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Fatality risk analysis of vulnerable road users from an Indian city

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ABSTRACT

Introduction: Road traffic fatalities are externalities associated with urbanization, motorization, and road infrastructure development. Globally, low and middle-income countries contribute to more than 90% share of total accidents. Bengaluru is India's fourth-largest populous city and has exponential vehicle growth, similar to other cities in a developing economy. Lack of safe road infrastructure to support this growth leads to an increased risk for road users resulting in more road accidents. *Method:* It is crucial to identify the vulnerable road users (VRUs) and assess the fatality risk that would help policymakers adopt adequate measures to reduce their risk. Bengaluru city accident data from First Information Reports (FIRs) for seven years is collected and analyzed for the current study. The Who-hit-whom matrices are developed for identifying VRUs. Further, a risk-based model is developed to estimate fatality risk, followed by sensitivity analysis for different transport scenarios. *Results:* The main results from the study are: 1) Increase in fatalities are observed with increase in motorization 2) Pedestrians and two-wheelers are the most vulnerable road user with highest risk 3) Fatality risk scenario analysis showed a maximum reduction in traffic fatalities with increased public transportation mode share as motorization level increase 4) Increasing the proportion of distance traveled by cycle helped in further decreasing the number of fatalities in high bus scenario. *Conclusion:* All the results favor sustainable transport policies for the city in reducing the number of road user fatalities. Practical applications: In light of accident investigation, the paper provides insight into sustainable transport strategies for transport decision-makers to enhance the safety of VRUs.

1. Introduction

Road accidents ranked as the eighth leading cause of casualties, globally. Nearly, 1.3 million road users die in traffic crashes every year (World Health Organisation, 2018). Low and Middle-Income Countries (LMICs) attribute to more than 93% of world road traffic crashes. Lack of strict law enforcement and inefficient post-crash care are the main challenges faced by LMICs resulting in high crash rate. India has third largest road networks in the world (Praveen, 2018) and is one of the fastest growing economies. Road network and vehicle population of India have increased tremendously since 2000 (Mishra and Mishra, 2017). India accounts for 11% of the total world traffic fatalities (Road Accdients in India, 2019). Nearly, 39% of accidental deaths in the country is due to traffic accidents (Accidental Deaths & Suicides in India, 2020). Bengaluru is the fourth largest populous city in India and has a very significant role to play in the economic development of the country. In 2020, Bengaluru ranked third in terms of traffic accident-related deaths accounting for 7.2% of total deaths, among 53 mega cities in the country (Accidental Deaths & Suicides in India, 2020). Globally, pedestrians, bicyclist and two-wheeler users are considered as Vulnerable Road Users (VRUs). The fatality rate is high for VRUs, as sharing the same road space with other motorized vehicles increases their susceptibility to crashes. In Bengaluru city, VRUs are accounts for 94% of the total person killed in road fatalities. Pedestrians and two-wheeler users constitute the major proportion. Several factors attribute to fatality including driver behaviour, vehicle characteristics, road infrastructure and system features.

In developing economies like India, the available road space is shared by all the road users i.e., heterogenous traffic. Over the past decade, increase in infrastructure-based solutions (Verma et al., 2021) to adhere to rising travel demand has resulted in tremendous growth in vehicular population (Transport Department, 2017). Increased motorized vehicles pose a great threat to VRUs and the impact of motorization on the risk of fatality is sparsely explored for developing economies. Thus, an attempt is made to model and assess the impact of different motorization levels for various vehicle mix and associated risk. In this

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study, Bengaluru city's road fatalities is analysed for seven years from 2011 to 2017. The objectives are (1) to understand the patterns and trends of road traffic fatalities in Bengaluru city. (2) to develop who-hits-whom matrix to identify threats to VRUs. (3) to analyse the change in risk for VRUs by comparing different motorization scenarios.

In the next section review of literature on traffic fatalities is explored. Data collection is discussed in the third section of the paper. A methodology flow chart with detailed explanation on each step is presented in section four. The section explains the development of fatality-risk model and eight traffic growth scenarios. The estimated traffic fatalities for different traffic growth scenario are critically discussed in Section 5 of the manuscript. Lastly, policy implications are discussed followed by conclusion and limitation of the paper.

2. Literature review

Abreu and Hoeffler (2021) studies the gain in life expectancy with reduction in road fatalities for South Africa. The study highlighted that men accounts for almost 76% of the road fatalities and reduction in traffic fatalities would increase their life expectancy by 0.85 years. Goel et al., (2018) studied positive association between flyovers and fatalities. Further, Vehicle Miles Travelled also has positive association with road fatalities. The severity of road traffic crashes is evaluated by developing Case Fatality Ratio in association with Human Damage (HD) for China (Wang et al., 2019). The study identified that the fatality rate could be substantially reduced by improving the infrastructure for VRUs. Logistic regression model is developed to examine the severity of traffic collisions involving VRUs and comparison is done among seven European countries (Olszewski et al., 2019). Type of urban area and lighting conditions are identified to be the significant variables among all the countries. The severity of traffic crashes involving pedestrians and the factors likely to influence the occurrence of crashes are studied using hierarchical ordered model (Kim et al., 2017). Modelling result shows that age of pedestrians, truck or heavy vehicles and weather conditions have significant impact on the severity of pedestrian accidents. Poisson-lognormal mixture regression model is developed to assess the traffic fatality incorporating commuter travel distance along with other variables for India (Goel, 2018). Shaaban et al. (2021) studied the traffic violations and its impact on fatalities for Qatar. Speed violations and careless driving are observed to be the key factors leading to road crash.

