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THEORETICAL AND EXPERIMENTAL METHODS FOR DETERMINING THE ALLOWABLE SPEED LIMITS ON HIGH-SPEED HIGHWAYS

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ABSTRACT: The condition of road pavements significantly affects vehicle speeds, traffic performance, and safety. Surface defects such as cracks, potholes, and irregularities reduce driving comfort, force speed reductions, and increase accident risks. This study aims to justify optimal minimum speed limits for high-speed and main roads by considering improvements in pavement conditions, as well as the growing user expectations for driving comfort and operational efficiency. Field data were collected from four highway sections with different levels of surface degradation. Speed measurements for both passenger and freight vehicles were analyzed under traffic conditions. The results confirm a clear relationship between pavement quality and vehicle speed. Based on this, a threshold-based algorithm is proposed. It recommends that the minimum speed differential between freight and passenger vehicles should be at least 15% of the passenger vehicle speed, and that the speed reduction caused by pavement degradation should not exceed 15% of the design speed. These findings support traffic management policies and timely maintenance planning to improve road performance and user satisfaction.

Keywords: Road, Speed limit, Traffic safety, Speed management, Pavement, Crack

1. INTRODUCTION

Design and driver performance, as assessed by the change in driver-selected vehicle speed under free-flow conditions and its relation to the design speed, is widely used to evaluate the quality of highway design in terms of road safety [1]. The idea of design consistency was first introduced by scientists [2] as an alternative to the design speed method: for any given design speed, the average actual speed of light vehicles on any section should not vary by more than 15 km/h.

Thus, the regulation of speed limits at accident-hazardous places is closely connected with establishing the maximum permissible value at this site, taking into account the transport-operational condition of road surfaces and the psycho-physiological state of the driver.

The Finnish experience is that permanent winter speed limits are introduced between November and February [3]. In subsequent years, winter speed limits are enforced on the same roads where the 100 km/h limit is normally enforced.

A significant contribution to the development of the issue of speed limits, as well as studies on road safety and the impact of speed limits on accidents, is presented in [4]. The implementation of winter restrictions led to a 21% reduction in the total number of accidents, with a 40% decrease in fatal accidents. Both outcomes are statistically significant. The intervention appears to have a particularly pronounced effect on head-on collisions on slippery roads involving drivers under the age of 26 [5].

High speeds on roads through settlements and other places where children are and play create the preconditions for accidents and pose a greater safety risk. Reduced speeds in residential areas pose less risk. However, the placement of speed limit signs (20, 30, or 40 km/h) does not always have the desired effect on speed levels in residential areas. Speed is particularly high on wide, straight roads [6]. To reduce speeds to the desired level, it becomes necessary to use enforcement measures that make it impossible or inconvenient to travel at high speeds.

Standards and regulatory documents emphasize the importance of incorporating pavement condition indicators into road infrastructure management and speed regulation practices. The normative documents [7] include methodologies for measuring macrotexture and linking pavement condition to operational safety. So, the best practices investigated the effectiveness of an intelligent driver assistance system in helping truck drivers comply with speed limits under various road conditions [8]. A study using traffic camera data from Edmonton, Canada, applied a negative binomial model to examine speeding behavior under various temporal and built environment conditions [9].

Variables included season, number of lanes, housing types, proximity to schools, and green space. The results showed that disaggregated models revealed stronger effects of posted speed limits and seasonal variation than aggregated models. Speed violations increased by about 40% in summer under disaggregated analysis, underscoring the importance of detailed modeling.

The work [10] examines the use of Unmanned Aerial Vehicles for initial photographic recording of the scene of an accident, which helps to improve the objectivity of the investigation and reduce the investigation time. The use of UAVs in "smart" transportation systems provides rapid collection of information, including from hard-to-reach areas, surveying from low altitudes, and obtaining high-resolution images without risk to the life and health of personnel.

