

Optimizing Speed Limits Towards Sustainable Urban Mobility: A Mathematical Model and Numerical Application



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<https://doi.org/10.18280/ijstdp.210426>

ABSTRACT

Received: 2 February 2026

Revised: 11 April 2026

Accepted: 16 April 2026

Available online: 30 April 2026

Keywords:

socio-economic optimization, total social cost, traffic noise externalities, Link-Specific Speed Limits, heterogeneous traffic, sustainable urban mobility

Effective traffic management, is essential for reducing the environmental footprint of transportation. Setting speed limits in urban areas involves a complex trade-off between mobility, “travel time,” and sustainability, “safety and noise pollution”. While traditional methods often rely solely on “design” or “85th-percentile speeds”, this study developed a novel computational framework, to determine the “Socially Optimal Speed” (SOS). Moreover, a generalized cost model was formulated to minimize total social costs explicitly internalizing the value of time (VOT), noise externalities, and safety risk. Furthermore, to validate the proposed framework it was applied to a numerical example using empirical data from a representative developing urban network. Numerical results revealed that optimal speeds differ significantly across classes, with 37 km/h on “commercial streets” constrained by noise costs, 48 km/h on “collector roads”, and 88 km/h on “arterials”, these values deviate from static posted limits, suggesting that current policies may be economically inefficient. Finally, a sensitivity analysis was performed to evaluate the model’s robustness against economic variations, specifically “VOT” confirming the adaptability of the proposed framework to dynamic “socio-economic” conditions. The proposed framework is generic and adaptable to any urban environment offering policymakers a robust tool for implementing “Link-Specific Speed Limits” strategies.

1. INTRODUCTION

From a sustainable planning perspective, the traffic congestion is not a capacity issue, but a multidimensional problem, affecting environmental quality and public health. (Stop and go) Waves typical in congested flow, contribute significantly to greenhouse gas emissions and fuel wastage. Therefore, Link-Specific Speed Limits are increasingly recognized as a green traffic management strategy. However, by harmonizing traffic speeds and suppressing shockwaves variable speed limits (VSL) can reduce acceleration and deceleration cycles, thereby lowering emissions and enhancing the overall sustainability of the urban transport system.

1.1 Urban mobility and sustainability imperative

In the rapid urbanizing landscapes of the 21st century, the governance of urban mobility has transcended traditional traffic engineering to become a “central pillar” of sustainable development worldwide [1]. Furthermore, as cities densify, the conflicting demands between vehicle mobility and urban livability have intensified prompting a global “re-evaluation” of streets’ function under the framework of the “United Nations Sustainable Development Goals (SDGs)”, particularly Goal 11.2, which mandates a safe and accessible transport

system for all [2]. However, modernized cities currently, face a lot of challenges, such as population growth, exacerbating environmental risks, the need to address very complex “social issues”, “energy efficiency” and “security”, ageing municipal infrastructure, worsening urban traffic, and many other challenges [3]. In the same context, contemporary urban planning literature argues, that the historic prioritization of the high speed arterial corridors has severed community cohesion and prioritized mechanical movement over social interaction necessitating a paradigm shift towards “Human-Centric” planning [4]. Moreover, speed management is now recognized not merely as a safety intervention, but also as a critical lever for achieving “broader environmental” and “economic sustainability” targets, in modern metropolitan areas [5].

1.2 Evolution of speed paradigms: From design to safety

Speed limits were established using the “85th percentile rule” which is a method predicated on the assumption that the majority of drivers should behave reasonably and that limits should reflect their natural speed choice [6]. However, this engineering centric approach, has faced mounting criticism for failing to account for the kinetic energy principle of the “safe system” approach and “vision zero” strategies adopted globally [5]. Empirical evidence from recent meta-analysis demonstrates that relying on driver preference often leads to

“socially inefficient” speeds, particularly in mixed- use zones where the presence of vulnerable road users (VRUS) requires a drastic reduction in kinetic impact forces [7]. The condition may be worse, when “transport demands” and “roadside activities” increase, which lead to inefficient traffic performance and increased “Side friction”, which is refers to a variable indicating the degree of interactions between the “roadside activities” and the “traffic flow” [8]. Thus, the modern consensus advocates for limits derived from biomechanical tolerance and social welfare optimization rather than free-flow behavior [9, 10].