3. Data collection

In India, the most widely available road crash data is from the traffic police department. There is still lack in adoption of advanced and scientific approach in road accident data collection and documentation. Many traffic accidents cases, especially minor injury cases are believed to be not reported for many known and unknown reasons in developing economies (Jacob and Aeron-Thomas, 2000). Hence, traffic fatalities cases are more reliable for analysis than underreported minor injury crashes. Therefore, in this study, traffic fatalities for Bengaluru city are utilized for analysing the vulnerability of VRUs for different motorization scenarios. Bengaluru is the capital city of the state, Karnataka, located in the southern part of India with an area of 740 sq. km. Road crash data for Bengaluru city is recorded and maintained by Bengaluru Traffic Police (BTP). First Information Report (FIR) summary of each case for seven years from 2011 to 2017 is collected from State Crime Record Bureau (SCRB). FIR is the first set of information documented by police as reported by the people involved in crash or by eyewitness or by the police official in the absence of any eyewitness. FIR summary is a brief version of the actual FIR, that has concise information on traffic fatalities. The information includes time and day of the road crash, crash location, brief description on accident, vehicles involved, and socio-demography of persons involved in crash. In addition, the traffic fatality data obtained from SCRB is translated to English, since FIR summary was documented in the local language 'Kannada'. Registered fatality cases with incomplete details are excluded from the analysis. The year wise summary of fatalities is given in Table 1.

The number of fatalities reduced from 2011 to 2017, however, 766 traffic fatalities is registered in the year 2019 (Bengaluru Traffic Police, 2021). The difference in the cases registered and number of fatalities reported explains that there is more than one person killed in few road crashes. Further, the number of non-reported cases is also reduced over the years.

4. Methodology

The flow chart of methodology followed in the study is presented in Fig. 1. Accident data language translation and extraction is followed by accident trend analysis. Year wise, hour wise, mode wise, age and gender wise trends in traffic fatalities is assessed for the years 2011–2017. Further, victim and offender interactions are reviewed using who-hits-whom matrix, followed by identification of VRUs. In this study, 'victim' refers to the road user killed in the event of crash and 'offender' is the road user whose interaction caused victim's death in the incident of road crash. For example, consider a case that a two-wheeler road user goes out of control and hit a car leading to death of the two-wheeler user; in this case, the fault is of two-wheeler road user. However, in the context of current study, 'victim' road user is two-wheeler user and 'offender' road user are car user i.e., who died by whom is studied without considering the actual reason leading to fatality. The assumption is one of the limitations of the paper, but the primary objective is to assess the vulnerability of road users sharing same space. Further, in the next steps, fatality-risk model is calibrated, and transport growth scenarios are defined followed by estimation and evaluation of traffic fatalities for different motorization scenarios.

4.1. Risk-based model

Risk-based method developed by Bhalla et al. (2007) is adopted to model and assess the fatality risk on VRUs. The method proposes that the probability of a fatal crash between two road users can be modelled as the product of the probability that road users involved in a crash and the probability of being a fatal crash. Thus, the probability of fatal crash is given as,

$$Fatal_{victim}^{threat} = C_{victim}^{threat} X r_{victim}^{threat} \tag{1}$$

where, C_{victim}^{threat} is the probability that a road user (victim) is struck by a vehicle (threat), and r_{victim}^{threat} is the Case Fatality Ratio (CFR) for the victim of the crash. For example, $r_{pedestrian}^{car}$ denotes the probability that pedestrian killed in a car-pedestrian crash, likewise for other pairs of transport modes users involved in a traffic fatality. Further, $r_{car}^{environment}$ demotes single-vehicle crash in which car is a victim road user and physical environment is threat.

The probability of a crash event between victim and threat C_{victim}^{threat} depends on several factors like population of road users belonging to victim's travel mode (U_{victim}), at-risk distance travelled by victim (d_{victim}), total number of vehicles belonging to threat's travel mode (M_{threat}),

Table 1
Year Wise Summary of Fatalities.

Year	No. of Cases Registered	No. of Fatalities Reported	Blanks/ Unknown Victim	Total Fatalities
2011	733	778	4	782
2012	778	801	8	809
2013	785	857	10	867
2014	749	789	3	792
2015	748	758	1	759
2016	797	816	1	817
2017	627	639	2	641

