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Dynamic Signs and Variable Speed Limits to Enhance Road Safety and Traffic Efficiency

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Abstract

The continuous expansion of the Internet of Things (IoT), Big Data systems, and Information and Communication Technologies (ICTs) has transformed traditional road infrastructure, leading to the development of "Smart Roads." These roads interact with vehicles through data exchanges to enhance traffic efficiency o and safety. For instance, in adverse weather conditions like rain or fog, temporary speed reductions communicated via in-vehicle systems or Variable Message Signs (VMS) can restore safety levels. This paper introduces an innovative algorithm for determining the maximum allowable speed on a road segment through real-time analysis of geometric and environmental factors. The system aims to proactively mitigate accident risks caused by non-ideal conditions by dynamically adjusting speed limits. A case study on the Grande Raccordo Anulare (A90) in Rome, a heavily trafficked highway, illustrates the algorithm's application. The methodology involves a detailed geometric modeling of the A90 and analysis of weather conditions, leading to adaptive speed recommendations. Results indicate that dynamic speed management can significantly reduce accident rates by ensuring that the available sight distance exceeds the stopping sight distance under various conditions. Implementing this system with VMS and on-board units can effectively communicate real-time speed adjustments to drivers, promoting safer and more efficient road usage.

Keywords: Smart Road; Intelligent Transportation System (ITS); Variable Message Signs; Variable Allowable Speed; Road Safety

1. Introduction

Road safety is a critical aspect in the management of road infrastructure, particularly concerning existing roads, most of which were designed and constructed before the commencement of the current Italian Functional and Geometric Standards for Road Construction (Ministry of Infrastructure and Transport, 2001). A significant number

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of these roads, for instance, lack the necessary roadway widenings required for adequate visibility due to their geometric characteristics (Singh et Singh, 2023; Cantisani et al., 2022). Visibility distances are crucial in road design, directly influencing user safety (Cantisani et al., 2019). Limited visibility, caused by curves, side obstacles, vertical alignments, or adverse environmental conditions, has been associated with an increased risk of accidents (Cantisani et al., 2023), especially in rural and mountainous areas where road geometry can be particularly complex (Godumula et Ravi Shankar, 2023). Adverse environmental conditions, indeed, such as rain, fog, or snow, reduce pavement's adherence due to the presence of water on the surface (Tan et al., 2023).

When it is not possible to directly improve visibility distances on existing infrastructure, alternative measures, such as reducing operating speeds, must be adopted. Lower speeds compensate for visual limitations, giving drivers more time to react to unforeseen obstacles and variable road conditions. Studies have shown that implementing lower speed limits in areas with limited visibility can lead to a significant reduction in road accidents (Martinelli et al., 2023). A methodology for prioritizing roadside improvements can further enhance safety, especially when resources are optimized based on calculated safety levels (Loprencipe et al., 2018). Advanced technologies, such as variable speed limit (VSL) warning systems, can enhance safety by dynamically adjusting speed limits based on real-time weather (Qiu et al., 2023) and road conditions (Hasan et Mahmoud, 2023), providing drivers with updated information, allowing them to adjust their speed to actual road conditions, thus reducing the risk of accidents (Jin et al., 2023).

Variable message signs (VMS) and on-board units (OBU) are effective tools for dynamically communicating speed limits and road conditions (Wu et al., 2024), providing information also directly within the vehicle, enhancing the timeliness and accuracy of communications (Evangeline et al., 2023). Combining these tools with advanced detection technologies, such as weather sensors and traffic monitoring systems, can further enhance the effectiveness of dynamic speed management, offering an integrated approach to road safety (Nigam et al., 2023). Figure 1 shows electronic signs along roadways, where VSL changes the displayed speed limit based on real-time data, informing drivers of current and upcoming speed limits well in advance for safe adjustments.

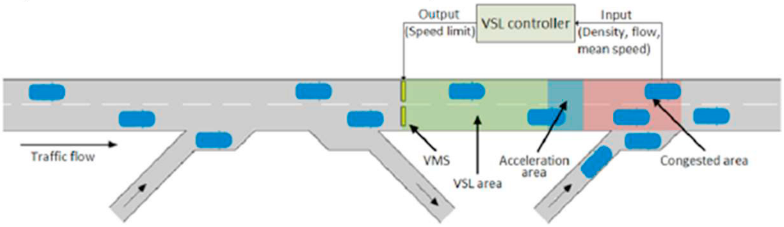

Fig. 1. Variable Speed Limits.