1.3 The economic valuation of travel time vs. externalities

The determination of optimal speed is fundamentally an economic trade-off. On one hand, higher speeds reduce travel time, which is traditionally valued highly in cost-benefit analysis (CBA) as a contributor to economic productivity [11, 12]. On the other hand, speed generates negative externalities-costs imposed on third parties-that rise exponentially with velocity. Leading transportation economists, argue that conventional models often overestimate the “Value of Travel Time Savings” (VTTS), while underestimating the marginal costs of “crash risk” and “environmental degradation” [13, 14]. The “Socio-Economic Optimization” framework, seeks to resolve this by internalizing these conflicting variables into a unified total cost function shifting the focus from maximizing flow to minimizing total social loss [15].

1.4 The underestimated burden of noise and pavement interaction

While safety is frequently analyzed the environmental cost of traffic noise remains an under addressed externality especially in developing nations [16]. Recent epidemiological reports by the European Environment Agency (EEA), have reclassified traffic noise from a minor annoyance to a major public risk linking it to cardiovascular diseases, cognitive impairment, and sleep disturbance [17]. Crucially, the noise generation mechanism is heavily dependent on the tire-pavement interaction. In regions with high pavement roughness typical of many developing infrastructures, the noise cost curve creates a binding constraint on optimal speed that is often stricter than safety constraints, a factor frequently ignored in standard international [18]. Many developing urban centers have witnessed rapid urbanization with a significant increase in vehicle ownership and population creating a lag in urban management. Furthermore, these cities often face

significant traffic flow problems especially in “Central Business District (CBD) areas”, which decreases air quality and threatens healthy urban [19].

1.5 Research gap in developing contexts

Despite the theoretical maturity of these optimization models their application remains predominantly concentrated in developed economies. In the same context, developing countries, characterized by heterogeneous traffic streams, aggressive driving behaviors, varying infrastructure quality, and a lack of localized optimization tools [20]. However, current policies in such contexts typically utilize static uniform speed limits across diverse road hierarchies are ignoring the distinct functional and economical characteristics of commercial vs arterial roads [21]. This study aims to bridge this gap, by developing a site specific socio-economic optimization model, for a heterogeneous urban network providing empirical evidence to support the transition to context- sensitive “Link-Specific Speed Limits”. Furthermore, a sensitivity analysis was conducted to verify the model’s stability and examine the effect of the “value of time” (VOT) on the optimization results.

2. MODEL APPLICATION AND NUMERICAL VALIDATION

To demonstrate the applicability and robustness of the proposed optimization framework primary empirical data were collected through on-site field surveys in Najaf-Iraq, this location serves as a representative urban network characterized by heterogeneous traffic conditions typical of developing cities. Furthermore, operational speeds and local driving behaviors were directly monitored, using field observations, also specific geometric and physical parameters essential for the cost function such as “pavement roughness” and “spatial activity types” were documented on site. However, the selected network features a dualistic urban fabric, combining organic high-density street patterns in the central core with a planned grid network in expansion zones. However, the network structure is hierarchical anchored by major Arterial Corridors that serve as the primary spine for daily commuting and inter-city connectivity. These corridors branch into collector streets which channel traffic from residential neighborhoods to the arterial system.

Table 1. Traffic and geometric characteristics of selected test links

Link	F.Class	(km)	Lanes	(IRI)	Act.type
Link I	Arterial	5.2	3 per direction	2.5 (Good)	High Mobility
Link II	Collector	2.8	2 per direction	4.2 (Fair)	Residential Access
Link III	Commercial	1.5	1 per direction	5.5 (Poor)	Intense Commercial

Obviously, traffic flow within the network, exhibits a distinct “centripetal” pattern where the highest congestion intensities and pedestrian-vehicle conflicts occur near the central commercial and cultural hubs, this creates a complex driving environment where speed optimization must account for significant side-friction factors.

For this numerical application three distinct road segments were selected to represent the primary functional classes within the network, these segments serve as the inputs for the

optimization model:

- 1- Link I (Arterial), which represents a high-mobility corridor with separated lanes.
- 2- Link II (Collector), which represents a transitional link connecting residential zones to arterials.
- 3- Link III (Commercial/Local), which represents a high-friction zone with intense pedestrian activity and commercial land use.