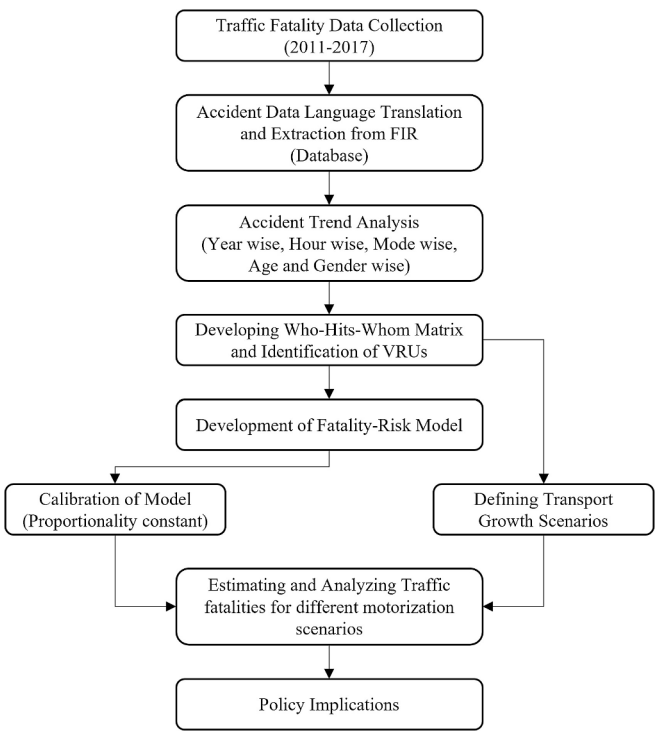

Fig. 1. Methodology Flow Chart.

distance travelled by threat vehicles (d_{threat}), vehicle attributes, driver attributes, road infrastructure and broader systematic attributes. Since the same road space is shared by all vehicles, it is assumed that all vehicles are equally exposed to each other. Thus, the probability of occurrence of crash event between two road users is given as,

$$C_{victim}^{threat} = K_{victim}^{threat} X U_{victim} X d_{victim} X M_{threat} X d_{threat} \quad (2)$$

where, K_{victim}^{threat} is the proportionality constant that accounts for vehicle attributes, driver attributes, road infrastructure and broader systematic attributes.

The CFR (r_{victim}^{threat}) is the probability of fatality in the event of road crash and depends on pre-crash variables that describe the characteristics of vehicles and victims, crash condition and post-crash victim care. The CFR matrix developed by Bhalla et al. (2007) based on different studies conducted in US and Delhi is presented in Table 2.

The CFR value for bicycle is assumed to be same as pedestrian in this study because of their similar vulnerable nature. The CFR values would

Table 2
Crash Fatality Ratio (CFR) Matrix.

	Threat				
Victim	Pedestrian	Two-Wheeler	Car	Bus	Environment
Pedestrian	0	0.040	0.080	0.135	0
Two-Wheeler	0.01	0.021	0.080	0.135	0.053
Car	0	0.002	0.009	0.072	0.030
Bus	0	0	0.001	0.009	0.037
Environment	NA	NA	NA	NA	NA

NA: Not Applicable.

change with technology advancements and infrastructure development. However, in this study, CFR values presented in Table 2 is adopted and kept constant to determine the probability of fatal crash, to assess the fatality rates for different motorization scenarios.

Thus, traffic fatalities for different victim-threat pairs are estimated using,

$$Fatal_{victim}^{threat} = K_{victim}^{threat} X U_{victim} X d_{victim} X M_{threat} X d_{threat} X r_{victim}^{threat} \quad (3)$$

The total traffic fatalities are computed by summing all victims in the event of crash because of all threats.

4.2. Model calibration

The proportionality constant, K_{victim}^{threat} is determined based on road accident statistics for Bengaluru city for the year 2011 (Bengaluru Traffic Police, 2011) and trip modal share characteristics of Bengaluru city (Comprehensive Traffic and Transportation Plan for Bangalore, 2007). For example, in Bangalore city, the modal share of pedestrians is 9.4% and that of two-wheeler is 33.2%, respectively. Consequently, K_{victim}^{threat} is calculated using Eq. (3) by applying CFR value of 0.040. Thus, $K_{pedestrian}^{two-wheeler}$ for pedestrian-two-wheeler road crash is approximately 72, 000. Similarly, K_{victim}^{threat} is estimated for other road user pairs. Further, the calibrated proportionality constant based on 2011 data is validated for the year 2017 based on road accident statistics for Bengaluru city for the year 2017 (Bengaluru Traffic Police, 2017) and trip modal share characteristics of Bengaluru city in 2017 (Vajjarappu et al., 2020). The model predicted the road traffic fatalities for the year 2017 with the accuracy of 94% and r^2 value is 0.93. Thus, the calibrated model is utilized to estimate the traffic fatality count for different vehicle-mix to assess pair-wise risk.

4.3. Traffic growth scenarios

The transport modes considered in scenario evaluation includes bus, car, two-wheeler, walk and bicycle. Eight different traffic growth scenarios representing the change in vehicle proportion is defined and presented in Table 3. The proportion of distance travelled by bus is kept as 50% for base case, high car, and high two-wheeler. The ratio of motorized distance travelled by car to two-wheeler is kept as 2:3 in base case. Likewise, the ratios are defined for motorized transport in other scenarios. In first four scenarios namely, base case, high bus, high car, and high two-wheeler; the ratio of distance travelled by pedestrian to bicycle is kept as 3:1 for all motorization levels. In next three scenarios, base case along with varying pedestrian to bicycle ratio is considered. Further, in last scenario, the proportion of distance travelled by pedestrian to vehicle is kept as 1:3 and is assessed along with high bus case (8:1:1) in which proportion of bus is assumed as 80%.

Table 3
Traffic Growth Scenarios.