Dynamic signage and variable speed limits (VSL) are essential for enhancing driver safety and efficiency by providing real-time information and adapting to changing conditions, using sensors and traffic management systems (Mekker et al., 2016). They display real-time hazard alerts about sharp curves, steep grades, or intersections (Zhao et al., 2015), and provide updates on traffic conditions like congestion, accidents, or roadworks, helping drivers adjust their speed and behaviour to maintain safe sight distances (Yuan et al., 2022), by optimizing lane usage and preventing sudden stops (Alhajyaseen et al., 2017). This ensures timely warnings, prompts speed reductions during adverse weather, and enhances overall driver awareness, promoting cautious driving behaviour (Ackaah et al., 2015). Variable speed limits (VSL) improve road safety and traffic flow by adjusting speed limits in real-time based on current conditions. They use sensors and communication systems to monitor traffic patterns, weather, and road surface status, providing optimal speed limits for different road sections (Zhang et Liang, 2021). VSL reduces accident risks, and manages traffic flow around incidents, minimizes congestion, resulting in smoother traffic flow and reduced vehicle emissions (Strnad et Marsetič, 2023). Both dynamic signage and VSL leverage real-time data to maintain clear visibility, optimal sight distances, and safe driving conditions, enhancing road safety and efficiency. The use of ITS devices has also proven effective in analyzing and improving the safety of powered two-wheelers, particularly in urban environments like Rome (Sgarrra et al., 2014). As technology advances, these systems are expected to become more sophisticated and widespread, further improving their effectiveness.

This paper proposes an innovative algorithm to determine the maximum allowable speed for vehicles, considering the geometric characteristics of the road infrastructure and various environmental conditions. The algorithm uses planimetric and altimetric data of the road layout and meteorological information to calculate optimal speed limits on an Italian highway section, comparing available sight distances (ASD) to stopping sight distances (SSD). The method aims to implement warning systems for users, utilizing variable message signs (VMS) and on-board units (OBUs).

These systems can communicate variable speed limits in real-time, dynamically adapting to actual road and weather conditions.

2. Algorithm for data processing

The algorithm developed in this study is specifically designed to determine the maximum permissible speed for vehicles based on a comprehensive analysis of the geometric characteristics of the infrastructure and various environmental conditions. This algorithm integrates data from multiple sources to provide a robust and dynamic speed management system. The comparison between the Available Sight Distance (ASD) and the Stopping Sight Distance (SSD) is crucial for road safety. Adequate ASD ensures that drivers have sufficient visibility to react and stop within the SSD, preventing accidents. If the ASD is shorter than the SSD, drivers may not be able to stop in time to avoid a collision. It has to note that wet or icy roads can increase braking distance. Proper road design, maintenance, and adaptive traffic management systems are key to maintaining the balance between these two distances.

The ASD refers to the length of road ahead visible to a driver. It is the distance over which a driver has an unobstructed view of the road surface and any potential hazards. It depends on both horizontal (Figure 2) and vertical characteristics of the road (Figure 3).

For the road layout planimetric characteristics:
- The type of road;
- The number of lanes in each travel direction;
- The shoulder width, both internal and external;
- The lane width;
- The median width, where present;
- The radius of the circular arc;
- The travel direction of the curve.