Another approach used in traffic flow research represents vehicle speed as the sum of two components: deterministic and stochastic [11]. Within this framework, the deterministic component reflects the movement of the main body of traffic flow — that is, the average or characteristic speed determined by road conditions and infrastructure. The stochastic component, in turn, captures individual deviations from the overall speed, caused by actions such as lane changes, overtaking, or other non-standard maneuvers performed by individual drivers. This approach allows for more accurate modeling of real traffic behavior by accounting for both the general movement trends and the random fluctuations occurring at the level of individual vehicles.

Scientists also noted that uncomfortable road conditions lead to increased mental and physiological stress [12]. Higher driving speeds and deteriorating pavement quality were associated with elevated phasic skin conductance and heart rate. This indicates activation of the autonomic nervous system in response to less favorable driving environments. Thus, the soundscape and road quality can significantly affect urban well-being.

Also, study [13] examines the impact of dynamic loading caused by pavement roughness on the accuracy of measurements obtained using the Traffic Speed Deflectometer. Using a semi-analytical finite element method, it was shown that as the dynamic loading coefficient increases, the error in deflection estimation also increases.

Investigation [14] demonstrates the use of Traffic Speed Deflectometer (TSD) data to calculate structural indexes that distinguish between weak and strong pavements. Using historical data from the US National Parks network, performance models were developed, showing that incorporating TSD-based structural indicators—such as center deflection and structural number ratios—improves prediction accuracy, particularly for the International Roughness Index.

Despite extensive research, many aspects of the problem remain unresolved, particularly the influence of road and operational conditions on driving speed. This study aims to determine acceptable speed limits on highways by evaluating pavement quality along with other key factors influencing traffic flow and road safety. In addition to theoretical analysis, field data were collected from four highway sections with varying pavement conditions. These experimental speed measurements were used to validate the proposed threshold-based approach and to quantify the impact of surface degradation on vehicle speed.

2. RESEARCH SIGNIFICANCE

This study focuses on the insufficient consideration of minimum safe speed thresholds under deteriorated pavement conditions. While most prior research emphasizes maximum or design speeds, the present work focuses on lower operational limits necessary to maintain safety and efficient traffic flow. By combining field observations with theoretical analysis, a 15% deviation threshold is proposed to guide speed regulation decisions. The findings offer a quantitative framework for evaluating the impact of pavement degradation on vehicle speed, contributing to road maintenance planning, traffic safety improvements, and more effective infrastructure management strategies under varying road conditions.

3. MATERIALS AND METHODS

3.1 Theoretical Basis For Road Pavement Impact On Speed

For the effective functioning of intelligent transportation systems, several factors influencing the safety and efficiency of traffic flows must be considered. One of the most critical aspects is the condition of road infrastructure, which directly affects the speed and safety of movement. Pavement defects, such as cracks and potholes, can reduce road adhesion [15], forcing drivers to decrease speed to avoid accidents [16].

Additionally, the condition of artificial structures, such as bridges and overpasses, can limit the road's capacity and influence vehicle speed. Moreover, traffic intensity and dynamic changes in traffic flow are significant factors that determine the operational characteristics of the road [17]. To assess all these parameters, Subsystem D (automobile road) is used, allowing for the collection and analysis of data on various aspects of road conditions [18]. Therefore, a comprehensive study of these indicators contributes to improving safety and enhancing the quality of road infrastructure [19].

Table 1 systematizes key parameters affecting road performance, including geometry, pavement condition, traffic intensity, and safety indicators [3]. In this study, it is used to objectively assess the factors contributing to speed reduction. The collected data serves as the basis for calculating the speed adequacy coefficient and for justifying the permissible speed under varying operational and pavement conditions [20].

The relative danger of road sections with different friction coefficients is assessed by the values of accident rates [3]: for an friction coefficient of 0.3, the accident rate coefficient is 8; for 0.4, it is 3; for 0.5, it is 2; for 0.6, it is 1.5; for 0.7, it is 1; and for 0.8, it is 0.5 [21].

