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Mathematical Modeling of Safe Vehicle–Pedestrian Distance with Interactive Visualization

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***Abstract*—Pedestrian safety in road traffic is a critical factor for reducing traffic accidents. A key parameter determining safety is the safe distance between a vehicle and a pedestrian, ensuring timely stopping without collision. This study proposes a mathematical model for calculating the safe distance based on vehicle speed, pedestrian speed, and the distance traveled by the pedestrian. An interactive MATLAB-based tool is developed to visualize the model and analyze different scenarios in real time. The proposed approach is applicable in traffic safety analysis, accident reconstruction, and engineering evaluation. The model is extended to include driver reaction time and practical engineering applications.**

***Keywords*— mathematical modeling, MATLAB, safe distance, traffic safety, vehicle–pedestrian interaction**

I. Introduction

Pedestrian safety is a key factor in reducing road traffic accidents and ensuring safe interaction between vehicles and vulnerable road users. One of the main parameters defining this safety is the safe distance between a vehicle and a pedestrian, which allows sufficient time and space to avoid collision.

Similar relationships have been studied in the field of vehicle dynamics and traffic theory [1], [2], [3], [4]. In real traffic scenarios, this distance depends on the speed of the vehicle, the speed of the pedestrian, and their relative positions. Modern intelligent transportation systems and driver assistance technologies increasingly rely on real-time vehicle–pedestrian interaction models for collision prevention [5], [6], [7].

The aim of this study is to develop a mathematical model for determining the safe vehicle–pedestrian distance and to implement an interactive MATLAB-based visualization tool for analyzing different scenarios.

II. General Regulations

A. Parameters and Definitions

The model uses the following parameters:

Symbol	Description
s_0	safe distance [m]
s_p	pedestrian traveled distance [m]
v_c	vehicle speed [m/s]
v_p	pedestrian speed [m/s]
a_x, a_y	initial coordinates [m]
Δx, Δy	positional offsets [m]

B. Motion Equations

The motion of the vehicle and the pedestrian is described as:

$$x_{car} = a_x + v_c t, y_{car} = a_y$$

$$x_{ped} = \Delta x + v_p t, y_{ped} = \Delta y \quad (1)$$

C. Velocity Ratio Condition

To ensure collision avoidance, the ratio of distances is expressed as:

$$\frac{x_{car} - \Delta x}{x_{ped} - a_x} = \frac{v_c}{v_p} \quad (2)$$

After transformation:

$$v_p(a_x + v_c t - \Delta x) = v_c(\Delta x + v_p t - a_x) \quad (3)$$

which leads to:

$$a_x = \Delta x \quad (4)$$

This relationship is consistent with classical kinematic and traffic safety models [5], [8].

D. Safe Distance Formula

After simplification, the safe distance is obtained as:

$$s_o = \frac{v_c . s_p}{v_p} \quad (5)$$

Interpretation:

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- Increasing vehicle speed v_c leads to larger s_o
- Increasing pedestrian speed, v_p reduces s_o
- The relationship is linear and proportional

E. Extended Model Including Driver Reaction Time

In real traffic conditions, the braking process is not instantaneous and includes a reaction time of the driver before braking is initiated. This reaction time plays a critical role in determining the safe distance. Similar approaches for incorporating driver response delay into stopping distance analysis are discussed in recent transportation safety studies [5], [7].

Let t_r denote the driver reaction time. During this period, the vehicle continues to move with its initial speed vc, covering an additional distance s_r:

$$s_r = v_c t_r \tag{6}$$

Therefore, the total safe distance must include both the reaction distance and the braking-related distance:

$$s_{total} = s_r + s_0 \tag{7}$$

Substituting the expression for s_r, the model becomes:

$$s_{total} = v_c t_r + (v_c t_r)/v_p$$

This extended formulation provides a more realistic representation of the safety conditions in real traffic environments, where driver response delays significantly influence the required stopping distance.