International roughness index (IRI) impacts on tire-

pavement noise emissions, are explicitly embedded within the “link-specified functional weighting (λ Noise)”. The empirical IRI values presented in Table 1 directly informed the baseline noise penalties. For instance, the poor pavement condition of “link III” (IRI = 5.5), significantly exacerbates rolling noise thereby justifying its maximum assigned environmental penalty weight of 0.05 USD/dB (A). Conversely, the high-quality smooth pavement of “Link I” (IRI = 2.5), minimizes baseline noise generation which directly corresponds to its lowest assigned penalty of 0.01 USD/dB(A). Furthermore, a detailed sensitivity analysis on the generalized noise cost parameter was conducted as presented in Section 4.6.

3. MATHEMATICAL FORMULATION OF THE OPTIMIZATION FRAMEWORK

3.1 General optimization framework

The primary objective of this study is to formulate a Socially Optimal Speed (SOS) determination framework, applicable to heterogeneous urban traffic environments. Unlike traditional, traffic engineering approaches that define speed limits based on the “85th percentile speed” or design speed, this study adopts a “Socio-Economic” Optimization approach. Furthermore, the core hypothesis of this study, is that the optimal speed corresponds to the equilibrium point, where the marginal benefit of travel time savings equals the marginal social cost of safety risks and environmental externalities.

The total social cost function $Z(v)$ represents the summation of three distinct cost components normalized per kilometer of travel [22]. The optimization problem is defined as in Eq. (1):

$$\text{Minimize } Z(v) = C_{\text{Time}}(v) + C_{\text{Noise}}(v) + C_{\text{Safety}}(v) \quad (1)$$

where:

- V: The operating speed (km/h)
- $Z(v)$: Total generalized social cost (\$/km)
- C_{Time} : User cost related to travel time (\$/km)
- C_{Noise} : External cost of noise pollution (\$/km)
- C_{Safety} : External cost of accident risk (\$/km)

The optimization seeks to find the speed v^* . The first derivative of the total cost function equals zero ($dz/dv = 0$).

3.2 User cost modeling (time valuation)

Travel time savings represent the primary economic utility of increasing speed. However, the cost of time is modeled as an inverse function of speed. Furthermore, to ensure the framework reflects the economic reality of developing cities “VOT” was not applied uniformly. Instead, a function-based calibration was performed assigning higher “VOT” values to arterial highways (reflecting business and long distance trips) and lower to local streets [11]. The cost function is expressed as in Eq. (2) [23]:

$$C_{\text{Time}} = \text{VOT}_{\text{class}} \times \frac{1}{v} \quad (2)$$

($\text{VOT}_{\text{class}}$) is the value of time calibration for the specific road functional class, such as commercial, collector, or arterial.

The term $(1/v)$, represents the time required to travel one kilometer (hrs/km). This differentiation acknowledges that the urgency and economic value of trips vary significantly across the urban network [24].

3.3 Environmental cost modeling (empirical noise approach)

Instead of relying on theoretical noise prediction models such as “FHWA” and “TNM”, which often fail to account for local conditions such as, high pavement roughness and older vehicle fleets. This study developed site specific empirical noise cost functions.

In the same context, data collected from the representative numerical application Speed vs. Noise dB, were analyzed using non-linear polynomial regression in OriginPro to drive an empirical relationship for each road topology. However, the economic valuation follows the “Hedonic Pricing Method”, monetizing the annoyance level above a health threshold as in Eq. (3) [18]:

$$C_{\text{Noise}} = \lambda_{\text{Noise}} \times \max(0, L_{\text{eq}}(v) - L_{\text{Threshold}}) \quad (3)$$

where:

$L_{\text{eq}}(v)$ is the empirical polynomial function representing the noise level at speed v .

$L_{\text{Threshold}}$ is the annoyance threshold set at 55 dB(A) following WHO guidelines.

λ_{Noise} is the marginal monetary cost per decibel increase.