Based on these accident rate coefficients, it is evident that as the friction coefficient increases, the relative risk of accidents decreases significantly. This correlation underscores the importance of maintaining road surface quality to ensure adequate friction, particularly in regions prone to adverse weather conditions. Roads with lower friction coefficients, such as those with damaged or aged pavement, pose a higher risk to vehicle stability and control, especially at higher speeds.

The travel speed is evaluated based on the operational coefficient of the provided design speed (K_s), where the technical level and operational condition of Subsystem D ensure road traffic safety for individual vehicles under favorable ($K_s \geq 1$) and unfavorable weather and climatic conditions ($0 < K_s < 0.75$; $K_s < 0.5$), with maximum travel speeds corresponding to the category of the operating road.

Table 1. Comprehensive Characteristics of Subsystem D [3]

No.	Indicator, Parameter, and Characteristic	Components of the Comprehensive Characteristics
1	General Data about the Road	- road number and location area; - road category, length; - road-climatic zone; - managing authority and service organization.
2	Geometric Parameters and Characteristics	- width of the roadway and shoulders, the main reinforced surface of the road and reinforcement strips; - longitudinal and transverse slopes of the roadway and shoulders; - radii of curves in plan and bend slope; - intersections and junctions.
3	Characteristics of Road Pavement and Surface	- road pavement structure and surface type; - strength and condition of the road pavement and surface (presence, type, location, and characteristics of defects); - longitudinal evenness of the surface; - transverse evenness of the surface (rutting); - coefficient of friction between the vehicle tires and the surface.
4	Artificial Structures	- location, type, length, and dimensions of bridges, overpasses, viaducts, and tunnels; load-bearing capacity of bridges, overpasses, and viaducts; presence and height of curbs; type and condition of bridge decks; presence, material, type, dimensions, and condition of pipes.
5	Traffic Characteristics on the Road	- traffic intensity on characteristic sections and its dynamic change over the last 3-5 years; - composition of the traffic flow and its dynamic changes; - data on traffic accidents (accidents) over the past 3-5 years, concerning mileage and highlighting the number of incidents by road conditions.
6	Facilities and Equipment	- mile markers and signaling posts; traffic signs and their locations; road markings, compliance with standards and regulations; - barriers, their design, location, length, condition, compliance with standards and installation regulations; - junctions, intersections with roads and railways, their type, location, and compliance with design standards; - bus stops and pavilions, rest areas, stopping and parking areas for vehicles, their main parameters, and compliance with regulatory requirements; - additional lanes and transition-speed lanes, their main parameters.
7	Protective Structures	- snow protection fences, noise and wind protection devices, and devices to protect roads from snow avalanches, landslides, and other natural hazards.
8	Service Facilities for Traffic and Road Maintenance	- customs points (control points); weigh stations; road police posts; gas stations (fuel stations), service stations, campsites, traffic police points, bus stations, exits, and entries.
9	Settlements and Characteristics of Adjacent Areas	- the presence of settlements; - special traffic regulations within settlements; - presence of settlements located off the road (up to 20 km), with indications of distance to them from the road.

The permissible values of V_{max} for all road categories are presented in Table 2 [3].

Table 2. Permissible Maximum Speed Limits by

Road Category

Weather and Terrain Conditions	Permissible Vmax values for road categories, km/h					
	I-a	I-б	II	III	IV	V
1	2	3	4	5	6	7
Under favorable weather and climatic conditions						
On the main road sections	120-150	100-120	100	80	60	
On difficult sections of the rough terrain	100-120	90-100	80	60	40	
On difficult sections of mountainous terrain	75-80	60	50	40	30	
Under unfavorable weather and climatic conditions						
On the main road sections	90-100	80-90	75	60	45	
On difficult sections of the rough terrain	80-90	70-75	60	45	30	
On difficult sections of mountainous terrain	60	45	40	30	20	

These values reflect national practice in Kazakhstan, where seasonal and terrain-related factors are considered. In most foreign countries, speed limits are not seasonally adjusted. One of the key factors influencing speed regulation is the overall pavement condition [22].

