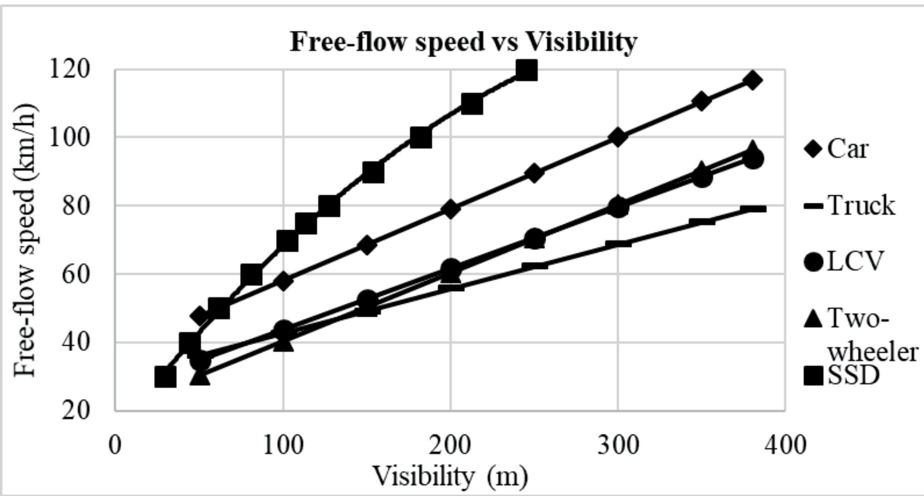


***Figure 9** Linear regression plots of Free flow speed vs Visibility for Regime 1 and safe stopping sight distances for different visibilities*

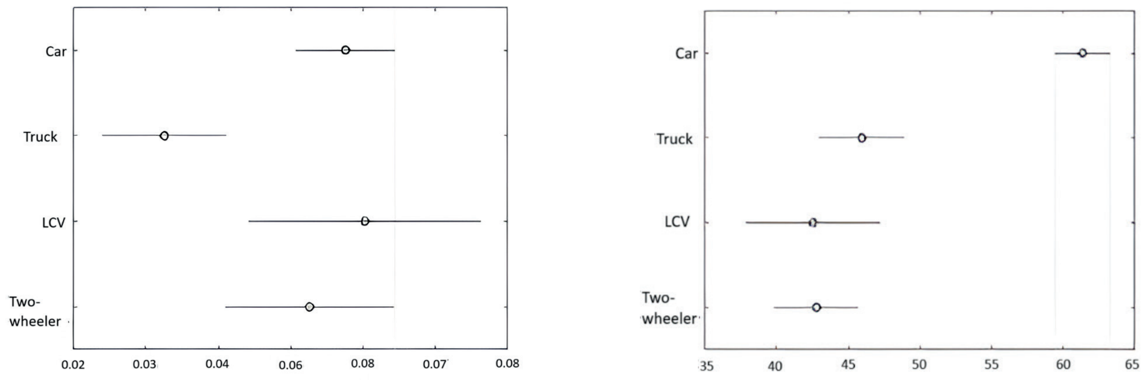


Figure 10 *Slope (left) and intercept (right) comparison of the regression models for different vehicle types*

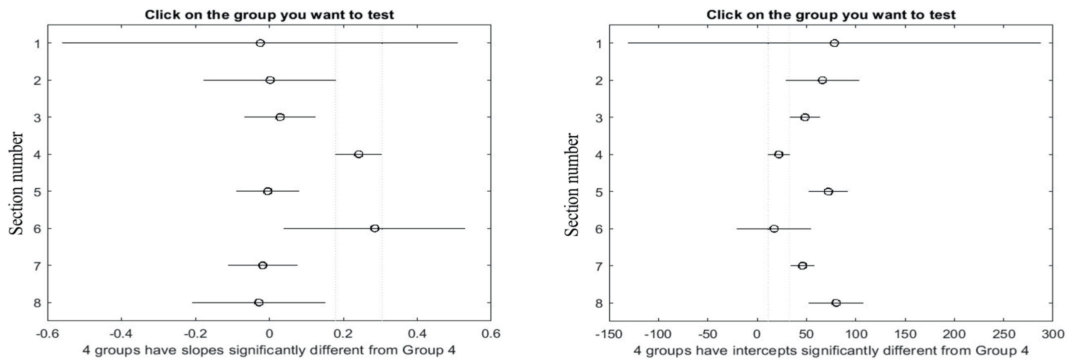


Figure 11 *Slope (left) and intercept (right) comparison of the regression models for different sections*

to improve the road safety by informing the development of targeted safety campaigns for car drivers, adaptive traffic control measures for over-speeding vehicles, and effective traffic regulations during dense fog.