The baseline value for λ_{Noise} was set at 0.05 USD/dB(A) for exposure levels exceeding the 55 dB (A) threshold; this threshold explicitly conforms to the World Health Organization (WHO), Environmental Noise Guidelines (2018). In the same context, recognizing that noise impact heavily depends on spatial context and population exposure, a functional weighting approach was applied, consistent with the methodology outlined in the European Commission’s Handbook on the External Costs of Transport. Furthermore, the “baseline cost” was adapted, to the functional classification of each link:

Link I (Arterial Road) is assigned a weight of (0.2) yielding (0.01) USD/dB(A). The better geometric design and separation from residential structures, significantly reduce direct human exposure and allow the model to prioritize mobility.

Link II (Collector Road) is assigned a weight of (0.8), yielding (0.04) USD/dB(A), this accounts for localized traffic routing through residential neighborhoods necessitating higher noise protection for residents.

Link III (Commercial Road) retains the maximum baseline penalty of (0.05) USD/dB (a) weight of (1.0) due to high daytime pedestrian activity, dense retail presence, and maximum human exposure to noise externalities.

Finally, a sensitivity analysis, was conducted on these baseline values, + 20% and +50%, to ensure the optimization model’s robustness as detailed in the results section.

3.4 Safety cost modeling (calibrated power model)

To internalize the cost of crash risks the study adopts the “Power Model”, which empirically relates speed to safety outcomes, based on kinetic energy principles. Moreover, a risk factor (α) was calibrated, according to the road’s functional classification as shown in Eq. (4) [25].

The safety cost function is defined as:

$$C_{\text{safety}} = \alpha_{\text{class}} \times \left(\frac{v}{v_{\text{ref}}}\right)^4 \quad (4)$$

where:

V_{ref} : a reference speed, typically the design speed or 60 km/hr

α class is a calibrated risk coefficient:

high α : assigned to commercial streets, to account for high pedestrian density and conflict points.

Low α is assigned to arterial highways, to reflect safer geometric design and segregated traffic.

This calibration, ensures that the model penalizes speed heavily in pedestrian zones, while allowing higher speeds on protected arterials.

4. NUMERICAL RESULTS AND SENSITIVITY ANALYSIS

This section presents the outcomes of the “socio-economic” optimization model, based on the graphical analysis of the three representative functional road classifications defined in the numerical application using OriginPro [26]. The figures below illustrate the trade-offs between the User Cost, Environmental Cost, and Safety Cost, to determine the minimum “Total Social Cost”.

4.1 Scenario 1: Commercial Road (Link C)

Figure 1 presents, the cost breakdown for the commercial street, the visual analysis reveals, that environmental externalities are the primary constraint on speed in this zone. However, the graph shows that the environmental cost curve, exhibits a steep exponential growth as speed increases; this behavior reflects the “noise annoyance levels” aggravated by high pavement roughness in commercial districts. However, this steep rise intersects early with the decreasing “User Cost” curve, although the Safety cost also trends upward the environmental burden is the dominant factor forcing the total cost curve to bottom out at low speeds. Moreover, the global minimum of the total cost function was identified at approximately 37 km/h, in the same context, operating at speeds above 40 km/h in commercial zones, results in a net social loss where the economic benefit of travel time savings is completely negated by the sharp increase in noise costs and pedestrians’ risks.

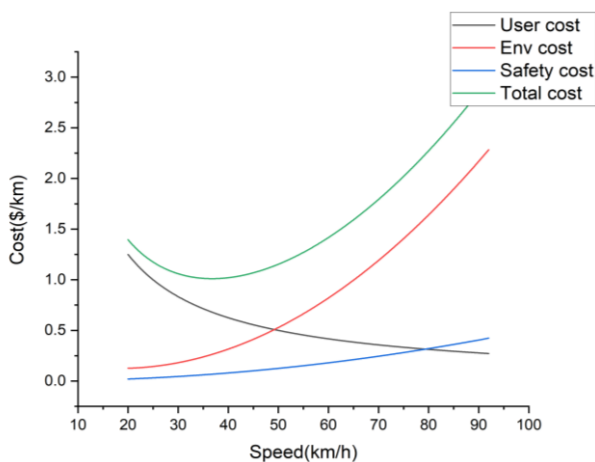


Figure 1. The cost breakdown for the (commercial street)

4.2 Scenario 2: Collector Road (Link B)

For the collector road, Figure 2 demonstrates, a balanced

interaction between the competing costs typical of transition zones, and the graph displays a symmetrical trade-off. Moreover, the user cost, decreases steadily, while the environmental and safety costs increase moderately. However, the interaction of these curves, creates a smooth “U-shaped Total Social Cost curve”, indicating a stable equilibrium point where no single cost component dominates the others. Also, the optimization yields, a SOS of approximately 48 km/h. Finally, this result aligns closely with the standard urban speed limit of 50km/h and empirically validates that the current limit is economically efficient for collector roads though not necessarily for other zones.