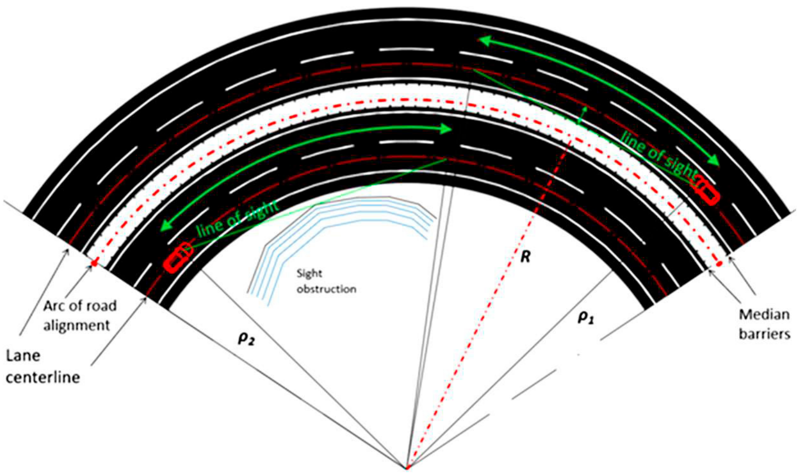

Fig. 2. Road layout planimetric characteristics affecting ASD.

For the road layout altimetric characteristics:
- The type of vertical curve (sag or crest);
- The radius of the vertical curve;
- The variation in longitudinal slopes

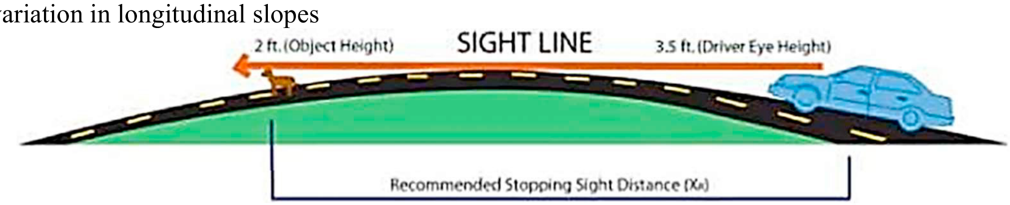

Fig. 3. Road layout altimetric characteristics affecting ASD.

The SSD is the minimum distance required for a driver to bring a vehicle to a complete stop after perceiving an obstacle on the road (AASHTO, 2011; Fambro et al., 1997). This distance includes the time it takes for the driver to perceive the hazard and react (perception-reaction time) and the actual braking distance, as defined by Equation 1:

$$SSD = \frac{V_0}{3.6}\cdot\tau - \frac{1}{3.6^2}\int_{V_0}^{V_1}\frac{V}{g\cdot\left[f_l(V)\pm\frac{i}{100}\right]+\frac{Ra(V)}{m}+r_0(V)}dV \qquad [1]$$

Where,
V_0 = initial speed of the vehicle [km/h];
τ = perception-reaction time [s]; the average reaction time is usually taken as τ=2.8-0.01·V;
V_1= final speed of the vehicle, equal to 0 km/h;
g = acceleration of gravity [m/s^2];
$f_l(V)$ = longitudinally engageable coefficient of adhesion for braking;
i = longitudinal slope of the path [%];
$Ra(V)$ = aerodynamic drag [N];
m = vehicle mass [kg];
$r_0(V)$ = unit rolling resistance, negligible [N/kg].

The design and safety of roadways are fundamentally influenced by their geometrical characteristics (AASHTO, 2011; Lamm et al., 1999). Understanding the interplay between road geometrical characteristics and SSD is essential for the development of safe and efficient road infrastructure. For instance, on a road with sharp horizontal curves, the available sight distance can be restricted by physical obstacles like trees, buildings, or cut slopes (Glennon et al., 1985). In such cases, reducing the speed limit or increasing the curve radius may be necessary to ensure drivers have sufficient SSD (Harwood et al., 2000). Vertical alignment also plays a crucial role. On crests of hills, the sight distance can be limited, requiring adjustments in the road design to avoid sudden hazards coming into view too late for safe stopping (Olson et al., 1994). Similarly, on descending gradients, the SSD must be increased to account for the longer braking distances due to gravitational forces (AASHTO, 2011).