3.2 Current State Of Road Infrastructure

In Kazakhstan, the total length of the road network is 96,000 kilometers, including 25,000 kilometers of republican roads and 71,000 kilometers of local roads [23]. Kazakhstan is characterized by a predominantly continental climate, with pronounced temperature amplitudes and relatively low precipitation levels.

The country's southern regions receive modest annual precipitation, ranging from 100 to 500 mm. These areas experience hot summers and mild winters, consistent with a typical continental arid or semi-arid climate.

In contrast, the northern part of Kazakhstan exhibits a sharply continental climate and belongs to the West Siberian climatic zone. Winters are long and harsh, lasting up to six months, while summers are moderately warm.

The average temperature in January is approximately −22 °C, and in July it reaches around +21 °C. Annual precipitation varies from 300 mm in the southern parts of the region to 450 mm in the north, with occasional peaks reaching up to 800 mm. For instance, a record precipitation of 780 mm was observed in Astana city.

However, the region often experiences soil moisture deficits despite a seemingly sufficient amount of precipitation. This is primarily due to the limited forest cover and intense solar radiation, leading to potential evapotranspiration levels ranging between 800 and 900 mm [24]. Droughts occur periodically, and in some years, the summer months are influenced by cold air masses descending from the northern seas. In July 2023, the average monthly temperature in Petropavlovsk was recorded at +15.7 °C [3].

Northern Kazakhstan lies between latitudes 49°N and 55°N, resulting in notable seasonal variation in daylight duration. Around 90% of the region accumulates approximately 2000 °C of active temperatures (above 10 °C), while southern areas reach up to 2800 °C [3]. Climatic conditions, particularly the significant daily and annual temperature fluctuations, have a considerable impact on transportation infrastructure.

The national road network supports regional and international connectivity, while local roads link rural areas to main routes. In Kazakhstan, speed limits are largely based on accident statistics, with limited consideration of underlying factors like pavement condition, speed bumps, raised crossings, and lane narrowing.

This gap hinders the effective implementation of targeted speed management measures. In turn, on modern high-speed roads, speed limits are, in most cases, imposed compulsorily at locations where the road's performance has deteriorated due to defective or slippery pavements in winter or at sections where pedestrian crossings were not foreseen at the time of the road's design.

The key directions for studying traffic accident data are essential for traffic management organizations. The first direction—assessment of the accident rate—involves collecting and analyzing data on road traffic crashes to identify patterns and trends. This process enables the evaluation of crash frequency at specific road sections or within broader geographic areas.

The second direction involves analyzing crash causes by examining road conditions, environmental factors, and driver behavior, including speeding, violations, and fatigue. It also includes identifying high-risk locations—such as sharp curves, steep grades, and low-visibility zones—where targeted engineering, regulatory, or organizational measures can be implemented to enhance traffic safety and reduce accident risks through evidence-based interventions and continuous monitoring.

Although the total number of accidents in Kazakhstan had increased since 2013, those caused by road conditions had decreased nearly fivefold [25], largely due to improved road performance and climatic factors. Table 3 shows accident numbers related to increased traffic speed [26]. Seasonal variations in accident rates were also significant (Fig. 1).

Table 3. Traffic accident statistics

Month	Year				
	2018	2019	2020	2021	2022 2023
1	5	6	7	8	
January	12/7	18/10	12/6	13/6	12/7
February	18/9	12/7	10/6	11/6	13/7
March	9/5	15/10	8/4	16/8	14/11
April	22/15	21/16	8/4	20/11	17/12
May	25/12	25/13	19/13	20/12	19/10
June	38/24	44/29	19/11	22/13	17/9
July	44/28	46/32	35/19	35/20	35/20
August	50/38	54/42	25/18	35/20	35/20
September	31/18	37/21	18/14	30/21	30/21
October	31/19	47/22	22/13	35/24	35/24
November	33/19	27/18	26/14	30/16	30/16
December	27/13	25/13	20/13	22/15	22/15