F. Extended Model with Spatial Offsets

For more realistic scenarios:

$$(a_x + s_o - \Delta x)(s_o - \Delta x - \Delta y) = (a_y + \Delta y)\Delta x \tag{8}$$

This allows visualization of the intersection point.

G. Sensitivity Analysis of the Model

The sensitivity of the proposed model with respect to changes in input parameters is an important aspect for evaluating its practical applicability.

The safe distance s_0 is directly proportional to the vehicle speed v_c and inversely proportional to the pedestrian speed v_p. Therefore, small variations in these parameters may lead to significant changes in the calculated safe distance. Such sensitivity effects are also observed in modern pedestrian collision risk assessment models [3], [6].

For example, increasing the vehicle speed by 10% results in a proportional increase in the required safe distance, while increasing the pedestrian speed reduces the required distance accordingly.

This sensitivity highlights the importance of accurate parameter estimation when applying the model in real traffic conditions.

H. Practical Implications of the Model

The proposed model can be directly applied in traffic safety assessment and urban planning. For example, the calculated safe distance can be used to define minimum visibility zones near pedestrian crossings and intersections.

In addition, the model can support the design of intelligent driver assistance systems, where real-time estimation of safe distance is required. Similar concepts are applied in ADAS and autonomous driving safety frameworks [4], [7]. By integrating sensor data and vehicle speed measurements, the model can be used to warn drivers in critical situations.

Such applications demonstrate the practical importance of combining mathematical modeling with computational tools for improving road safety.

I.Model Limitations and Future Extensions

Although the proposed model provides a simplified and effective approach for estimating safe vehicle–pedestrian distance, several limitations should be considered.

First, the model assumes constant speeds for both the vehicle and the pedestrian, which may not always reflect real traffic conditions. In practice, both participants may change their velocity during interaction, especially in emergency situations.

Second, the model does not explicitly account for driver behavior variability, such as reaction delay differences, braking intensity, or decision-making processes. These factors can significantly influence the actual safety distance required to avoid collision.

Third, environmental conditions such as road surface quality, weather, and visibility are not directly included in the model. These factors may alter the effective braking performance and reaction capabilities.

Future extensions of the model may include:

- incorporation of variable acceleration and deceleration profiles;
- inclusion of stochastic (probabilistic) behavior of drivers and pedestrians;
- integration with real-time sensor data for intelligent transportation systems. Recent studies demonstrate that combining sensor-based monitoring with predictive safety models significantly improves pedestrian protection systems [6], [9];
- validation using experimental or traffic monitoring data.

Such improvements would enhance the accuracy and applicability of the model in real-world traffic safety analysis.

III. FIGURES, TABLES AND EQUATIONS

A. Example Data

The following example values are used:

Parameter	Value
s_0	7 [m]
s_p	2.3 [m]

v_c	23 [km/h]
v_p	5 [km/h]
a_x	2.0 [m]
a_y	1.5 [m]
Δx	2.2 [m]
Δy	0.3 [m]

The obtained value of s_o represents the required safe distance under the given conditions.

B. MATLAB Interactive Simulator

An interactive MATLAB script is developed to analyze the model:

- sliders for v_c, v_p, and s_p
- vertically arranged controls to avoid overlapping the graph
- a red point indicating the current value of s_o
- visualization of the relationship between vehicle and pedestrian speeds

Similar simulation approaches are widely used in engineering analysis, intelligent transportation research, and traffic safety studies [10], [11], [12].

The model demonstrates that the safe distance increases proportionally with vehicle speed and decreases with increasing pedestrian speed.

As shown in Fig. 1, the safe distance increases linearly with vehicle speed.