The result of data processing is expressed in diagrams in which the maximum allowable operating speed is related to the associated sight distance (SD). Numerous diagrams showing the curves corresponding to the SDs in dry and wet conditions for a specific road type and a given horizontal alignment and a longitudinal gradient have been realized. In the specific cases of Figure 4 an extra-urban highway is presented. In the left-hand figure (4.a) a longitudinal slope equal to -6%, and a left-turn circular arc have been assumed with a radius related to the maximum design speed (horizontal analysis). In the rigth-hand figure (4.b) a radius R_v equal to 4000 m, and a longitudinal slope variation between the connected slopes (Δi) equal to 1% have been taken (vertical analysis):

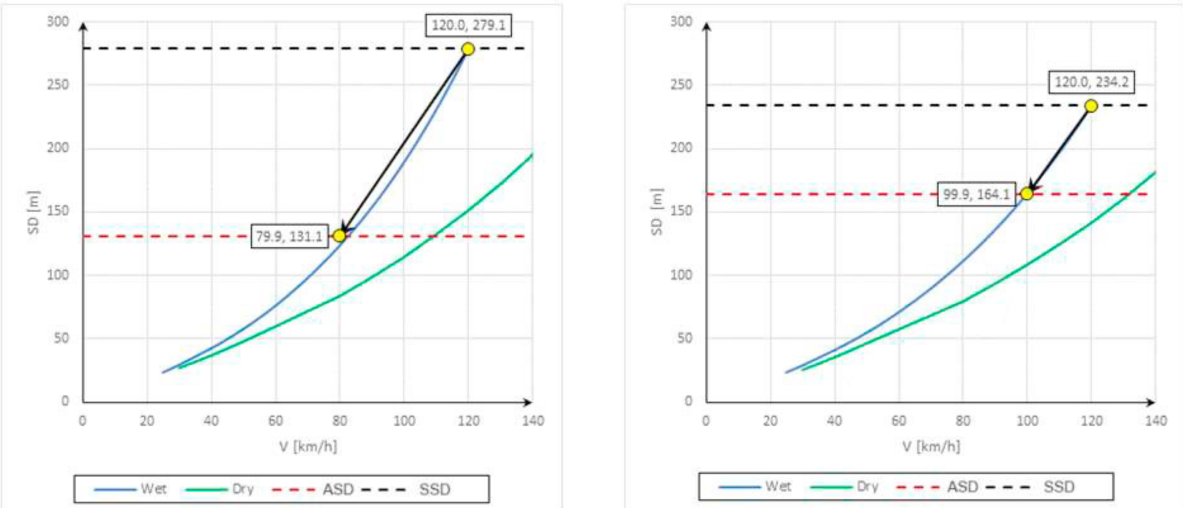

Fig. 4. SDs on extra-urban highways characterized by a dry or wet pavement: a. horizontal alignment i=-6%, left turn circular arc with max design speed, b. vertical alignment Rv = 4000 m and Δi = 1%.

The travel speed determination is based on comparing the available sight distance and the stopping sight distance. The former depends on the geometry of the route, while the latter depends on the environmental conditions. Additionally, the stopping sight distances are influenced by the design speed of the route, the slope of the longitudinal grade, and prevailing environmental conditions.