Scenario No.	Scenarios	Proportion of Distance Travelled by Motorized Transport Bus: Car: Two-Wheeler	Proportion of Distance Travelled by Non-Motorized Transport Pedestrian: Bicycle
I	Base Case (BC)	5:2:3	3:1
II	High Bus (HB)	8:1:1	
III	High Car (HC)	5:4:1	
IV	High Two-Wheeler (HTW)	5:1:4	
V	Base Case + Pedestrian to Bicycle	5:2:3	2:1
VI	Base Case + Pedestrian to Bicycle	5:2:3	1:2
VII	Base Case + Pedestrian to Bicycle	5:2:3	1:1
VIII	High Bus + Pedestrian to Bicycle	8:1:1	1:3

Each scenario starts with an assumption of all-pedestrian society (100% pedestrians) followed by incremental increase of proportion of motorized vehicles from 0% to 100%. In addition, walking is generally preferred as access to or egress from bus stops. Hence, 1/8th of bus trips is added as additional walk trips. Fig. 2 (I–VIII) demonstrates the variation in motorization levels for eight traffic growth scenarios defined in the study.

The scenarios are defined to assess the risk of fatality for different road use characteristics for Bengaluru city. Further, estimation of traffic fatalities corresponding to various proportion of mode shares and under varying proportion of motorization is discussed in the following section.

5. Results and discussion

The trends in road accidents, victim-threat interaction and pair-wise risk of different travel modes are discussed in this section.

5.1. Accident trend analysis

Accident trend analysis helps in assessing the pattern in the event of road crash based on accident time, locations, age, gender, travel mode, accident type, etc. The hour-wise distribution of road traffic fatalities in Bengaluru city for the years 2011 to 2017 is presented in Fig. 3. Less number of fatalities are observed between 01:00 AM and 04:00 AM for all the years. Increase in number of fatal accidents is observed after 05:00 AM and during morning hours, high number of cases are observed between 08:00 AM and 10:00 AM. Considering all seven years, maximum traffic fatalities are observed in the evening hours between 06:00 PM and 10:00 PM; further, peak hour of fatal road crash is observed as 07:0 PM to 08:00 PM. These hours are generally observed to be evening peak hours with high traffic volume and nature of trips would be return trip to home after office hours. The main reason could be fatigue and rash driving, thus, increasing the risk of the road users.

In 2011, out of 782 fatalities, 582 are male and 124 are female victims and 76 cases unknown gender. However, for the years 2014 to 2017, gender of all the road crash victim is recorded. It is evident from the data that risk associated with male road users are high than female road users. Male and female accounts for 84% and 15% fatalities, respectively. Male constitutes 61% of the total trips made in the city, and hence the higher risk compared to female (Vajjarapu, 2020). Fig. 4(a) shows the age-wise accident distribution of male victims. The age group at high risk are the productive age group (20–29 years) and the older age group (>40 years). Fig. 4(b) shows the age-wise accident distribution of female victims. The highest risk is observed for the age group 40–59 years. Nearly, 26% of the male and female victims' age is unknown or not recorded in the FIR.

Mode-wise distribution of accident fatalities for the year 2011 to 2017 is presented in Fig. 5. It is observed that nearly 91% of the total victims are VRUs i.e., pedestrians, bicyclists, and two-wheeler users.

5.2. Who-hits-whom matrix

The who-hits-whom matrices is developed for the crash fatality data of Bengaluru city for 2011 to 2017. The matrices for the years 2011 and 2017 are presented in Figs. 6 and 7.

The matrices reveal that pedestrians and two-wheelers have the highest share in total number of road crash fatalities and are the most VRUs. The main reasons could be lack of rigid protective covering like in other motorized vehicles and VRUs' mass is much lighter when compared to mass of other motorized modes such as car, bus, lorry, etc. Hence, VRUs are susceptible to high risk of fatality. Major threats to VRUs are two-wheelers, cars, buses and Heavy Goods Vehicle or Lorry as these motorized modes account for maximum crash fatalities. Further, two-wheeler road users are also observed to have faced risk from Right-of-Way (ROW) elements including median, kerb, electric post, etc. Two-wheeler to two-wheeler interaction-based fatality is also considerably high. In case of pedestrian fatalities, the major threat is from two-wheelers, followed by cars/jeeps.

5.3. Fatality-risk model

The traffic fatalities calculated for eight transport growth scenarios based on calibrated model for Bengaluru city is presented in Fig. 8. The comparison of pedestrian, bicycle, two-wheeler, car, and bus fatalities for the defined scenarios is shown in Fig. 8(a–e). Likewise, the comparison of scenarios for total fatalities is shown in Fig. 8 (f).