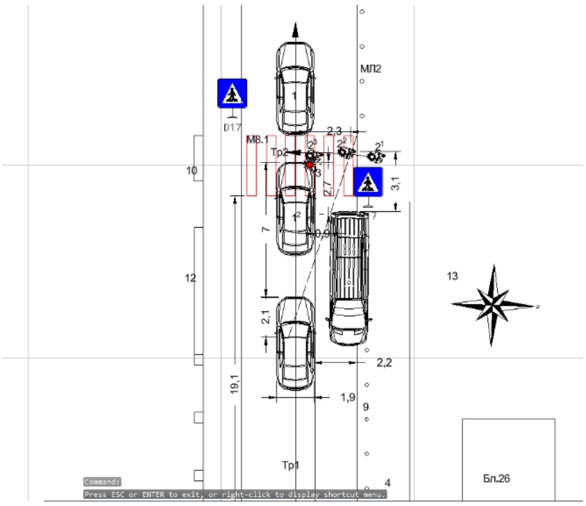

Fig. 1. Dependence of safe distance s_o on vehicle speed v_c.

As shown in Fig. 2, the safe distance decreases as pedestrian speed increases.

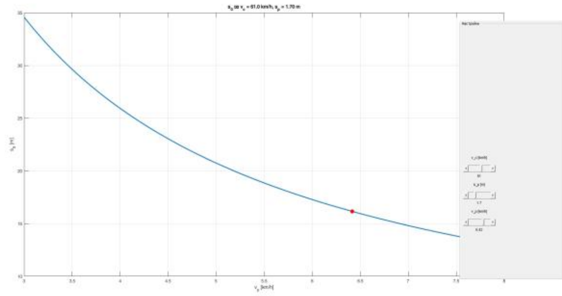

Fig. 2. Safe distance s_o as a function of pedestrian speed v_p for fixed vehicle speed and pedestrian distance

As shown in Fig. 3, the safe distance increases with increasing vehicle speed and decreases with increasing pedestrian speed. The surface clearly demonstrates the nonlinear interaction between the two variables.

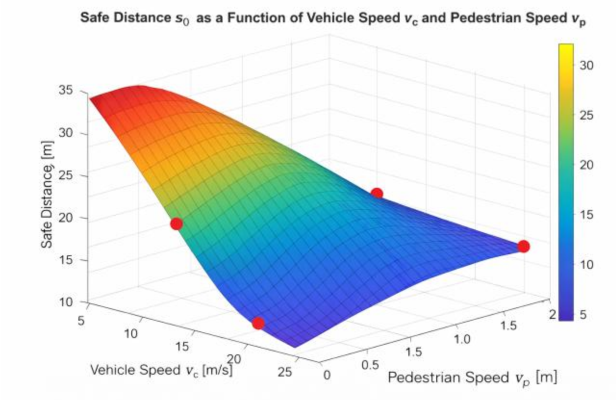

Fig. 3. Three-dimensional representation of safe distance s₀ as a function of vehicle speed v_c and pedestrian speed v_p.

Simulation results show that:

- higher vehicle speeds require significantly larger safe distances;
- slower pedestrian movement increases collision risk;
- small variations in pedestrian position may significantly affect safety conditions.

These results confirm the applicability of the model for analyzing real traffic scenarios and support its use in engineering and forensic practice.

The obtained results confirm that the safe distance is highly sensitive to changes in vehicle speed, especially at higher values. A nonlinear increase in safety requirements is observed when combining high vehicle speed with low pedestrian speed.

Furthermore, the 3D visualization presented in Fig. 3 provides a comprehensive view of the interaction between variables, allowing identification of critical safety scenarios in real traffic conditions.

These findings are consistent with established traffic safety principles and with recent research on vehicle–pedestrian conflict analysis in urban environments [3], [9].

The results can be used as a basis for engineering assessments and accident reconstruction analysis.

The simulation results also reveal that the interaction between vehicle speed and pedestrian speed is not trivial when analyzed in combined scenarios.

At higher vehicle speeds, even small reductions in pedestrian speed can significantly increase the required safe distance. Conversely, at lower vehicle speeds, the system becomes less sensitive to variations in pedestrian movement.

This behavior confirms that the model captures both linear dependencies and more complex interactions between variables, especially when visualized in three-dimensional space.