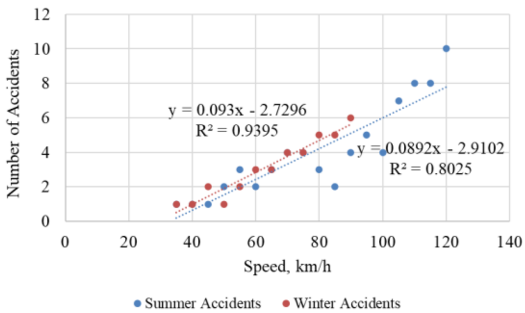


Fig 1. Accident Frequency vs Speed

According to recent census data, Kazakhstan has a population of 16.4 million and 2.63 million registered vehicles. This results in a national motorization level of 160 cars per 1000 inhabitants.

3.3 Object Of Investigation

The investigation involved data collection, speed distribution analysis, evaluation of deviations from design speed, assessment of indicator relationships, and development of recommendations. The selected segments reflect diverse terrain and traffic conditions: Almaty–Kapchagai (km 14–68): flat terrain, category Ia, six lanes, 9680 vehicles/day (Fig. 2a); Kapchagai–Shengeldy–Arkharly–Saryozek (km 78–150): mostly flat, category Ib, includes 4200 m Arkharly Pass, speed limit 70 km/h (Fig. 2b); Saryozek–Aynabulak–Balpyk Bi (km 150–247): mountainous terrain, category Ib, prone to ice and snow in winter (Fig. 2c); Balpyk Bi–Taldykorgan (km 247–259): through settlements, 35 km, category Ib, ice-prone (Fig. 2d).

– a)

b)

c)

d)

Fig.2 Sections with mandatory speed limits: a) Section 1; b) Section 2; c) Section 3, d) Section 4.

Field speed measurements were carried out on the selected segments of the highway. At the first stage, the data collection locations and the total number of speed observations per segment were defined. The road category and observation schedule were set in advance. According to the adopted methodology, each segment was observed once per year, regardless of its length or the time of day, following standard procedures for high-capacity roads.

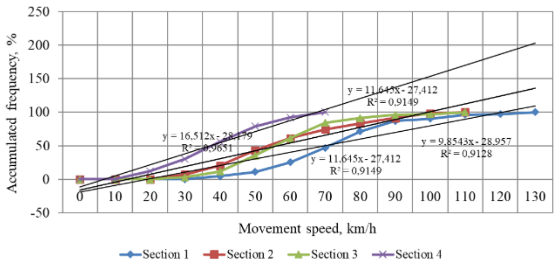
All measurements were conducted under representative traffic conditions relevant to the functional classification of each road segment, in line with standard traffic monitoring practices.

In field conditions, vehicle speeds were recorded using the “Iskra-1” radar device, operated under technical specifications [26]. This device is designed for remote monitoring of ground vehicle speed and is widely applied in traffic enforcement and patrol operations. It provides high measurement accuracy and meets the official standards for permissible error margins.

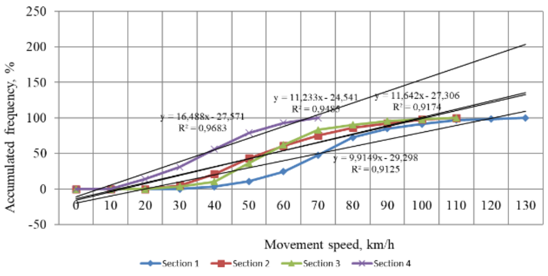
4. RESULTS

4.1 Case Study Results: Analysis Of Four Roads

The annual average daily traffic intensity is the average number of vehicles passing along a certain section of a highway during a day in the calendar year. This indicator is a key parameter for the development of the transport network and for determining priorities in infrastructure modernization. The cumulative curve of vehicle speed on the sections of the highway “Almaty-Ust-Kamenogorsk” is presented in Figure 3.