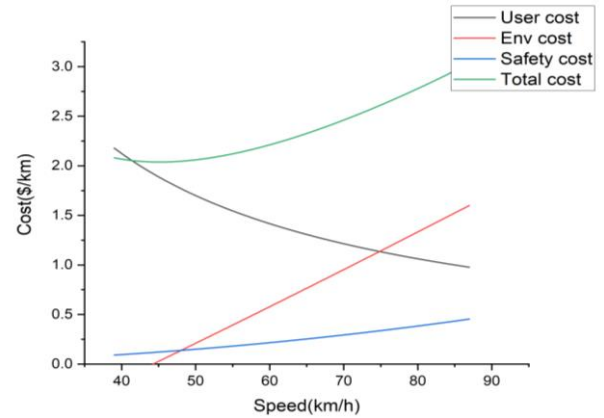


Figure 2. The cost breakdown for (collector streets)

4.3 Scenario 3: Arterial Corridor (Link A)

Figure 3 shows the arterial highway analysis of the cost profile, fundamentally driven by mobility needs. The total cost curve is largely dictated by the user cost, and due to better geometric design and separation from residential structures, the environmental cost and safety cost remain relatively flat at lower and medium speeds, penalizing higher speeds as severely as in commercial zones. Furthermore, the model identifies the optimal speed, at approximately (88 km/h).

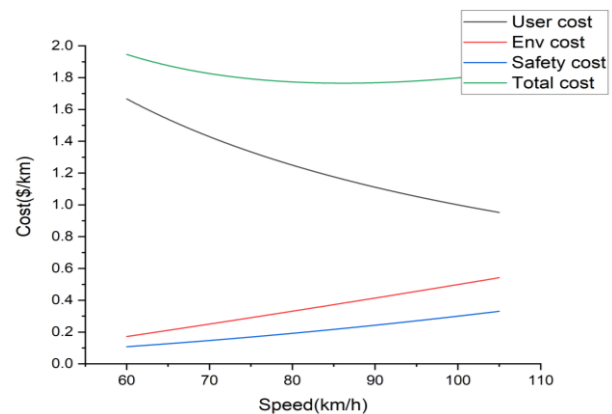


Figure 3. The cost breakdown for (arterial highways)

Restricting speed to (60 km/hr) on these arterials, creates a quantifiable economic “deadweight loss”. Based on the cost function, operating at the sub-optimal speed of 60 km/hr yield a total social cost of approximately 1.95 USD/km, compared to the minimized cost of 1.78 USD/km at the optimal speed of 88 km/h. This difference results in a Deadweight loss of 0.17 USD per vehicle-kilometer. However, society pays a heavy

premium in lost time (user cost) that is not justified by the marginal safety or environmental savings.

4.4 Comparative analysis

Figure 4 compares the total social cost curves for all three road types. The lateral shift of the optimal points- from 37 km/h to 88 km/hr, provides conclusive evidence that a uniform speed policy is mathematically incompatible with social welfare maximization in heterogeneous urban networks.

4.5 Summary of optimal speeds across network typologies

A comprehensive breakdown of the cost components at the mathematically derived optimal speeds for each road functional class is summarized in Table 2. The results, clearly highlight the contrast between mobility-driven arterials and environmentally constrained commercial zones.

4.6 Sensitivity analysis: Impact of value of time

The robustness of the proposed optimization framework, were evaluated by conducting a sensitivity analysis to examine how economic parameters influence SOS. Specifically, VOT was varied as it represents a significant component of the

“total social cost” and can differ based on “socio-economic” conditions. However, three scenarios were tested: a “low VOT” (5\$/hr), the “baseline scenario” (10\$/hr), and a “high VOT: (15\$/hr). The response of the optimal speed limits for commercial, collector, and arterial roads is illustrated in Figure 5.