5.3 Comparison of obtained model for different types of vehicles

Figure 10 shows the analysis of covariance and the variation in slopes and intercepts among vehicle types. Trucks have a statistically lower slope, indicating consistent driving despite a decline in visibility, as their speeds are already limited in clear conditions and do not significantly decrease further. Cars have a higher intercept, showing higher free-flow speeds at zero-visibility. The intercepts for trucks, LCVs, and two-wheelers are similar, but cars' intercepts are significantly higher. This indicates that cars are driven faster than other vehicles, and car drivers do not exercise sufficient caution at very low visibility levels.

5.4 Location-wise validation of the model

The site-wise variation of slope and intercept for the regime 1 dataset is examined through analysis of covariance (Figure 11) to determine if the relationship between the free-flow speed and visibility holds true across different locations. While there is a slight variation in slopes between sites, the intercept remains statistically consistent for each section, suggesting uniform driver behavior across these locations.

6 Summary of findings and future scope

In this study it was examined how fog affects vehicle free-flow speeds on inter-urban and urban highways in mixed traffic. Results show a rising trend between the fog levels and vehicle speeds at low visibility (below 382 m). In contrast, at higher visibility levels (382-800 m), drivers tend to drive faster than in clear conditions and do not significantly adjust their speed for fog. This behavior is consistent across all vehicle types, although trucks show less variation due to their lower maximum speeds. To summarise, the research conducted in this paper can provide the following insights:

1. Free-flow speeds in foggy weather increase initially with visibility up to 382 m, then remain consistent but higher than in clear weather conditions.
2. Drivers perceive fog levels differently, with consistent variations across vehicle types, as observed through clustering analysis. The fog perception for each regime (dense, shallow or no-fog) needs separate modelling.
3. Linear plots for driving in denser fog demonstrate that the free-flow speeds increase with visibility, with varying rates for different vehicle types. For cars, trucks, LCVs and two-wheelers moving in

foggy weather, the free flow speeds increase by 2.1, 1.3, 1.8 and 2 km/h, respectively, with every 10 m improvement in visibility levels.

4. In dense fog (< 382 m), 14.85% of cars exceed the safe speed, posing potential safety risks.
5. Speeds remain consistent in shallow fogs (382-800 m visibility) but are approximately 10% higher than in clear weather conditions for all the vehicle types.
6. Cars consistently have the highest speeds across all visibility conditions, while trucks are the least affected by visibility as their speeds are already limited in clear conditions.

The findings from this study can be useful input tools for traffic planners, road designers and for a work zone safety in fog. The authors propose the following suggestions for safe and efficient operations in foggy weather, as an immediate application of this paper.

- Practitioners can highlight this inadvertent speed increase in road safety programs using visual aids (e.g., photographs), implement it in driver training modules, enforce it through adaptive speed limit signs, and integrate it into advanced driver assistance systems to mitigate risky driving behaviors.
- As cars drive faster than safe stopping sight distances in low visibility (0-382 m), drivers need to stay alert to avoid speed variations. Practitioners can install dynamic warning systems, implement variable speed limits, especially on roads with changing geometries and at work zones.
- Variable speed limits can be implemented to mitigate the speed variation between changing fog levels, to prevent a sudden backward shockwave propagation. The speed limits can be ascertained by calculating safer accelerations or decelerations, along with the findings in this paper, as the fog levels vary on a longer stretch of road.

This study focused solely on free-flow speed for analysis, but a comprehensive understanding of driving in foggy weather should examine car-following characteristics like headway, acceleration, and deceleration in foggy conditions. Researchers can use the outcomes from this study to simulate how varying fog levels on a road affect vehicle speed and generate the simulated shockwaves resulting from abrupt visibility changes. Implementing these findings in live speed display devices can help to adjust speeds gradually, reducing the backward shockwave caused by sudden visibility drops. Future studies on shockwave propagation in fog can further reduce fog-related accidents. This paper provides foundational insights for such research and practical applications.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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