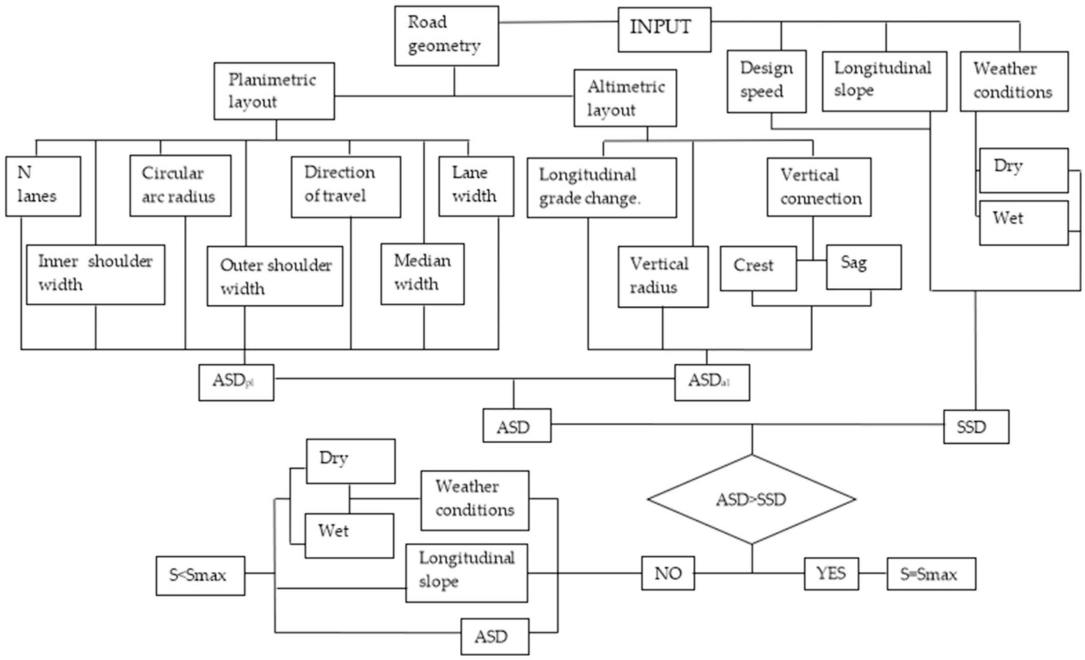

Fig. 5. Implemented methodology to compare available and stopping sight distances.

The implemented methodology (Figure 5) to compare available and stopping sight distances involves a systematic and detailed approach to evaluate the safety and efficiency of roadway designs. This methodology encompasses several key steps, including data collection, analysis, and comparison, each of which plays a crucial role in ensuring that sight distances are adequate for safe driving conditions. By analyzing any road route, the available sight distance (ASD) can be precisely evaluated. It has to be compared to the distance needed by users to stop safely in case of an unexpected, fixed obstacle, known as the Stopping Sight Distance. For the same road stretch, the SSD depends on the longitudinal friction coefficient and, therefore, on the pavement conditions (presence of water, snow, dry pavement).

$$\begin{cases} ASD \geq SSD_{,dry} \\ ASD \geq SSD_{,wet} \end{cases}$$

If the available sight distance is less than the required stopping sight distance, drivers may not be able to perceive potential hazards in time to react appropriately, increasing the risk of accidents or improper maneuvers. To enhance safety levels, it is feasible to reduce the maximum allowable speed, ensuring that the stopping sight distance at the new speed is less than or equal to the sight distance provided by the infrastructure. After processing data from infrastructure and traffic monitoring systems, it is essential to communicate any hazardous conditions and necessary speed reductions or increased following distances to drivers. This enables drivers to adjust their driving behavior promptly to prevent accidents. Such communications can be delivered via variable message signs placed along the roadway or directly to the vehicle through On-Board Units or smartphones. Variable message signs are screens equipped with LED lights installed on Smart Poles (Figure 6). They allow the display of alphanumeric messages and road signals, thereby enhancing the quality of information by associating the signal with a short-written text. The dimensions of the panel must be such that the user can immediately understand the message without distractions during driving. The variable message signs must comply with the standards prescribed in UNI EN 12966 (UNI EN 12966, 2014). To ensure efficient but not excessive communication, which could lead to non-compliance, the panels will not be placed on every pole but at approximately 1000 meters from each other.

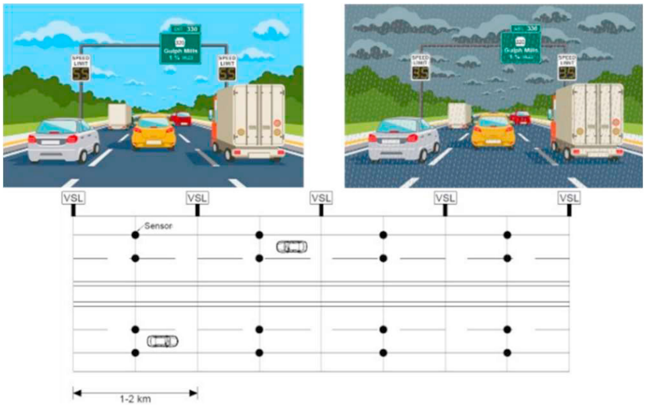

Fig. 6. Expected outcomes through Variable message signs.