Fatality trends for pedestrians' (Fig. 6-a) initially rises as proportion of motorization increases and then drops as the share of Non-Motorized Transport (NMT) decreases with incremental increase of motorized modes. Fatalities are not observed to reach zero for 100% indicating substantial share of pedestrians i.e., bus users at 100% motorization. Among eight scenarios, high car scenario shows greater risk of pedestrian fatalities, and the most favourable scenario is high bus with pedestrian to bicycle ratio of 1:3. Bicycle fatalities returns to zero at 100% motorization (Fig. 6-b), because of no bicycle share. The most unfavourable scenarios with high bicycle fatalities are base case with pedestrian to bicycle ratio of 1:2 and 1:1, respectively. The increase in fatal risk is due to shift in modes towards bicycle from equally VRUs (pedestrians and two-wheelers). The scenario with least fatality is high bus scenario. Two-wheeler and car fatalities are observed to rise with incremental increase in motorization from 0% to 100%. High two-wheeler scenario is the most unfavourable scenario with high two-wheeler fatality risk and similar trend is observed in high car scenario. Considering, two-wheeler and car fatalities, high bus with pedestrian to bicycle ratio of 1:3 is most favourable with less fatalities.

Fig. 6(f) illustrates the total fatalities for eight scenarios with varying motorization levels. The inverted-U shape for high care scenario indicates that the threat to non-motorized mode users increases with rise

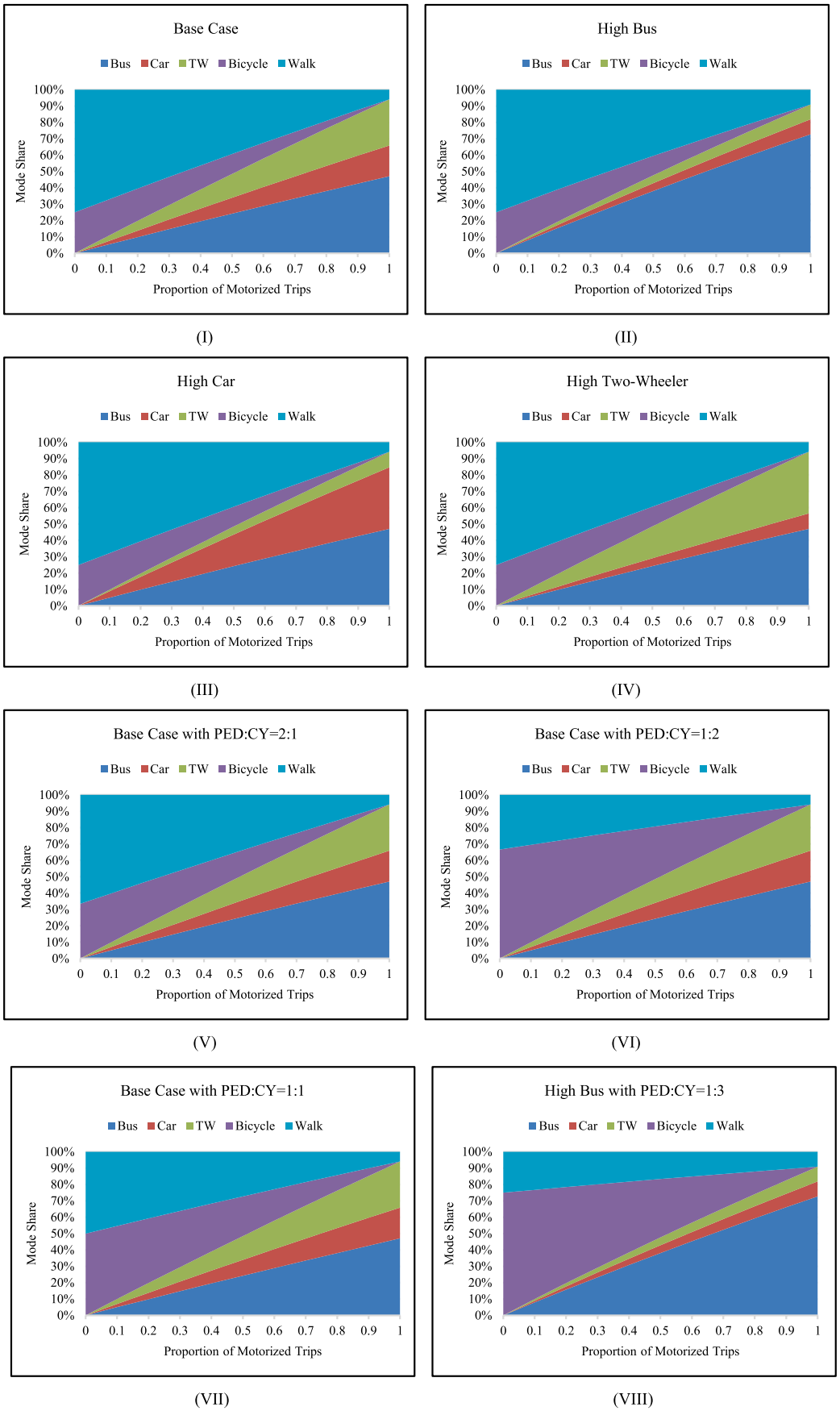

Fig. 2. Traffic Growth Scenarios.