TABLE I. INFLUENCE OF SPEED PARAMETERS ON SAFE DISTANCE

vc (km/h)	vp (km/h)	s_0 (relative)
Low	Low	Medium
High	Low	High
High	High	Medium

Table I presents a qualitative evaluation of how the relationship between vehicle and pedestrian speeds influences the safe distance. The results show that high vehicle speed combined with low pedestrian speed creates the most critical safety conditions.

Additional Theoretical Interpretation

The obtained analytical relationships can also be interpreted from a physical and safety-oriented perspective. The safe distance represents a balance between the motion of the vehicle and the pedestrian, ensuring that sufficient time is available to prevent collision.

From a kinematic point of view, the model reflects the interaction between two moving bodies with different velocities. The vehicle motion is typically dominant due to higher speed, while the pedestrian motion introduces variability in the system.

The linear dependence of the safe distance on vehicle speed highlights the critical role of speed control in urban environments. Even moderate increases in vehicle speed may lead to disproportionately higher safety requirements.

This interpretation confirms the importance of speed regulation and supports the use of the proposed model in traffic safety policies and engineering practice.

IV. OTHER RECOMMENDATIONS

A. Programs and Codes

The mathematical model and simulation results presented in this study are supported by an interactive MATLAB implementation. The developed script allows dynamic variation of vehicle speed, pedestrian speed, and pedestrian traveled distance, providing real-time visualization of the safe distance.

The program includes graphical user interface elements such as sliders and real-time plotting functions, enabling intuitive analysis of the relationship between input parameters.

A simplified excerpt of the MATLAB code used for simulation is presented below:

```
vc = 23/3.6; % vehicle speed [m/s]
vp = 5/3.6;  % pedestrian speed [m/s]
sp = 2.3;    % pedestrian distance [m]

s0 = (vc * sp) / vp;

fprintf('Safe distance s0 = %.2f m\n', s0);

vp_range = linspace(1, 8, 50);
s0_values = (vc * sp) ./ vp_range;

plot(vp_range, s0_values, 'b', 'LineWidth', 2);
xlabel('Pedestrian Speed v_p [km/h]');
ylabel('Safe Distance s_0 [m]');
```

The presented code segment demonstrates the core computational logic of the model. The complete implementation includes additional interactive controls and visualization features.

The MATLAB implementation can be further extended by incorporating real-time data acquisition and dynamic parameter updates. This would allow the model to be used in real-world driving scenarios and integrated into advanced driver assistance systems (ADAS).

A mathematical model for determining safe vehicle–pedestrian distance has been presented.

The study shows that:

- the safe distance depends linearly on vehicle and pedestrian speeds;
- the model can be effectively visualized using MATLAB;
- the approach is suitable for traffic safety analysis and accident reconstruction.

The proposed model provides a practical tool for evaluating safety distances in real traffic environments.

The model can be further extended using probabilistic methods and real-world data analysis. The proposed model can also be extended to include reaction time and braking dynamics, which would further improve its applicability in real-world traffic scenarios. Future research may focus on integrating probabilistic approaches and experimental validation.

The model can also serve as a basis for educational simulations and training tools in traffic safety analysis.

Practical Applications and Engineering Relevance

The proposed mathematical model has practical relevance in several engineering and safety-related domains. It can be applied in the design of pedestrian crossing systems, urban traffic planning, and the development of intelligent transportation systems and autonomous vehicle safety platforms [4], [7], [11], [12].

In engineering practice, the model can assist in evaluating visibility distances and defining safety zones in areas with high pedestrian activity. It can also be used in forensic analysis to estimate whether a driver had sufficient distance to avoid a collision.

Furthermore, the integration of the model into simulation environments and driver assistance systems allows real-time assessment of safety conditions. This makes the approach particularly valuable for modern traffic management and smart mobility solutions [13], [14],[15].

The model provides a bridge between theoretical analysis and practical implementation in traffic safety engineering.

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