3. Case study: A90 in Rome

Focusing on the Lazio region the Grande Raccordo Anulare of Rome (A90), the road was chosen as a case study because it is the road infrastructure with the highest traffic statistical indicators. According to the Italian National Institute of Statistics (ISTAT, 2019), the A90 recorded over 500 traffic accidents in 2019, making it a critical area for implementing and testing advanced traffic management systems. The city of Rome experiences during a year an average of 285 days without rain, 78 days with precipitation greater than 1 mm, 27 days with precipitation greater than 10 mm, 10 days with precipitation greater than 20 mm, and 1 day with precipitation greater than 50 mm. It is assumed that on days with precipitation greater than 1 mm, the system does not intervene because the water film level and the intensity of the rain, which limits visibility, are so high that safe driving at high speeds is not possible, even on highways.

3.1. Geometric Modeling of the Road Axis

The dimensions of the planimetric geometric elements that make up the road axis - lane width, shoulder width, median width, number of lanes, and radii of circular curves - were obtained by reconstructing the A90 route using the "AutoCAD" program, based on 1:5000 scale regional technical maps (CTR). According to Figure 7, which shows the number of accidents – gray 0 accident, green 1 accident, yellow 2 accidents, red 3-4 accidents, and black 5 or more accidents – per kilometer in 2019, it is possible to infer the correlation between the geometry of the road axis and accidents, thereby identifying the deficient aspects of the infrastructure that need attention.

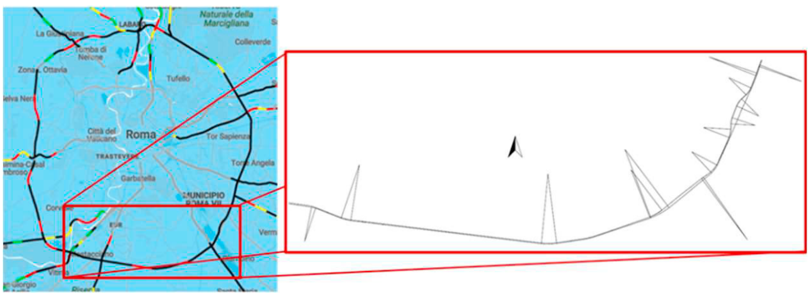

Fig. 7. Number of accidents per kilometre in 2019 along the A90 – horizontal alignment for the section between km 41+400 and km 43+200.

Specifically, the southeast area is the most critical one, with the highest number of accidents. In the reconstruction of the horizontal alignment (zoom in Figure 7), it was observed that the sequence of geometric elements does not comply with current design standards: circular curves are directly connected to straight sections without the use of transition curves, because the segment of the A90 was completed before the current regulations were enacted. For the altimetric layout, a gradient of 0% was considered since the terrain is almost flat.

3.2. Evaluation of Reduced Speeds

Using the methodology described before, the maximum permissible speed was evaluated for varying weather conditions while maintaining the same road geometry. Additionally, by reducing the dimensions of the planimetric geometric elements, it is possible to simulate scenarios such as stationary vehicles, obstacles, or roadworks on the infrastructure and determine the corresponding permissible speed. Once the radii of the circular curves are determined, the curvatures can be derived. The design speeds of the individual planimetric elements for both climatic conditions can be determined. Figure 8 shows that it is necessary to reduce the speed on five curves in the event of wet pavement. Furthermore, since the first two curves are close together and have identical reduced speeds, it is possible to also reduce the speed on the straight section to make the speed indications more consistent.

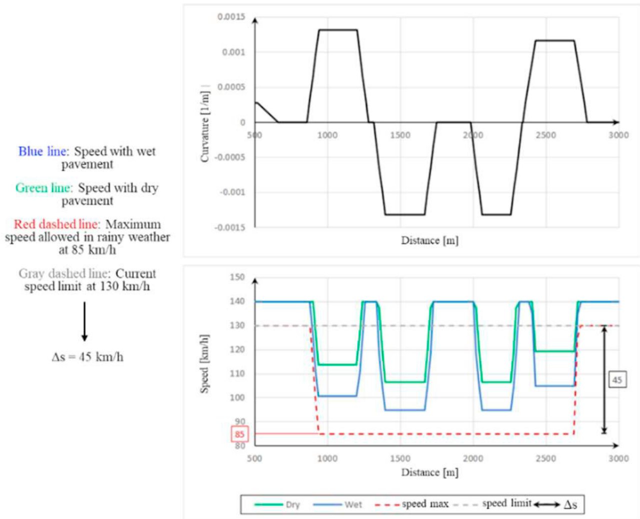

Fig. 8. Curvature and speed diagram for the section between km 41+400 and km 43+200.