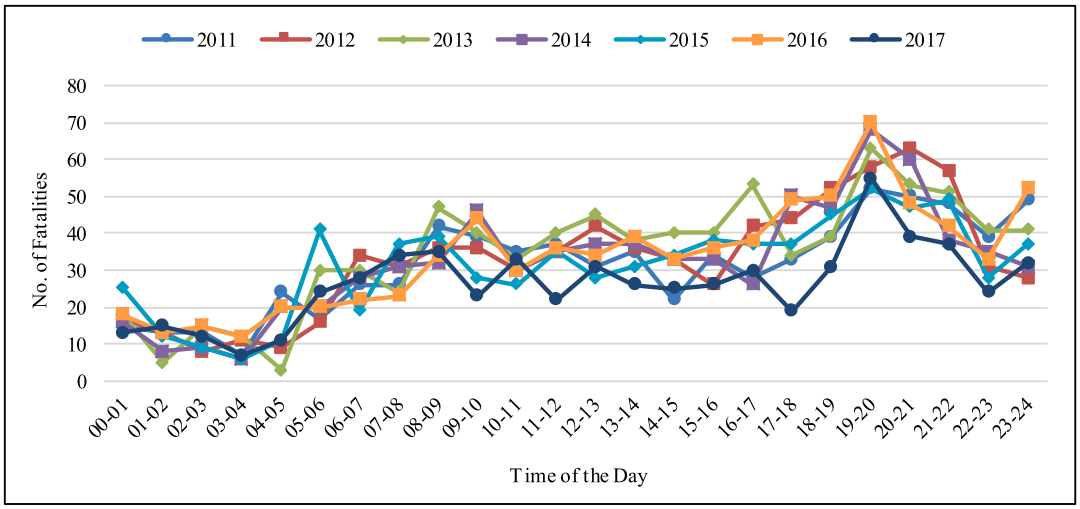

Fig. 3. Hourly Distribution of Accidents.

Fig. 4. Age and Gender Wise Distribution of Accidents: (a) Male (b) Female.

in motorization levels and fatal crash count starts decreasing when motorization levels reached 60%. Also, for none of the scenarios, the

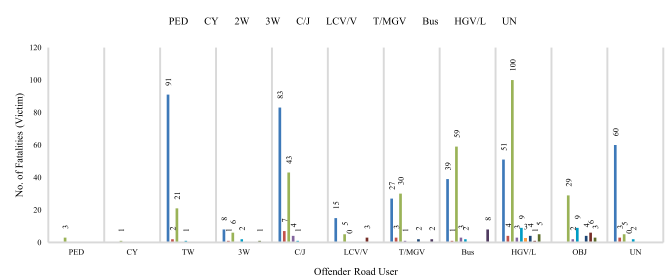

Fig. 6. Summary from Who-Hits-Whom Matrix, 2011

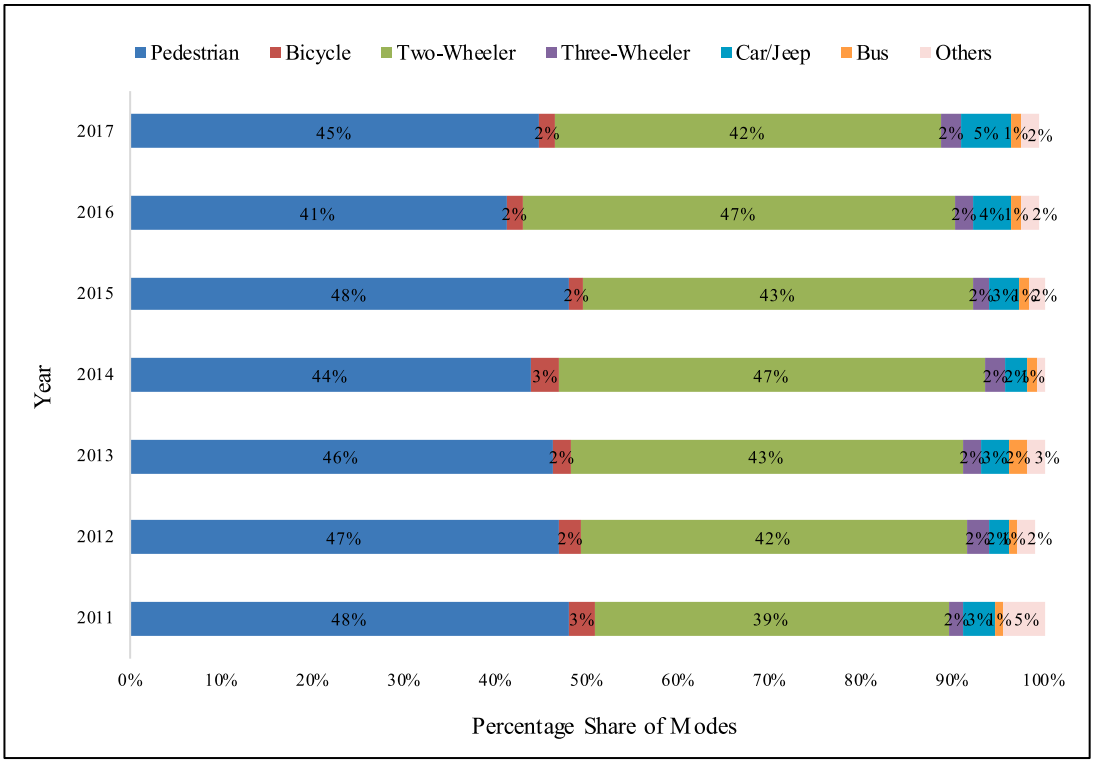

Fig. 5. Mode Wise Distribution of Accident Fatalities.

