ScienceDirect

Transportation Research Procedia 00 (2026) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

ELSEVIER

Road Safety and Simulation 2026 – RSS2026

Using the Impact Modification Factor to Link Road Safety and Environmental Performance under the Safe System Approach

Stella Roussou[a*], Apostolos Ziakopoulos[a], Maria Oikonomou[a], Amna Chaundry[b], Amir Hossein Kalantari[b], Shanna Lucchesi[c], Amir Pooyan Afghari[b], George Yannis[a]

[a]*Department of Transportation Planning and Engineering, National Technical University of Athens, 5 Heroon Polytechniou Str.*
[b]*Safety and Security Section, Faculty of Technology, Policy and Management, TU Delft, Delft Netherlands*
[c]*International Road Assessment Programme: iRAP (Based Porto/PT)*
** Corresponding author: s_roussou@mail.ntua.gr*

Abstract

Assessing how road network interventions impact both safety and emissions at the same time is a challenging task, even at a singular study area, while assessing the transferability of these impacts to new study areas is even harder to perform. To that end, this paper introduces the concept of the Impact Modification Factor (IMF), expressed as the fluctuation of the examined impacts before and after interventions. IMFs offer a top-down indicator to compare different scenarios by demonstrating how much a measure affects an impact relative to existing conditions. In this study, IMFs were estimated separately for emissions, iRAP star rating results, and road safety indicators, ensuring consistency with the corresponding simulation and iRAP results. This methodology was applied to road sections of the Athens urban network to explore how selected interventions influence safety outcomes and pollutant emissions, within the context of the Phoebe Project. Three scenarios were implemented in a traffic simulation environment: (i) the baseline, (ii) an intervention scenario with infrastructure changes, and (iii) an intervention scenario with infrastructure changes and a zonal 30 km/h speed limit reduction. The infrastructure changes include modifications to geometry, lane layout, and traffic management.

Each simulation produced information on flow, speed, and travel time for every road section. Using these outputs, the London Emission Model (LEM) estimated CO_2 and NO_x emissions, reported in grams for each segment. Road safety was analysed separately through the iRAP protocol. Specifically, each segment was described by its key physical and operational features, such as lane width, number of lanes, intersection type, and speed limit. The iRAP model then generated Star Rating Scores (SRS) and Fatal and Serious Injury (FSI) indicators for pedestrians, cyclists, motorcyclists, and vehicle occupants. All datasets were merged using a common identifier, ensuring that every segment carried both safety and emission data. The IMF was then derived for each case. For safety indicators, a value above one indicated improvement compared with the baseline, whereas for emission indicators, a value above one represented deterioration, since higher values correspond to increased pollutant levels.

Out of two hundred ninety-one segments, ninety-six featured IMF values under one, showcasing network improvements. Two-lane arterials presented the largest number of improvements, whereas wider divided roads showed mixed results. In certain central corridors, such as along Fillelinon and Vasilissis

Amalias, IMF values for the iRAP and road safety indicators were above one, demonstrating the benefits of the interventions. In contrast, narrower sections with more consistent traffic flow tended to show positive changes in both emissions and safety indicators.

By using IMFs, comparisons between design alternatives become more straightforward, since both environmental and safety outcomes are expressed on a single scale. The approach also helps reveal cases where one goal improves at the expense of the other, giving decision-makers a clearer view of trade-offs that might otherwise remain unnoticed. Moreover, IMFs facilitate the transferability of results of one road network sub-section to another, when segments are comparable, in order to have an initial rough estimate of how interventions might affect the road environment.

Keywords: Impact Modification Factor (IMF), Road Safety, Environmental Performance, Traffic Simulation, Safe System Approach

1. Introduction

Road safety and environmental sustainability are increasingly seen to be among the most pressing issues in urban transport systems. Contemporary transport policies not only seek to minimize road crashes and ensure safety for all road users, but they also seek to minimize emissions of greenhouse gases and air pollutants arising from road transport. However, in reality, it has been observed that transport interventions may not be able to satisfy both objectives simultaneously. For example, it has been observed that investments in improving safety through infrastructure improvements may cause slower speeds, resulting in delays and hence an increase in emissions, while investments in managing traffic for reducing emissions may cause faster speeds, thus impacting safety conditions. There is thus an increasing need for integrated assessment tools for addressing safety and sustainability issues.

