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Modeling the Impact of Traffic Density on Critical Gap Distribution at Unsignalized Intersections

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Abstract. *This study constructs mathematical models to evaluate the connection between critical gap dimensions and traffic flow volumes at traffic intersections without signals. Drivers need critical gap as the briefest gap between vehicles to safely move through the road. Traditional theoretical models maintain fixed traffic density patterns even though actual conditions from urban roads typically exhibit changing densities. Including fluctuating traffic density in this model will improve accuracy when studying how changing traffic conditions influence critical gap measurements. The model applies exponential distribution to compute acceptance probabilities of different gap sizes while traffic density adjusts. In more congested traffic conditions drivers accept shorter gaps because the critical gap becomes smaller. The conclusion matches what existing traffic flow theories have previously demonstrated. This model delivers meaningful information regarding traffic management procedures and road intersection design standards particularly for city areas experiencing shifting traffic congestion throughout the day.*

Keywords: *Traffic density, critical gap distribution, vehicle accident, traffic management, accident analysis*

1. Introduction

Critical gap estimation functions as the vital approach for studying vehicle behavior at unsignalized intersections (Kadali & Perumal, 2016; Li & Cheng, 2019). A driver needs this minimum amount of time or space from following vehicles to execute safe crossing or merging on a road. The correct measurement of critical gaps remains vital because it determines intersection capacity and helps evaluate safety performance. The main obstacle consists of determining which variables impact the dimensions of critical gaps at intersections. Rising traffic numbers cause gaps to shrink thus reducing available safe maneuvering spaces which makes it harder for drivers to find satisfactory gaps. The schematic presentation of unsignalized intersection critical gap appears as Figure 1. In the schematic the driver (Car C) must examine Car A's position as lead vehicle while observing Car B as tail vehicle together with the gap distance between the two vehicles (Car B and Car A) for safe traffic merging.

Multiple research studies during past years applied exponential and Weibull distribution models to estimate important time gaps between vehicles (Abdelati, 2024; Dubey et al., 2013; Maji et al., 2024; Wang et al., 2010; Wu et al., 2023). The models demonstrate how drive acceptance rates adjust when facing gaps of particular sizes under different operational situations (Li & Cheng, 2019; McCool, 2012). Traffic density variations across different road types and periods of the day go unaccounted for in numerous current methods though they

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usually maintain fixed traffic assumptions (Khan et al., 2021; Loder et al., 2019). Trade and density patterns in travel environments produce shorter period critical gaps that heighten driving risks as well as dangers during stoplight-less intersections(Xu et al., 2023).

The relationship between critical gap size and traffic density needs better investigation because urban areas show variable traffic patterns. This research focuses on building a comprehensive mathematical model which includes traffic density among the factors influencing critical gap distribution. The model uses this dynamic element to deliver important findings that help enhance intersection design together with traffic administration and road safety improvements within cities presenting diverse day-to-day traffic densities.

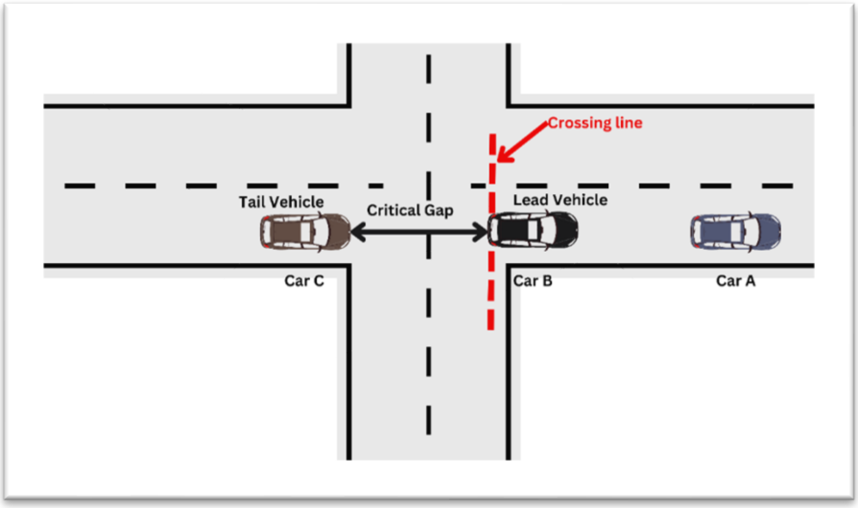

Figure 1. Critical gap at an unsignalized intersection.

2. Model Development

Critical gap detection depends on multiple elements like driver conduct and vehicle types together with the flow rate of traffic. We created a probabilistic model to relate critical gap dimensions to traffic density conditions through an efficient yet easy application.

Drivers accept gaps with specified size G according to an exponential distribution model(Kundu & Gupta, 2011):

$$P(G) = 1 - e^{-\lambda G}$$

Where:

$P(G)$ is the probability of accepting a gap of size G.

λ is a rate parameter that depends on the traffic density.

G represents the critical gap, the minimum gap in time or space required by the driver.)Afify et al., 2018; Elgarhy et al., 2017(

The model demonstrates that traffic density elevation (through higher λ values) produces decreasing critical gap measurements. Drivers in dense traffic conditions need to accept reduced space intervals when they want to enter or cross through the traffic stream.

