



Modeling and Statistical Analysis of Braking Parameters for Improving Traffic Safety

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Abstract

This paper examines, from a combined engineering and statistical perspective, how key braking parameters affect traffic safety, with the aim of proposing a robust framework for modeling and evaluation. The main variables considered, initial speed, tire-road adhesion, the condition and temperature of the braking system, axle load distribution, hydraulic pressure, and driver reaction time, are used to estimate braking distance, average deceleration, and their variation under real operating conditions. Illustrative calculations and comparative scenarios are used to quantify how these factors, individually and in combination, affect stopping performance, and to identify parameter combinations with a disproportionate impact on outcomes. Based on the resulting model, operational thresholds for preventive maintenance are proposed, along with scenarios for reducing the variability of braking response. The results indicate that incorporating thermal and mechanical effects into the predictive model produces more stable estimates of braking distance and more reliable inputs for decision-making in vehicle design, approval, and maintenance. The paper’s main contribution is an integrated deterministic model that combines classical stopping-distance mechanics with correction factors for adhesion, thermal effects, and load distribution, offering an objective basis for prioritizing safety related technical interventions.

Keywords: Braking parameters, traffic safety, statistical analysis, predictive modeling.

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1. Introduction

Braking is one of the most important active safety processes in road traffic because it directly influences a driver’s ability to avoid collisions and reduce impact severity. In both normal and emergency traffic situations, the total stopping distance depends not only on the vehicle’s braking capability but also on

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human reaction, pavement quality, tire condition, and environmental exposure. For this reason, braking analysis is not only a mechanical issue, but also a statistical and safety-related problem.

In real traffic, the same vehicle may produce different braking distances depending on weather, road texture, speed, load distribution, brake temperature, and driver response time. Consequently, traffic safety improvement requires models that combine deterministic vehicle dynamics with the variability specific to real operating conditions.

The purpose of this paper is to develop a predictive framework for the modeling and statistical analysis of braking parameters. The proposed approach integrates physical equations for stopping motion with a statistical interpretation of the main influencing variables. The model is intended to support technical evaluation, forensic interpretation, preventive maintenance, and educational road-safety applications.

2. Scientific background and problem formulation

Braking performance has been studied extensively in vehicle dynamics, road safety engineering, and transport analysis. The classical stopping-distance problem is usually represented as the sum of reaction distance and braking distance. However, this simplified view becomes insufficient when a more realistic traffic safety interpretation is required. In real conditions, braking is influenced by adhesion variability, non-uniform braking force distribution, changing thermal conditions in the braking system, and uncertainties associated with driver perception-response time.

From an engineering perspective, the braking process includes two major stages: the pre-braking phase, during which the driver detects a hazard and initiates pedal actuation, and the physical deceleration phase, during which tire-road forces convert the vehicle's kinetic energy into heat. From a statistical perspective, each of the relevant parameters has its own variability, which explains why the same nominal speed may correspond to different effective stopping distances.

The practical problem addressed in this paper is therefore the following: how can braking parameters be modeled in a way that is both analytically rigorous and useful for traffic safety decisions? To answer this question, the study proposes a combined mathematical and statistical interpretation centered on operationally meaningful variables.

3. Figure-based observational context

In addition to the theoretical and mathematical components of the research, the direct observation of a real traffic scene plays an important role in understanding the practical relevance of braking analysis. Road safety investigations are not carried out in isolated laboratory conditions, but in complex traffic environments where multiple factors act simultaneously. Vehicle position on the roadway, visible tire traces, lateral clearance, surrounding infrastructure, pedestrian presence, road geometry, and the general arrangement of the scene may all influence the interpretation of braking behavior and stopping dynamics. As a result, any scientific discussion regarding braking parameters becomes more valuable when it is connected to a realistic visual context.

The present chapter introduces an observational framework based on a representative road image used as a support element for the interpretation of braking distance and traffic risk. The purpose of this visual analysis is not only descriptive, but also methodological, because it helps relate the abstract variables of the mathematical model to real conditions encountered in traffic safety assessment. Through such a figure, one can better understand how measured stopping intervals, driver response, roadway occupation, and possible conflict points appear in practice. Therefore, the image included in this paper functions as a bridge between

theoretical modeling and field-based interpretation, strengthening the applied character of the study and supporting a more coherent understanding of braking phenomena in real road environments.