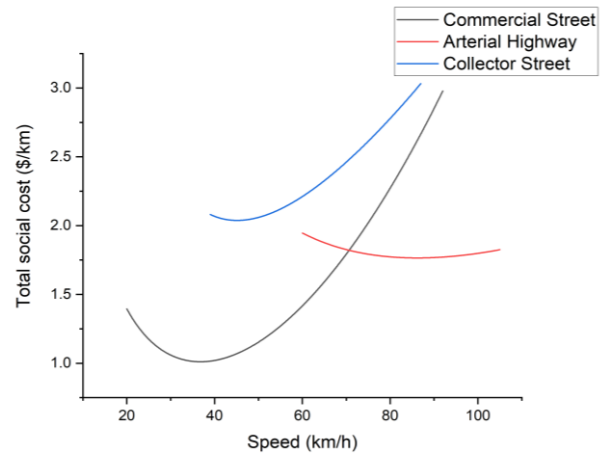


Figure 4. Comparative analysis of the total social cost curves for all three road types

Table 2. The cost breakdown for arterial highways

Road Topology	Current Limit km/hr	Optimal Speed km/hr	User Cost km/\$	Safety Cost km/\$	Env. Cost km/\$	Total Cost km/\$
Link I (Arterial Road)	60	88	1.15	0.25	0.38	1.78
Link II (Collector road)	50	48	1.75	0.15	0.15	2.05
Link III (Commercial street)	40	37	0.72	0.05	0.24	1.01

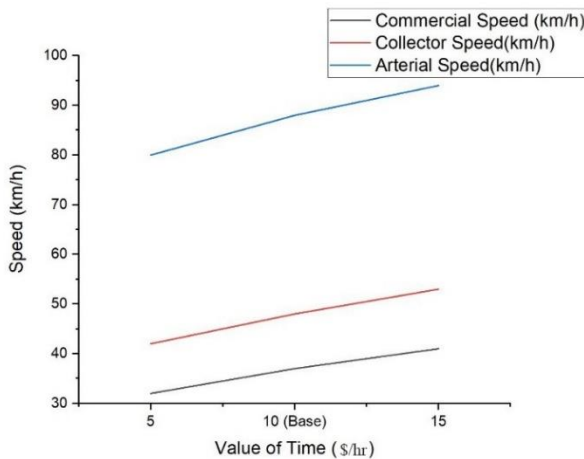


Figure 5. Sensitivity analysis of optimal speed limits with respect to variations in the Value of Time (VOT)

4.7 Sensitivity analysis: Impact of environmental noise cost

The robustness of the proposed model, was evaluated by conducting a sensitivity analysis, on the maximum environmental noise cost parameter (λ Noise). The baseline value of 0.05 USD/dB(A), applied to the highly vulnerable commercial street (link III), was varied by -20%, +20%, and +50%, as shown in Table 3. While the minimum total cost was predicted to scale with the environmental penalty (rising from 0.95 to 1.13 \$/km), the optimal speed remained relatively stable, fluctuating only between 33 and 39 km/hr. In

conclusion, the commercial zones strictly dictate lower speeds due to environmental externalities remains solid regardless of minor pricing variations.

Table 3. Sensitivity analysis of noise cost on optimal speed (commercial link)

Scenario	Noise Cost (λ Noise) USD	Optimal Speed (km/h)	Minimum Total Cost (\$/km)
Decrease (-20%)	0.04	39	0.95
Baseline	0.05	37	1.01
Increase (+20%)	0.06	35	1.06
Max Stress (+50%)	0.075	33	1.13

5. CONCLUSIONS

Based on the “socio-economic” optimization framework and the analysis of the numerical application data the following conclusions are drawn as listed below:

1- Functional Road Hierarchy: The study provides empirical evidence that the “SOS” is not uniform, but varies fundamentally based on road function and urban context. However, the optimization results identified specific optimal speeds of 37 km/h for commercial streets and 48 km/h for collectors, and also 88 km/h for arterials. Finally, these findings challenge the validity of relying solely on single

design speed, advocating instead for a flexible, zone-based approach to traffic management.