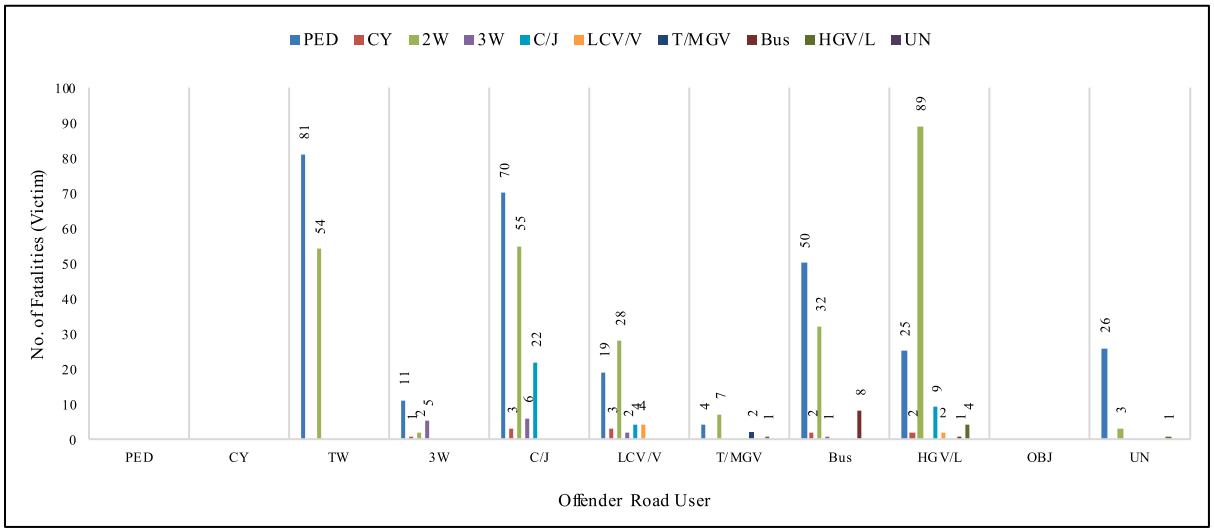

Fig. 7. Summary from Who-Hits-Whom Matrix, 2017

number of fatalities reaches zero even with 100% motorization levels. The reasons are fatality risk existing among different motorized modes and share of pedestrians since bus trips involve walk as an access or egress mode. This residual fatalities are maximum for high car scenario and the value changes with change in proportion of bus use. The least residual fatalities are observed for scenario II (High bus with PED:CY = 3:1) and scenario VIII (High bus with PED:CY = 1:3). Fatalities corresponding to scenarios with high pedestrian share is high, since pedestrians share same road space with other motorized modes leading to increased risk. Traffic fatalities rises with incremental increase of motorized modes and falls beyond 60% share of motorized modes for almost all the scenarios except scenario VIII. The fall in fatality is only due to reduction in VRUs. Further, the highest number of fatalities is observed for scenario III (High car) and the least is observed for scenario VIII. Scenario II and scenario VIII with bus share of 80% have least fatalities compared to other scenarios. Also, in scenario VIII, traffic fatalities increase monotonically because of high CFR values of walking involved with bus trips.

5.4. Policy implications

The trend analysis shows that most of the fatalities are concentrated in evening peak duration. The reason could be driver, vehicular, road infrastructure and system characteristics. A study suggested that enforcing speed limits during night and improving lighting at the intersections are identified as few best solutions to reduce exposure of VRUs to severity (Olszewski et al., 2019). In Bengaluru city, near 84% of the person killed in accident are male. Apart from majority of the trips made by males, such situation also explains the need for strict policies to monitor the driver behaviour and rigid licensing system. Strict monitoring of driver's health also plays a critical role in reducing fatality (Ali et al., 2019). Several legislative actions such as mandatory helmet use, seat belt use, penalty for drunken drive, speed restrictions are in place to improve road safety in India (Sustainable Mobility for Bengaluru, 2020). However, lack of strict enforcement results in no improvement towards road safety. Several studies highlighted that bringing road user behavioural change would help in reducing the deaths due to road crashes (Abreu and Hoeffler, 2021; Ali et al., 2019). Few studies suggested changing social norms in road usage, making it more people centric than vehicular centric would also help in improving safety. Some studies also emphasized incorporating road safety aspects education system starting with primary school itself. In India, majority of the travel demand issues is addressed by increasing the road network or widening the road capacity to accommodate motorized vehicles resulting in increased threat. Transport measures should be focussed to enable shift from private vehicles to public transport and non-motorized transport, since the risk is relatively less compared to dependency on other motorized modes (Goel, 2018).