4. Conclusions

The methodology implemented for comparing available and stopping sight distances offers a comprehensive approach that integrates data collection, analytical modeling, and practical safety interventions. By rigorously assessing sight distances, this approach aims to enhance roadway safety, reduce accident risks, and ensure road designs meet necessary safety standards under various driving conditions. The results from the case study on the Grande Raccordo Anulare (A90) in Rome demonstrate the algorithm's effectiveness in dynamically adjusting speed limits based on real-time data. This leads to safer driving conditions by ensuring the available sight distance exceeds the stopping sight distance, particularly in adverse weather conditions.

Smart roads represent a significant leap forward in creating a safer, more efficient, and environmentally friendly transportation system. By leveraging advanced technologies, these intelligent infrastructures not only enhance road safety but also improve the overall driving experience. As technology continues to evolve, the sophistication and widespread adoption of smart road systems are expected to increase. This advancement will further improve their effectiveness, contributing to the ongoing efforts to enhance road safety and traffic efficiency. Future research should focus on refining the algorithm, exploring additional environmental variables, and expanding the application to other road types and regions. This continued innovation will play a crucial role in shaping the future of transportation, making roads safer and more reliable for all users.

References

AASHTO (2011). "A Policy on Geometric Design of Highways and Streets." American Association of State Highway and Transportation Officials.

Ackaah, W., Huber, G., & Bogenberger, K. (2015). Quality evaluation method for variable speed limit systems: incident detection and warning potential. Transportation research record, 2484(1), 80-89.

Alhajyaseen, W. K., Ratrout, N. T., Assi, K. J., & Hassan, A. A. (2017). The integration of dynamic lane grouping technique and signal timing optimization for improving the mobility of isolated intersections. Arabian Journal for Science and Engineering, 42, 1013-1024.

Cantisani, G., Borrelli, C. C., Del Serrone, G., et Peluso, P. (2023). Optimizing road safety inspections on rural roads. Infrastructures, 8(2), 30.

Cantisani, G., Loprencipe, G., & Moretti, L. (2022). Median design to provide stopping sight distance along horizontal curves in urban freeways. Advances in transportation studies, 58.

Cantisani, G., Moretti, L., & De Andrade Barbosa, Y. (2019). Safety problems in urban cycling mobility: A quantitative risk analysis at urban intersections. Safety, 5(1), 6.

Evangeline, C. S., Sarah, M., Lenin, A., Reddy, J. H. V., Mary, X. A., et Karthiga, M. (2023, May). Design of On-Board Unit for Vehicular Applications. In 2023 2nd International Conference on Vision Towards Emerging Trends in Communication and Networking Technologies (ViTECoN) (pp. 1-6). IEEE.

Fambro, D. B., Fitzpatrick, K., & Koppa, R. J. (1997). Determination of stopping sight distances (Vol. 400). Transportation Research Board.

Fitzpatrick, K., Fambro, D. B., & Stoddard, A. M. (2000). Safety effects of limited stopping sight distance on crest vertical curves. Transportation Research Record, 1701(1), 17-24.

Glennon, J. C., Neuman, T. R., & Leisch, J. E. (1985). "Safety and Operational Considerations for Design of Rural Highway Curves." Transportation Research Record.

Godumula, D. T., et Ravi Shankar, K. V. R. (2023). Safety evaluation of horizontal curves on two lane rural highways using machine learning algorithms: a priority-based study for sight distance improvements. Traffic injury prevention, 24(4), 331-337.

Harwood, D. W., et al. (2000). "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, Federal Highway Administration.

Hasan, T., Abdel-Aty, M., et Mahmoud, N. (2023). Freeway crash prediction models with variable speed limit/variable advisory speed. Journal of transportation engineering, Part A: Systems, 149(3), 04022159.