2- Inefficiency of Static Limits: The prevalent static speed limit, is proven to be economically and environmentally unsustainable. The model demonstrates, that a uniform limit creates a double negative effect, generating excessive environmental footprints, “emissions” and safety costs in commercial zones, where the optimal is about 37 km/h, while simultaneously restricting economic productivity on arterials, where the optimal is 88 km/h.

3- Environmental Constraints in High-Density Areas: A critical finding for urban planning, is the governing role of the environmental cost in high density districts, and due to the local pavement roughness factor the noise cost curve was observed to rise more sharply than the safety cost curve at low speeds. However, this implies that in high friction urban centers, noise pollution represents a stricter binding constraint on optimal speed than crash risk directly impacting urban livability.

4- Resource Utilization on Arterials: The analysis of arterial highways reveals a significant gap between (the posted limit) and the (optimal speed). This gap, represents a measurable economic “deadweight loss”, caused by unexploited travel time savings. Furthermore, the flat profile of the external cost curves in this zone, suggests that increasing speed limits poses minimal social and environmental risks compared to the substantial economic gains.

5- Tool for sustainable planning: The application of the proposed non-linear optimization model using OriginPro to generate a continuous total social cost curve, proved superior to traditional discrete scenario analysis. Moreover, this methodological approach, offers urban planners and decision-makers a “robust quantitative” tool to visualize the exact trade-offs between “mobility needs” and “sustainability goals”.

6- Socio- Economic Robustness: The sensitivity analysis, confirmed the robustness of the proposed model against “socio-economic” variables. On the other hand, it was observed, that the optimal speed limit is positively correlated with “VOT”, higher “VOT” values are justify higher speed limits to minimize travel delay costs while lower “VOT” values shift the optimization focus towards safety and fuel saving highlighting the model’s adaptability to different economic environments.

REFERENCES

- [1] Banister, D. (2008). The sustainable mobility paradigm. *Transport Policy*, 15(2): 73-80. <https://doi.org/10.1016/j.tranpol.2007.10.005>
- [2] United Nations Office for Disaster Risk Reduction. (2023). *Global Assessment Report on Disaster Risk Reduction 2023: Mapping Resilience for the Sustainable Development Goals*. Stylus Publishing, LLC. <https://doi.org/10.18356/9789210028301>
- [3] Kalenyuk, I., Tsymbal, L., Uninets, I., Celika, M. (2025). Smart development of cities: Ukrainian experience, trends and prospects. *International Journal of Sustainable Development and Planning*, 20(10): 4159-4168. <https://doi.org/10.18280/ijstdp.201007>
- [4] Nieuwenhuisen, M.J. (2020). Urban and transport planning pathways to carbon neutral, liveable and healthy cities; A review of the current evidence. *Environment International*, 140: 105661. <https://doi.org/10.1016/j.envint.2020.105661>
- [5] OECD. (2021). *Transport Strategies for a Net-Zero System by Design*. OCESD Publishing. <https://doi.org/10.1787/0a20f779-en>
- [6] Larue, G.S., Naweed, A. (2020). Understanding why drivers cross the line at activated railway crossings. *Transportation Research Record: Journal of the Transportation Research Board*, 2674(8): 1-11. <https://doi.org/10.1177/0361198120912238>
- [7] Fondzenyuy, S.K. (2025). Advancing knowledge on speed management and developing a speed prediction model for a mixed traffic. <https://hdl.handle.net/11573/1732587>.
- [8] Mansour, A.I., Al-Jameel, H.A.E. (2023). Traffic flow impacts on the environment along urban streets under mixed traffic conditions in Al-Najaf city. *IOP Conference Series: Earth and Environmental Science*, 1129: 012046. <https://doi.org/10.1088/1755-1315/1129/1/012046>
- [9] Global Road Safety Partnership. (2022). *Speed management: A road safety manual for decision-makers and practitioners*. https://www.grsroadsafety.org/wp-content/uploads/2023/05/Speed_management_English.pdf.
- [10] World Health Organization [WHO]. (2023). *Global Status Report on Road Safety 2023*. <https://www.who.int/teams/social-determinants-of-health/safety-and-mobility/global-status-report-on-road-safety-2023>.
- [11] Small, K.A., Verhoef, E.T., Lindsey, R. (2024). *The Economics of Urban Transportation*. Routledge. <https://doi.org/10.4324/9781315157375>
- [12] Litman, T. (2023). *Transportation cost and benefit analysis: Techniques, estimates and implications*. https://www.researchgate.net/publication/235360398_Transportation_Cost_and_Benefit_Analysis_Techniques_Estimates_and_Implications.
- [13] Xiao, Y., Coulombel, N., De Palma, A. (2017). The valuation of travel time reliability: Does congestion matter? *Transportation Research Part B: Methodological*, 97: 113-141. <https://doi.org/10.1016/j.trb.2016.12.003>
- [14] Lu, D.Y., Kou, C.X., Wang, S.T., Wang, L., Wang, Y.B., Lv, Y.J. (2025). Multi-objective optimal scheduling of park-level integrated energy system based on trust region policy optimization algorithm. *Electronics*, 14(24): 4900. <https://doi.org/10.3390/electronics14244900>
- [15] ITF. (2021), *Reversing Car Dependency: Summary and Conclusions*, ITF Roundtable Reports, No. 181. OECD Publishing, Paris. <https://doi.org/10.1787/bebe3b6e-en>
- [16] Brown, A.L., Van Kamp, I. (2017). WHO environmental noise guidelines for the European region: A systematic review of transport noise interventions and their impacts on health. *International Journal of Environmental Research and Public Health*, 14(8): 873. <https://doi.org/10.3390/ijerph14080873>
- [17] Emerald Publishing. (2012). *European Environment Agency (EEA) report – an experimental framework for ecosystem capital accounting in Europe. Management of Environmental Quality: An International Journal*, 23(4). <https://doi.org/10.1108/meq.2012.08323daa.014>
- [18] Navrud, S. (2002). The state-of-the-art on economic valuation of noise. *Final Report to European Commission DG Environment*. <https://www.researchgate.net/profile/Stale->