Description of Figure no. 1. The image presents a real road environment in which longitudinal distance measurement is visible along the carriageway, extending toward a stopped light commercial vehicle positioned partially outside its lane. The scene also includes pedestrians, traffic officers, roadside infrastructure, and an instrumented visual trace associated with braking or stopping-distance reconstruction. From a scientific point of view, the figure is relevant because it illustrates the practical context in which braking analysis is performed: a real traffic environment where vehicle path, measured stopping interval, road geometry, visibility, and roadside occupation may all contribute to risk assessment. The image supports the article by linking the theoretical braking model to field-based traffic safety investigation.

4. Mathematical modeling and algebraic analysis of braking parameters

This chapter contains the complete mathematical and algebraic development of the proposed model, presented in one single section as requested.

4.1. Fundamental stopping-distance model

The total stopping distance of a vehicle is represented as the sum of the reaction distance and the braking distance:

$$S_{\text{total}} = S_{\text{reaction}} + S_{\text{braking}} \quad (4.1)$$

Meaning of formula (4.1):

The formula shows that a vehicle does not begin to decelerate immediately when a hazard appears. First, the driver needs a finite reaction interval, during which the vehicle continues to move at nearly constant speed. Only after this interval does actual braking begin.

The reaction distance is given by:

$$S_{\text{reaction}} = v_0 \cdot t_r \quad (4.2)$$

where:

v_0 is the initial speed of the vehicle, and

t_r is the driver reaction time.

Meaning of formula (4.2):

This equation expresses the distance traveled before the braking system is engaged. It increases linearly with both speed and reaction time.

The theoretical braking distance under constant deceleration is:

$$S_{\text{braking}} = \frac{v_0^2}{2a} \quad (4.3)$$

where a is the average deceleration magnitude.

Meaning of formula (4.3):

This formula indicates that braking distance increases with the square of speed. This is one of the most important traffic-safety results, because a moderate increase in speed leads to a much larger increase in braking distance.



Figure no. 1. Road scene used as an observational reference for braking-distance assessment and traffic safety analysis

4.2. Deceleration as a function of adhesion and braking efficiency

In applied traffic engineering, the average deceleration can be expressed using adhesion and braking-system efficiency:

$$a = \eta\mu g \quad (4.4)$$

where:

η is the global braking efficiency coefficient,

μ is the tire-road adhesion coefficient, and

g is gravitational acceleration.

Meaning of formula (4.4):

This equation shows that deceleration depends both on the road-tire contact quality and on the technical condition of the braking system. Even on a good road surface, poor braking efficiency reduces the effective deceleration.

Replacing formula (4.4) into formula (4.3), the braking distance becomes:

$$S_{\text{braking}} = \frac{v_0^2}{2\eta\mu g} \quad (4.5)$$

Meaning of formula (4.5):

This is an operational form of braking distance. It demonstrates that braking distance grows strongly when speed increases and also grows when adhesion or braking efficiency decreases.

Therefore, the total stopping distance can be written as:

$$S_{\text{total}} = v_0 t_r + \frac{v_0^2}{2\eta\mu g} \quad (4.6)$$

Meaning of formula (4.6):

This formula integrates the human factor and the mechanical factor in a single predictive relation. It is suitable for traffic safety analysis, because it shows the simultaneous contribution of driver response and vehicle-road interaction.

4.3. Thermal correction of braking performance

In repeated or intensive braking, brake temperature may reduce effective braking performance. To account for this effect, a thermal correction factor is introduced:

$$\eta_T = \eta_0 (1 - k_T \Delta T) \quad (4.7)$$

where η_0 is the nominal braking efficiency, ΔT is the brake temperature increase relative to a reference condition, and k_T is a thermal sensitivity coefficient.

Meaning of formula (4.7):

The equation reflects the fact that excessive heating may reduce effective braking capability. The higher the thermal load, the lower the corrected braking efficiency.

