Determining Recommended Vehicle Speed Under Varying Road Conditions

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Abstract: This paper proposes a practical and transparent framework for determining recommended vehicle speeds under varying pavement and environmental conditions. The method links a road-condition classification (dry-smooth, dry-rough, wet, icy) to an explicit engineering decision rule based on two safety constraints: (i) a stopping-distance requirement and (ii) a curve-stability requirement for representative horizontal-curve scenarios. When continuous field measurements are unavailable, friction coefficients are adopted as typical literature- and standards-based ranges for scenario calculations, while the resulting speeds are interpreted as indicative values subject to local calibration. To quantify uncertainty caused by variability in tire-road friction and driver reaction time, a Monte Carlo simulation is implemented with uniform sampling of friction within class ranges and reaction time within 0.8-1.2 s (N_{sim} = 10,000). The output is reported as the median recommended speed and the 95% uncertainty interval [P2.5, P97.5] for each pavement class, enabling conservative engineering margins. Under the studied assumptions (V_{limit} = 110 km/h, D = 80 m, k_{safety} = 0.90), the median recommended speed decreases from 92.0 km/h for a representative dry-curve case to 71.2 km/h for wet straight segments and 45.2 km/h for an icy curve. The proposed approach supports condition-responsive speed management and can serve as a computational core for future ITS deployment after calibration using local friction and surface-condition measurements.

1 INTRODUCTION

Road traffic safety and operational efficiency depend strongly on the ability to select an appropriate driving speed under changing pavement, weather, and traffic conditions. In real operation, drivers often choose speed based on subjective perception, while key determinants such as friction potential, surface condition, and visibility can vary significantly across road segments and seasons. These variations increase speed dispersion and risk, especially on wet or icy surfaces.

International practice increasingly applies adaptive and condition-responsive speed management (e.g., variable speed limits and weather-responsive control). However, many local implementations still lack a transparent link between measurable pavement indicators, explicit calculation rules for recommended speed ranges, and uncertainty bounds that engineers can use for safe margins.

Objective. This study aims to determine recommended speed ranges for typical road and environmental conditions using literature-based surface-condition indicators, with the possibility of later calibration using local measurements, and an analytical decision rule with uncertainty quantification. Terminology and regulatory context follow the Republic of Uzbekistan Law No. ZRU-900 “On Road Traffic” and national traffic regulations [1], [2]. Global road safety remains a major challenge, which motivates evidence-based speed management [3]. Speed management guidance and operating speed practices are widely discussed in international manuals and reports [4]-[7]. Condition-responsive approaches, including variable and weather-responsive speed management, have also been investigated in the literature [8]-[11].

Contributions. The main contributions are:

1) a road-condition classification scheme based on operational friction classes;
2) a decision rule for recommended speed selection considering stopping-distance and curve-stability constraints;

Table 1: Road condition classes and adopted friction ranges (typical values).

Class	Descrip-tion	μ (typical range)	Notes	Source
A	Dry, smooth	0.75-0.90	clean asphalt/concrete	[14]
B	Dry, rough	0.65-0.80	textured/aged surface	[14]
C	Wet	0.35-0.55	wet or polished surface	[14]
D	Icy	0.10-0.20	compact ice	[14], [15]

Note: μ values are typical ranges adopted from literature/standards; actual values depend on tire type, temperature, contamination, and measurement method. Typical friction ranges were adopted from literature/standards [14], [15].

3) a Monte Carlo uncertainty analysis providing 95% uncertainty intervals for engineering application.

Novelty of the study. Unlike conventional studies on speed management that primarily focus on control policies or traffic-flow optimization, this study provides a transparent engineering framework that directly links pavement-condition classes to recommended speed values through explicit stopping-distance and curve-stability constraints. The novelty lies in combining (1) a practically interpretable road-condition classification, (2) a deterministic decision rule for recommended speed selection, and (3) Monte Carlo-based uncertainty quantification for operational safety margins. This makes the proposed approach suitable not only for analytical assessment, but also as a computational core for future condition-responsive ITS deployment after calibration with local road-surface measurements.

2 MATERIALS AND METHODS

2.1 Study Design and Assumptions

This study presents a scenario-based assessment for representative road segments under common operating conditions. The recommended speed is determined from a stopping-distance constraint using a conservative available stopping distance D and a safety coefficient k_{safety}. These parameter values were selected as conservative baseline assumptions representative of high-speed road segments: D corresponds to a typical available sight distance on such roads, while k_safety provides a 10% margin for operational safety. Unless local measurements are available, pavement friction parameters are adopted as typical ranges from published literature/standards for each surface class (Table 1). The following baseline assumptions were used in calculations: posted speed limit V_{limit} = 110 km/h, available stopping distance $D = 80\ m$ (conservative), mean driver reaction time $\bar{t}_r$ = 1.0 s, and safety coefficient k_{safety} = 0.90.

The stopping distance D=80 m was selected as a conservative available distance representing limited available stopping conditions on representative high-speed road segments.