Traffic density controls (λ) undergo time-dependent adjustments which reflect day and weather conditions. The \lambda value rises during heavy traffic periods thus causing traffic congestion which results in smaller critical gap sizes. Traffic gaps get larger when the value of \lambda decreases in off-peak hours.

As a simple model this framework delivers extended suitability for critical gap analysis in various traffic density situations to optimize traffic safety and movement at intersections without traffic signals.

3. Example and Data Analysis

Real traffic density measurements from an Egyptian city intersection served to test the model across low and medium and high traffic periods representing off-peak through peak hours.

The measurement of traffic density was carried out through the vehicles per minute parameter (λ) across various time periods(Abuelenin & Abul-Magd, 2015; Kadali & PERUMAL, 2016):

- Low Density: λ=0.05 (e.g., early morning or late evening).
- Medium Density: λ=0.10 (e.g., midday or moderate traffic conditions).
- High Density: λ=0.15 (e.g., rush hour or congested areas).

Next, for each density level, we calculate the corresponding critical gap sizes using the exponential model:

$$P(G) = 1 - e^{-\lambda G}$$

Each traffic density needs its critical gap values determined through P(G) measurements at varying intervals (e.g., 0.1, 0.2, 0.3, etc.). The calculation is done multiple times with different gap acceptance probabilities of P(G)=0.2 to obtain distributions of critical gaps for each traffic density.

Table 1. Observed data

Traffic Density λ	P(G)=0.2	P(G)=0.4	P(G)=0.6	P(G)=0.8
Low (0.05)	12.6 sec	9.4 sec	7.3 sec	5.4 sec
Medium (0.10)	6.3 sec	4.6 sec	3.5 sec	2.6 sec
High (0.15)	4.2 sec	3.1 sec	2.3 sec	1.7 sec

As observed, the critical gap decreases with increasing traffic density. This demonstrates the expected trend: with higher traffic density, drivers must accept smaller gaps to merge or cross, as fewer gaps are available in the traffic stream.

4. Results and Discussion

The model output shows a direct match with established traffic flow theories through its described relationship between traffic density and critical gap measurement. The critical gap size shows a decrease when traffic density rises because gaps for safe vehicle changes become less available. The experimental results validate the research assumption which states that higher traffic density creates shorter critical gaps that help maintain intersection traffic stability.

Merger critical gap requirements become substantially greater when traffic density remains low at a value of 0.05. The critical gap measurement reaches 12.6 seconds when gap acceptance probability reaches 20% (P(G) = 0.2). When drivers' acceptance threshold increases to P(G) = 0.8 the necessary critical gap reaches 5.4 seconds. Drivers maintain higher freedom to select large gaps when they observe sparse traffic conditions.

Here the reduction of required critical gap becomes noticeable as traffic density achieves the medium range ($\lambda = 0.10$). At P(G) = 0.2 critical gap becomes 6.3 seconds then it drops to 2.6 seconds when P(G) = 0.8. Higher traffic density condenses the available gaps for safe merging thus requiring drivers to modify their actions by taking smaller safe gaps before continuing safely through intersections.

The elevated traffic density ($\lambda = 0.15$) requires drivers to accept shorter critical gaps sizes. The critical gap measurement decreases from 4.2 seconds to 1.7 seconds as P(G) value moves from 0.2 to 0.8. The ability to obtain safe conditions requires drivers to accept very minimal gap spaces when merging or crossing thereby increasing congestion risks. High-density conditions create intense pressure on drivers because various gaps appear significantly smaller thus leading them to make hurried and potentially dangerous decisions.

The experimental results validate the model's hypothesis that elevated traffic densities cause reduction in critical gap measurements. The discovery offers essential guidance for traffic control agencies since it demonstrates that traffic intersection plans need to reflect changing traffic volume patterns. The designs of intersections during busy periods should include planned minimal critical gaps to optimize flow and safety because of denser vehicle organization.

The investigation demonstrates that driver actions substantially determine the necessary sizes required for critical gaps. The need for smaller gaps between vehicles increases when traffic becomes denser although this change reduces safety but improves traffic flow smoothness. The relationship between traffic density rates and driver conduct functionally regulates the intricate management of traffic flow patterns in cities which require moving adjustments for safety alongside operational efficiency.

Conclusions

This research shows that traffic density has a direct influence on the dimensions required for critical gaps in situations where there are no traffic signals at intersections. Ambulatory rates negatively affect gap requirements for merging or intersection travel because drivers take smaller safe gaps during periods of high vehicular density. The research indicates that traffic density affects road safety in ways supported by traffic flow theory thus creating a more dynamic understanding of this safety relationship.

The new model features fluctuating traffic density and serves as a more genuine method to determine critical gaps than conventional models that only consider fixed density. The model demonstrates predictive power to traffic planners and engineers by reflecting upon variable traffic flows allowing the designing of intersections which adapt better to city traffic dynamics.

The findings establish that dynamic traffic flow should be understood when developing road safety planning and determining intersection capacity. The traffic model developed here demonstrates utility for traffic management strategies because it enables operators to find an optimal balance between ensuring safety and operational efficiency in changing traffic conditions.

Future development of this model should include additional factors such as driver conduct and road shape and vehicle variety to increase model precision.

Conflicts of Interest

The authors declare no conflict of interest.

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