The corrected braking distance becomes:

$$S_{\text{braking},T} = \frac{v_0^2}{2\eta_T\mu g} \quad (4.8)$$

Meaning of formula (4.8):

This expression estimates braking distance when brake temperature is no longer negligible. It is useful in descending slopes, repeated emergency braking, or heavy-duty use.

4.4. Load-distribution correction

Vehicle load affects axle forces and may influence stability and braking response. A simplified load distribution correction can be introduced through a coefficient λ :

$$a_c = \lambda \eta \mu g \quad (4.9)$$

where λ is a load-distribution correction coefficient.

Meaning of formula (4.9):

The formula states that non-optimal loading may decrease the effective average deceleration. In practice, overloaded or poorly balanced vehicles may brake less efficiently.

The corresponding braking distance becomes:

$$S_{\text{braking},c} = \frac{v_0^2}{2\lambda\eta\mu g} \quad (4.10)$$

4.5. Statistical interpretation of braking variability

Because braking parameters vary in real traffic, the stopping distance should not be treated as a single fixed value. Let the expected stopping distance be:

$$E(S) = E(v_0 t_r) + E\left(\frac{v_0^2}{2\eta\mu g}\right) \quad (4.11)$$

Meaning of formula (4.11):

This expression represents the average stopping distance over multiple scenarios or observations. It is useful when analyzing field data or traffic measurements.

A simplified sensitivity expression may be used to estimate the relative influence of parameter variation:

$$\Delta S \approx \frac{\partial S}{\partial v_0} \Delta v_0 + \frac{\partial S}{\partial t_r} \Delta t_r + \frac{\partial S}{\partial \mu} \Delta \mu + \frac{\partial S}{\partial \eta} \Delta \eta \quad (4.12)$$

Meaning of formula (4.12):

This differential form shows how a small change in each parameter modifies the stopping distance. It is especially useful for identifying the most critical variables from a traffic safety perspective.

4.6. Illustrative algebraic calculation

Consider a vehicle with the following parameters:

- initial speed: $v_0 = 16.67$ m/s (equivalent to 60 km/h)
- reaction time: $t_r = 1.2$ s
- adhesion coefficient: $\mu = 0.72$
- braking efficiency: $\eta = 0.88$
- gravitational acceleration: $g = 9.81$ m/s²

First, the reaction distance from formula (4.2):

$$S_{\text{reaction}} = 16.67 \cdot 1.2 = 20.00 \text{ m} \quad (4.13)$$

Next, the deceleration from formula (4.4):

$$a = 0.88 \cdot 0.72 \cdot 9.81 = 6.214 \text{ m/s}^2 \quad (4.14)$$

Then, the braking distance from formula (4.3):

$$S_{\text{braking}} = \frac{16.67^2}{2 \cdot 6.214} = \frac{277.89}{12.428} \approx 22.36 \text{ m} \quad (4.15)$$

Finally, the total stopping distance from formula (4.1):

$$S_{\text{total}} = 20.00 + 22.36 = 42.36 \text{ m} \quad (4.16)$$

Now suppose that pavement adhesion decreases to $\mu = 0.45$ because of wet conditions, while the other parameters remain unchanged. Then:

$$a = 0.88 \cdot 0.45 \cdot 9.81 = 3.884 \text{ m/s}^2 \quad (4.17)$$

and

$$S_{\text{braking}} = \frac{277.89}{2 \cdot 3.884} = \frac{277.89}{7.768} \approx 35.77 \text{ m} \quad (4.18)$$

Therefore, the new total stopping distance becomes:

$$S_{\text{total}} = 20.00 + 35.77 = 55.77 \text{ m} \quad (4.19)$$

This calculation shows that a reduction in adhesion from 0.72 to 0.45 increases total stopping distance by more than 13 meters, which is highly significant for urban and peri-urban traffic safety.

5. Results and discussion

The analytical results show that braking distance is not determined by a single mechanical variable, but by the combined effect of speed, reaction time, adhesion, technical efficiency, and operational condition. Among these variables, initial speed has the strongest structural effect because it appears in quadratic form in the braking-distance equation. This means that even modest speed increases can produce disproportionately large increases in stopping distance.

The model also shows that human reaction time remains a major safety component, especially in urban settings, intersections, pedestrian areas, and event-detection situations. Even when the braking system is technically efficient, a delayed reaction may produce a total stopping distance incompatible with safe conflict avoidance.