The curve radius R=300 m with e=0 was adopted as a representative scenario when local geometry data are not available; this choice is consistent with standard geometric design and safety guidance [12], [13].

2.2 Pavement Condition Classification

Pavement condition is represented by four operational classes: dry-smooth, dry-rough, wet, and icy. Where direct on-site friction measurements are not available for all scenarios, representative (typical) friction ranges are adopted from literature/standards. Therefore, the resulting recommended speed values should be interpreted as indicative ranges and require calibration using local measurements for operational deployment.

The symbols, definitions, and corresponding units used throughout this study are summarized in Table 2.

Table 2: Notation and units used in the study.

Symbol	Meaning	Unit
S	stopping distance	m
v	vehicle speed (in equations)	m/s
V_{limit}	posted speed limit	km/h
V_{rec}	recommended speed	km/h
t_r	driver reaction time	s
g	gravitational acceleration	m/s²
μ	tire-road friction coefficient	-
D	available stopping distance	m
R	curve radius	m
e	superelevation	-
f	side-friction factor (conservatively (f=\mu))	-
k_{safety}	safety coefficient	-

Note: Speeds in equations are in *m/s*; values reported in tables are converted to *km/h* (1 m/s = 3.6 *km/h*).

2.3 Recommended Speed Model

The recommended speed is derived from a combined analytical/scenario-based approach using two primary safety constraints: stopping-distance and curve stability.

Stopping-distance constraint:

$$S(v) = vt_r + \frac{v^2}{2g\mu}, \quad (1)$$

where S is the stopping distance, v is speed, t_r is driver reaction time, g is gravitational acceleration, and μ is the friction coefficient (or its adopted proxy). The constraint is defined as:

$$S(v) \leq D, \quad (2)$$

where D is available stopping distance (e.g., sight distance or required safe distance on the segment). The stopping-distance formulation follows standard highway safety practice and is consistent with widely used design guidance [12], [13].

Curve stability constraint (for horizontal curves):

$$v_{curve} = \sqrt{gR(e+f)}, \quad (3)$$

where R is curve radius, e is superelevation (if applicable), and f is a side-friction proxy related to pavement condition class. For scenario-based calculations on curves, a representative radius R = 300 m was adopted, and superelevation was assumed as e = 0 (if not measured). The side-friction proxy was taken conservatively as f = μ, where f denotes the side-friction factor used in the curve-speed formula, which is consistent with standard vehicle-dynamics formulations for lateral stability on horizontal

Decision rule for recommended speed:

$$V_{rec} = min\{v_{stop}, v_{curve}, V_{limit}\} \cdot k_{safety}, \quad (4)$$

where V_{limit} is the posted/administrative limit and $k_{safety}=0.90$ is a safety margin coefficient selected for conservative operation. In this study, $k_{safety} = 0.90$ was adopted as a conservative coefficient.

2.4 Uncertainty Analysis (Monte Carlo)

To account for variability in friction and driver response, uncertainty is quantified using Monte Carlo simulation.

$\mu \sim$ Uniform (μ_{min}, μ_{max}) from Table 1; $t_r \sim$ Uniform (0.8, 1.2) s; N_{sim} = 10,000; 95% UI = [P2.5, P97.5].

Uniform distributions were used because only plausible lower/upper bounds are available for scenario-based analysis (i.e., a conservative non-informative choice within the adopted ranges). As a brief robustness check, we repeated the simulation using a triangular reaction-time distribution (min 0.8 *s*, mode 1.0 *s*, max 1.2 *s*) and a narrower μ-range (±10% trimmed). The median V_{rec} changed by less than ~1 *km/h* across classes and the 95% interval boundaries shifted only slightly, indicating that the reported conclusions are robust to these reasonable distributional assumptions.

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Input: D, Vlimit, ksafety, R, e;
friction range [μmin, μmax]; reaction
time range [0.8,1.2].
 1)   For i = 1..Nsim: sample
 μi~U(μmin, μmax), tr,i~U(0.8, 1.2).
 2)   Compute vstop,i  using (1)-(2).
 3)   Compute vcurve,i using (3) (if
 curve scenario is considered).
 4)   Compute Vrec,i = min{vstop,i,
 vcurve,i, Vlimit}·ksafety (4).
Output: median(Vrec), UI95% = [P2.5,
P97.5].
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Algorithm 1: Recommended speed with uncertainty (Monte Carlo).

2.5 Model Consistency and Benchmarking

Because this study is scenario-based, empirical field validation is outside its present scope; therefore, model assessment is provided through consistency checks and benchmarking against physical constraints and literature-based expectations. First, the model is internally consistent: V_{rec} decreases monotonically with lower μ and higher t_r, and always satisfies $S(v) \leq D$ by construction. Second, the obtained ranges are benchmarked against published evidence showing that adverse road-weather conditions require substantial speed reductions, as reflected in weather-responsive and variable speed management approaches [9], [10].