- Navrud/publication/254318936_The_State-Of-The-Arton_Economic_Valuation_of_Noise/links/53fcc5a00cf2dca8ffff4ae3/The-State-Of-The-Arton-Economic-Valuation-of-Noise.pdf.
- [19] Mansour, A.I., AL-Jameel, H.A.E. (2023). Side-friction impacts on urban streets performance in divided and undivided streets. *Pollack Periodica*, 18(3): 147-153. <https://doi.org/10.1556/606.2023.00817>
- [20] Hamim, O.F., Hossain, M.S., Hadiuzzaman, M. (2022). Developing empirical model with graphical tool to estimate and predict capacity of rural highway roundabouts. *International Journal of Transportation Science and Technology*, 11(4): 726-737. <https://doi.org/10.1016/j.ijtst.2021.10.002>
- [21] Shaaban, K., Alsoub, M. (2022). Evaluating the effect of dynamic message signs and lane control signs on driver behavior in a developing country. *Infrastructures*, 7(8): 105. <https://doi.org/10.3390/infrastructures7080105>
- [22] Boardman, A.E., Greenberg, D.H., Vining, A.R., Weimer, D.L. (2018). *Cost-Benefit Analysis: Concepts and Practice* (5th ed.). Cambridge: Cambridge University Press. <https://doi.org/10.1017/9781108235594>
- [23] American Association of State Highway and Transportation Officials. (2010). *User and Non-user Benefit Analysis for Highways: September 2010*. AASHTO. <https://share.google/nMSuEij10G9j1UayC>.
- [24] Mackie, P.J., Jara-Diaz, S., Fowkes, A.S. (2001). The value of travel time savings in evaluation. *Transportation Research Part E: Logistics and Transportation Review*, 37(2-3): 91-106. [https://doi.org/10.1016/s1366-5545\(00\)00013-2](https://doi.org/10.1016/s1366-5545(00)00013-2)
- [25] Elvik, R. (2013). A re-parameterisation of the Power Model of the relationship between the speed of traffic and the number of accidents and accident victims. *Accident Analysis & Prevention*, 50: 854-860. <https://doi.org/10.1016/j.aap.2012.07.012>
- [26] OriginLab. (2019). *OriginPro 2019b User Guide*. <https://docs.originlab.com/user-guide/>