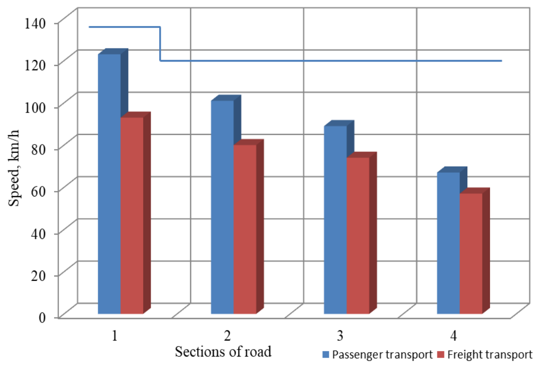
a)



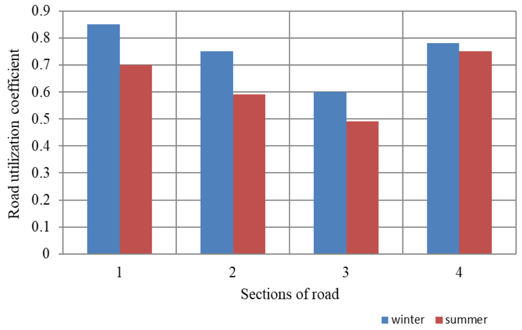
b)

Fig.3 Driving speed a) passenger transport; b) freight transport

The speed of vehicles on each section of the road and the road utilization coefficient in winter and summer are presented in Figure 4.



a)



b)

Fig.4 Indicators on-road sections a) speed of vehicles; b) road utilization coefficient

According to the results of the data obtained on the sections of the road “Almaty-Ust-Kamenogorsk” the level of reduction of technical speed of movement relative to the actual speed of movement from the technical speed, adopted in the design process, was assessed. In almost all sections of the road under study, the difference in the actual speed of vehicles is significantly reduced from the technical speed.

Reductions in travel speed are mainly related to the quality of operational works and operational indicators (snow drifting, slipperiness, various defects, etc.). In this case, in international practice, to reduce the accident rate at “bottlenecks,” make decisions to limit the speed of traffic and install a road sign “Maximum Speed Limit” [27].

The consumer performance of the road sections was evaluated based on the ratio between operational speed and design speed of the road, Almaty-Ust-Kamenogorsk:

- Section 1 – 0.66 and 0.87 for freight and passenger vehicles, respectively.
- Section 2 – 0.76 and 0.93 for freight and passenger vehicles, respectively.
- Section 3– 0.72 and 0.84 for freight and passenger vehicles, respectively.
- Section 4– 0.52 and 0.92 for freight and passenger vehicles, respectively.
-

4.2 Proposed Algorithm For Speed Limit Determination

Based on the study, an algorithm was developed (Fig.5), which is a sequence of steps aimed at a reasonable determination of the maximum allowable speed of traffic, considering the condition of the road surface, operational factors, design speed, and actual speed of vehicles.

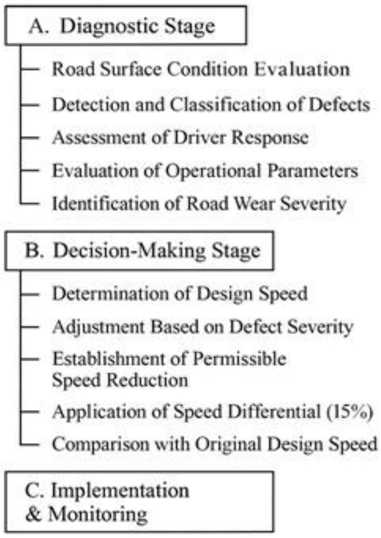


Fig. 5 Algorithm for determining the permissible level of vehicle speeds

The first stage of the algorithm involves assessing pavement conditions through visual and instrumental inspection. This is followed by defect identification, including cracks, potholes, and deformations. Simultaneously, the deterioration level is evaluated based on traffic loads and climatic influences. These diagnostic steps form the basis for subsequent decisions.