Additionally, the average speed reduction relative to the posted limit is reported as $\Delta V = V_{limit}-$median (V_{rec}) for each class, which provides an operationally interpretable benchmark for the recommended speed ranges. As a simple baseline, the recommended values are compared with the posted limit V_{limit}=110 km/h. Using the Table 2 medians, the implied reductions are ΔV=18.0 km/h (16.4%) for class A (curve), 22.7 km/h (20.6%) for class B, 38.8 km/h (35.3%) for class C, and 64.8 km/h (58.9%) for class D (curve), which is consistent with conservative speed reductions expected under adverse surface conditions.

Practical application example. To demonstrate the engineering applicability of the proposed framework, the model was applied to a representative high-speed road scenario relevant to local operating conditions in Uzbekistan with V_{limit}=110 km/h, D=80 m, k_{safety}=0.90, and R=300 m for curve cases. Under these assumptions, the framework produced median recommended speeds ranging from 92.0 km/h for the dry-curve case to 45.2 km/h for the icy-curve case, while the wet straight-segment case yielded 71.2 km/h. In operational terms, this corresponds to a reduction of 16.4% to 58.9% relative to the posted limit, demonstrating that the model can generate interpretable and practically conservative speed recommendations for condition-responsive traffic management. After local calibration with measured pavement-friction and geometry data, the same framework may be embedded into advisory or variable-speed control logic within road weather information systems and ITS-based speed management platforms.

3 RESULTS

3.1 Recommended Speed Ranges with Uncertainty

Table 3 reports representative recommended speed outputs and corresponding 95% uncertainty intervals for selected pavement-condition and geometry scenarios. The results show a systematic reduction in recommended speed under deteriorated friction conditions, and a widening of uncertainty bounds for low-friction classes.

Table 3: Recommended speed values with 95% uncertainty intervals.

Scenario	Class	V_{rec} median (km/h)	95% UI (km/h)
Curve (R = 300 m)	A	92.0	85.7-99.0
Straight	B	87.3	80.9-94.2
Straight	C	71.2	61.6-80.0
Curve (R = 300 m)	D	45.2	37.9-51.4

Table 2 presents representative scenario outputs rather than a fully uniform cross-class comparison. Curve scenarios are shown for classes A and D as upper and lower friction extremes, whereas straight-segment scenarios are shown for classes B and C as intermediate operating cases. Therefore, the table is intended to illustrate the sensitivity of the framework to different road conditions and geometric scenarios, rather than to provide direct one-to-one comparison across all classes.

3.2 Effect of Speed on Stopping Distance

To illustrate the physical effect of speed under different friction levels, Table 4 reports stopping distances computed from (1) with t_r = 1.0 s, μ_{dry} = 0.825 (midpoint 0.75-0.90) and μ_{wet} = 0.45 (midpoint 0.35-0.55).

Table 4: Stopping distance versus speed (illustrative calculation).

Speed (km/h)	Dry (m)	Wet (m)
50	25.8	35.7
90	63.6	95.8
100	75.4	115.2
130	116.7	183.8

4 DISCUSSION

The results confirm that friction is the dominant factor determining safe recommended speed under adverse conditions. Compared to dry pavement, wet and icy classes lead to substantial speed reductions and wider uncertainty bounds, reflecting real-world variability of friction and driver response. The obtained behavior is consistent with the rationale of weather-responsive and variable speed management approaches, where speed recommendations are reduced under adverse pavement and weather conditions to improve safety [9], [10], [18]. The proposed framework provides a transparent engineering link between assumed/measured friction ranges, stopping distance constraints, and recommended speed ranges with uncertainty margins.

Limitations include the scenario-based nature of some inputs (typical μ ranges) and the simplified representation of road geometry and traffic interactions. Local context and general road safety considerations in Uzbekistan are discussed in [19], [20]. Future work should focus on collecting local friction and roughness datasets, refining curve-stability parameterization with site-specific geometry, and extending the framework toward traffic-flow-aware real-time ITS implementation.

5 CONCLUSIONS

This study developed a scenario-based framework for determining recommended vehicle speeds under varying pavement conditions using measurable or literature-based surface-condition indicators and a transparent engineering decision rule. The proposed logic combines a stopping-distance constraint and, where applicable, a curve-stability constraint, while also introducing a conservative operational margin through a safety coefficient. In the absence of continuous local measurements, typical friction ranges were adopted for four operational pavement classes (dry-smooth, dry-rough, wet, icy), and the resulting speed recommendations were interpreted as indicative values requiring local calibration for operational deployment. Uncertainty arising from friction variability and driver reaction time was quantified using Monte Carlo simulation (N_{sim} = 10,000), yielding median recommended speeds and 95% uncertainty intervals for each class. Under the selected assumptions (V_{limit} = 110 km/h, D = 80 m, k_{safety} = 0.90), the results indicate substantial speed reductions on low-friction surfaces, from 92.0 km/h for the representative dry-curve case to 45.2 km/h for the icy-curve case. These quantified ranges can support transparent and practically interpretable speed-management decisions. Future work should focus on collecting local friction and roughness datasets, refining geometric inputs, and extending the framework toward real-time ITS implementation for dynamic condition-responsive speed recommendation.

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