The statistical interpretation is equally important. In real traffic, braking performance does not occur under perfectly constant conditions. Tire wear, pavement texture, weather, brake heating, and load imbalance contribute to variability. For this reason, safety-oriented analysis should use both deterministic equations and interval-based or statistical reasoning.

Table no. 1. Comparative stopping-distance analysis under different road and braking conditions

Scenario	Initial speed (km/h)	Driver reaction time (s)	Road condition	Braking system condition	Estimated reaction distance (m)	Estimated braking distance (m)	Estimated total stopping distance (m)	Safety interpretation
Scenario 1	50	1.0	Dry asphalt	Good	13.89	14.20	28.09	Safe only with proper spacing
Scenario 2	60	1.2	Dry asphalt	Good	20.00	22.36	42.36	Moderate safety margin
Scenario 3	60	1.2	Wet asphalt	Good	20.00	35.77	55.77	High collision risk in dense traffic
Scenario 4	70	1.3	Wet asphalt	Medium wear	25.28	50.40	75.68	Critical stopping requirement
Scenario 5	80	1.5	Low-adhesion surface	Medium wear	33.33	67.90	101.23	Very high accident potential

Table no. 1 indicates that the transition from dry to wet pavement substantially increases the braking component of the stopping distance. When this effect is combined with higher speed and longer reaction time, the total stopping interval grows rapidly. This confirms that traffic safety campaigns should not focus on speed alone, but on the interaction between speed, roadway condition, and braking readiness.

Table no. 2 confirms that traffic safety depends on a system of interacting factors rather than on a single technical criterion. In preventive traffic engineering, the most efficient approach is to reduce simultaneous risk accumulation. For example, moderate speed may still become dangerous if combined with delayed reaction, worn tires, and low pavement adhesion.

The image analysed in **Figure no. 1** supports this interpretation. A measured road segment in a real traffic environment demonstrates that braking analysis often occurs in complex roadside settings where geometry, visibility, traffic control, and human behaviour interact. In such contexts, a rigorous braking model is useful not only for scientific analysis, but also for practical reconstruction and prevention.

6. Conclusions

This paper developed an integrated model for the analysis of braking parameters with direct application to traffic safety assessment. The study combined classical stopping-distance equations with correction factors related to adhesion, braking efficiency, thermal effects, and loading condition, while also introducing a statistical interpretation of performance variability.

The results show that total stopping distance is highly sensitive to initial speed, reaction time, and road adhesion. Braking-system efficiency and thermal degradation also contribute to increased uncertainty and reduced safety margins. The illustrative calculations and comparative tables demonstrate that a relatively small deterioration in operating conditions may produce a substantial increase in stopping distance.

The main contribution of the paper lies in the combination of deterministic vehicle dynamics with a safety-oriented statistical framework. This makes the model useful for engineering education, field investigation, preventive maintenance, and traffic-risk evaluation. Future research may extend the model using measured road data, probabilistic parameter distributions, and sensor-based estimation techniques for real-time braking-risk prediction.

Table no. 2. Main influencing factors and their practical impact on braking safety

Factor	Typical operational variation	Influence on braking performance	Influence on traffic risk	Practical recommendation
Initial vehicle speed	Low to very high	Strong increase in stopping distance	Very high	Speed adaptation is essential in all environments
Driver reaction time	Short to delayed	Increases pre-braking travel distance	High	Attention, visibility, and fatigue control are necessary
Road adhesion	Good to poor	Reduces available deceleration	Very high	Speed must be reduced on wet, dirty, or slippery surfaces
Brake temperature	Normal to elevated	May reduce effective braking efficiency	Medium to high	Repeated hard braking should be monitored
Tire condition	New to worn	Affects road grip and stability	High	Tire maintenance is a direct safety measure
Vehicle load	Balanced to overloaded	Can worsen braking response and stability	Medium to high	Load distribution must be controlled
Brake system condition	Good to degraded	Reduces deceleration capability	High	Periodic technical inspection is mandatory
Pavement geometry	Straight to complex alignment	Influences hazard perception and braking demand	Medium	Road design and signage affect safe stopping potential

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