6. Conclusions

Traffic fatality risk of road users is explored in this study. Road accident trend analysis is carried out for seven years of fatal accident data. Maximum number of road crashes are observed to occur in the evening peak hours. Age and gender wise distribution of accidents showed high risk for the age group 21–29 years and more than 40 years for males. In case of females age group 40–59 years are the most vulnerable and subjected to high risk. Who-hit-whom matrix for Bengaluru city signifies that two-wheelers, pedestrians, and bicyclists accounts for nearly 90% of the total fatal accident victims. VRUs share the same road space with other motorized modes, thus, increased exposure with other modes rises the risk of fatality. Fatality risk is critically assessed for different vehicular growth scenarios for Bengaluru city. The results shows that the increasing motorization levels pose a great threat to VRUs. The study highlighted that High Bus scenario with 80% of total motorized distance travelled by bus would reduce the risk of fatality to a larger extent. This calls for the sustainable transport measures to push private vehicle users to shift to public transit services. Further, the study has few limitations leaving scope for future works. Although the model is calibrated for Bengaluru city, hypothetical scenarios are evaluated. In future, the vehicle-mix could be defined based on sustainable transport policy scenarios. The model assumes time-invariant constant, but several characteristics changes including road infrastructure, vehicle characteristics, etc. Also, the model is developed by considering only the

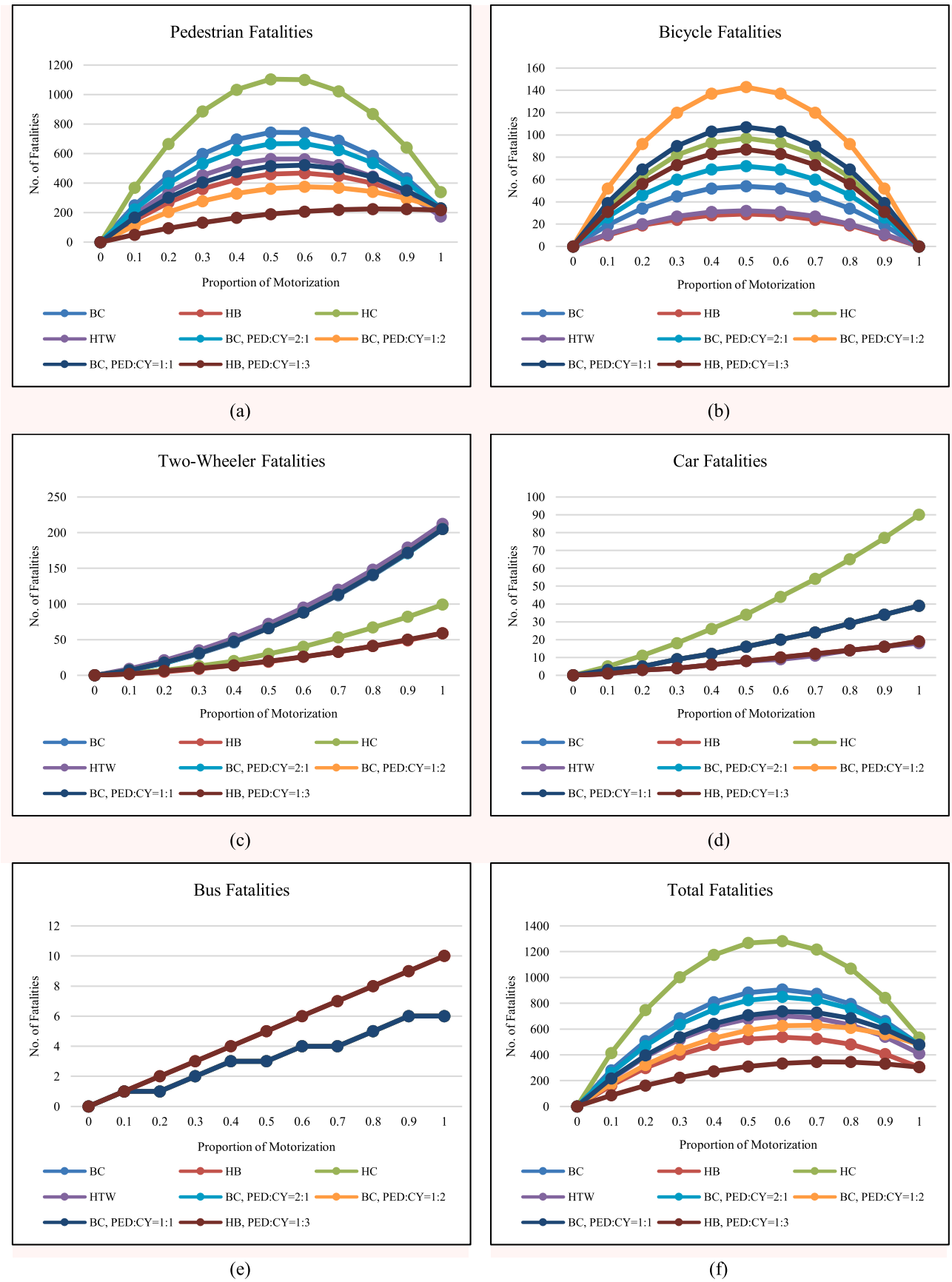

Fig. 8. Comparison of Estimated Fatalities for Different Transport Growth Scenarios

proportion of motorized distance travelled by the road users. Thus, the model could be improvised incorporating other aspects relevant to traffic fatalities such as impact of time, space, drive behaviour, vehicular characteristics, road infrastructure and system characteristics.

CRediT authorship contribution statement

Ashish Verma: Conceptualization, Methodology, Data curation, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing. **Sajitha Sasidharan:** Methodology, Data curation, Formal analysis, Writing – original draft. **Kavi Bhalla:** Conceptualization, Methodology, Writing – review & editing. **Hemanthini Allirani:** Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – review & editing.

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