Italian National Institute of Statistics [ISTAT]. (2019). I.Stat - Statistiche ISTAT; [accessed 2024 July 10].

Jin, J., Huang, H., Li, Y., Zhang, G., Dong, Y., Zhou, B., et Xue, H. (2023). Variable speed limit modelling to improve traffic safety and efficiency of mixed traffic flow by a two-stage framework. Transportmetrica A: Transport Science, 1-25.

Lamm, R., Psarianos, B., & Mailaender, T. (1999). "Highway Design and Traffic Safety Engineering Handbook." McGraw-Hill.

Loprencipe, G., Moretti, L., Cantisani, G., & Minati, P. (2018). Prioritization methodology for roadside and guardrail improvement: Quantitative calculation of safety level and optimization of resources allocation. Journal of traffic and transportation engineering, 5(5), 348-360.

Martinelli, V., Ventura, R., Bonera, M., Barabino, B., et Maternini, G. (2023). Estimating operating speed for county road segments–Evidence from Italy. International journal of transportation science and technology, 12(2), 560-577.

Mekker, M. M., Remias, S. M., Bunnell, W. A., Krohn, D. W., Cox, E. D., & Bullock, D. M. (2016). Variable speed limit study upstream of an Indiana work zone with vehicle matching. Transportation Research Record, 2555(1), 53-64.

Ministero delle Infrastrutture e dei Trasporti. Decreto Ministeriale n.6792 del 05/11/2001. Norme Funzionali e Geometriche per la Costruzione delle Strade. In Gazzetta Ufficiale della Repubblica Italiana; Ministero delle Infrastrutture e dei Trasporti: Roma, Italy, 2001.

Nigam, N., Singh, D. P., et Choudhary, J. (2023). A review of different components of the intelligent traffic management system (ITMS). Symmetry, 15(3), 583.

Olson, P. L., Cleveland, D. E., Fancher, P. S., & Kostyniuk, L. P. (1994). "NCHRP Report 400: Parameters Affecting Stopping Sight Distance." Transportation Research Board, National Research Council.

Qiu, H., Zhu, W., Wang, J., et Zeng, Z. (2023, October). Variable speed limit in foggy conditions considering dynamic sight distance and friction. In Proceedings of the Institution of Civil Engineers-Transport (pp. 1-9). Emerald Publishing Limited.

Sgarrra, V., Di Mascio, P., Corazza, M.V., & Musso, A. (2014). An application of ITS devices for powered two-wheelers safety analysis: The Rome case study. Advances in Transportation Studies, 33, 85-96.

Singh, D., et Singh, G. (2023). Impact of shoulder as a road safety countermeasure: A literature Review: Dampak bahu jalan sebagai penanggulangan keselamatan jalan: Tinjauan pustaka. Journal of Multidisciplinary Science, 2(2), 101-112.

Strnad, I., & Marsetič, R. (2023). Differential evolution based numerical variable speed limit control method with a non-equilibrium traffic model. Mathematics, 11(2), 265.

Tan, Y., Li, J., Xu, H., Li, Z., et Wang, H. (2023). The mechanisms, evaluation and estimation of anti-skid performance of snowy and icy pavement: A review. Journal of Road Engineering.

Wu, Y., Liu, J., Zhang, N., et Rong, J. (2024). Effectiveness, influence mechanism and optimization strategies of variable message Sign: A systematic review. Transportation Research Part F: Traffic Psychology and Behaviour, 105, 116-137.

Yuan, C., Shi, Y., Pan, B., & Li, Y. (2022). Developing a Variable Speed Limit Control Strategy for Mixed Traffic Flow Based on Car-Following Collision Avoidance Theory. Mathematics, 10(16), 2987.

Zhang, Y., Ma, M., & Liang, S. (2021). Dynamic control cycle speed limit strategy for improving traffic operation at freeway bottlenecks. KSCE Journal of Civil Engineering, 25(2), 692-704.

Zhao, X. H., Huang, L. H., Guan, W., & Rong, J. (2015). Evaluation of effects of warning sign position on driving behavior in horizontal sharp curves. Advances in Mechanical Engineering, 7(2), 971290.