The next stage assesses how surface defects impact road safety, vehicle maneuverability, and the necessity of adjusting speed limits. Driver responses such as speed reduction, lane changes, or sudden braking are also considered, as these actions increase the risk of accidents. Following this, the algorithm evaluates key operating conditions, including traffic volume, vehicle type distribution, seasonal weather patterns, and the overall technical condition of the infrastructure. These inputs inform the determination of the design speed, defined as the maximum safe speed set during the road's planning phase.

Based on this data, the algorithm analyzes whether the current road condition allows for maintaining the design speed without compromising safety. If not, a defect-based speed adjustment is introduced. The actual speed of vehicles is then assessed through observations and video recordings. By comparing the design and observed operational speeds, the permissible speed reduction is established. In line with the provisions of this study, the reduction should not exceed 15% of the design speed, and the speed difference between cars and trucks should be at least 15% of the car speed.

The algorithm further provides for maintenance or repair interventions aimed at restoring pavement quality and potentially increasing speed limits. After implementing such measures, continuous monitoring is conducted to evaluate their effectiveness. This includes analyzing updated data on road conditions, speed behavior, and accident statistics to assess whether safety and performance objectives have been met.

The final stage involves adjusting the speed limits based on monitoring results, ensuring alignment with current road conditions and safety standards. One notable observation in this study is the consistent reduction of actual operating speeds compared to design speeds. This trend is likely driven by rising expectations for road quality and maintenance, factors that are often not fully addressed in current speed regulation practices.

One limitation of speed regulation based on actual operating speed is that, in some cases, speed reduction is implemented solely using traffic signs. This may serve as a substitute for comprehensive road infrastructure improvements and can indicate underlying systemic issues in the road sector. Therefore, traffic signs should be considered as part of an integrated road safety strategy, rather than being the only means of ensuring safe travel conditions.

4.3 Practical Recommendations

Based on the findings of this study, the following recommendations are proposed to improve the alignment between design speeds and actual operating conditions, thereby enhancing the safety and efficiency of road infrastructure:

1. Establishing a minimum operational speed threshold: It is recommended that the difference between the design speed and the actual operating speed should not exceed 15% for both passenger and freight vehicles. Maintaining this threshold can reduce traffic flow inconsistencies and improve network predictability.
2. Implementing adaptive speed limits: seasonal or temporary speed limits should be introduced based on surface conditions, friction coefficient, and weather patterns.
3. Comprehensive assessment of road conditions: A systematic approach is advised, involving regular evaluation of pavement quality, road geometry, traffic intensity, and accident rates. This can be

integrated into a diagnostic subsystem (Subsystem D) to support timely decision-making.

4. Use of physical speed management measures: in high-risk zones, it is suggested to implement physical interventions such as road narrowing, raised pedestrian crossings, rumble strips, and refuge islands to enforce lower speeds.
5. Enhancing road operation culture and innovation: investment in training for road maintenance personnel and the adoption of innovative technologies for road monitoring and rehabilitation are strongly encouraged to improve long-term infrastructure performance.

5. CONCLUSIONS

This study confirms that the operational condition of the roadway has a significant influence on drivers' speed choices and, consequently, on overall road safety. Practicing engineers should consider not only the design parameters but also the actual surface and traffic conditions—such as traction, smoothness, visibility, and flow intensity—when setting or reviewing speed limits.

To support informed decision-making, a step-by-step algorithm was developed that assesses pavement condition, traffic characteristics, and design parameters to determine permissible speed reductions. One of the key recommendations is to maintain the allowable speed reduction within 15% of the road's design speed; exceeding this threshold can disrupt traffic flow, reduce capacity, and increase accident risk.

For practitioners, this integrated approach offers a practical tool for aligning safety standards with real-world conditions. It emphasizes the importance of systematic diagnostics and highlights the need to avoid over-reliance on speed limit signs as a substitute for infrastructure improvements. Instead, speed regulation should be part of a broader safety strategy that considers both engineering design and actual road performance.

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