Traditionally, road safety assessments are carried out through crash data analysis, statistical methods, road safety performance indicators, and infrastructure-based risk assessment methods. Performance indicators for road safety have been developed, which help in identifying and characterizing some of the most critical aspects of the road transport system, influencing road safety performance, and assessing road safety even in the absence of sufficient crash data. Infrastructure-based road safety assessment approaches are also in line with the Safe System concept that recognizes the importance of infrastructure and speed management in limiting the severity of crashes and enhancing road safety performance (Wegman et al., 2017).

On the other hand, environmental impacts of transport systems are commonly evaluated using traffic simulation models combined with emission models in order to estimate emissions such as CO_2 and NOx based on traffic flow, speed, and vehicle operation conditions. Simulation-based emission estimation has been widely used in transport studies to evaluate the environmental impacts of traffic management and infrastructure interventions under different traffic scenarios (Abou-Senna and Radwan, 2013).

Despite the significant strides that have been made in the development of road safety and environmental assessment methods, the two issues have always been viewed in isolation. This makes it hard for the overall impact of the interventions in the transport sector to be well understood by the policymakers. As a solution to this problem, integrated approaches in the impact assessment process that enable the assessment of various impacts simultaneously are being recommended in the transport planning process and the evaluation of the transport policies so that the overall impact can be assessed in terms of trade-offs between road safety and the environment (Elvik, 2013).

In this context, this paper proposes the concept of Impact Modification Factor (IMF), which is defined as the variation of safety and environmental indicators between different scenarios in relation to a baseline. The IMF derives from the Crash Modification Factor, which is a multiplier predicting crash change after a countermeasure (FHWA, 2014). The IMF is a simple and comparable measure that can be used to assess various performance indicators. The methodology combines traffic simulation outputs, emission estimates, and infrastructure safety assessment results and applies the IMF framework to an urban road network. The aim of this study is to develop and apply an integrated framework for evaluating the impact of infrastructure and traffic management interventions on both road safety and environmental performance using Impact Modification Factors and to explore the potential of this approach to support decision-making and transferability of results between different road networks.

2. Literature Review

2.1 Road safety assessment methods

Road safety assessment is traditionally carried out using crash data analysis techniques. It is also done using statistical models to establish the relationship between the frequency and severity of crashes and the characteristics of the traffic, infrastructure, and environment. Crash data is limited because crashes rarely occur. Moreover, crashes are not reported. Due to these limitations, proactive road safety assessment techniques were developed. These techniques include road safety performance indicators and infrastructure risk assessment techniques (Papadimitriou et al., 2013). Infrastructure risk assessment techniques involve the assessment of road safety using road design characteristics, traffic volume, traffic speed, and the roadside environment. These techniques are used to carry out road safety inspections and road rating (iRAP, 2021). Using these techniques, road safety can be assessed even without the use of crash data. This is because the techniques are based on the safe system concept. The safe system concept recognizes the importance of safe infrastructure and safe speeds in reducing the severity of crashes (Wegman et al., 2017).

In addition to the techniques based on crash data, surrogate safety techniques have been used to evaluate the safety conditions on the road using the interactions between vehicles. Time to Collision (TTC), Post Encroachment Time (PET), and traffic conflicts can be used to evaluate the safety conditions using the interactions between vehicles. Using these techniques, the effect of infrastructure and traffic interventions can be evaluated before the interventions are carried out (Tarko, 2012).

2.2 Emissions and environmental assessment in transport

Environmental impact assessment of road transport normally employs emission models to calculate emissions based on vehicle activities, speed, traffic flow, and fleet composition. Traffic simulation models can be employed to model traffic flow, speed, and other traffic conditions, after which an emission model can be applied to calculate various emissions such as CO_2, NOx, and PM, among others (Abou-Senna and Radwan, 2013).

Various studies have indicated that traffic management strategies can affect vehicle emissions through speed, acceleration, and congestion levels. For instance, speed reductions can be effective in reducing emissions, but they can also increase emissions because of increased time spent on the road, leading to congestion. Therefore, traffic management strategies and vehicle emissions have a complex relationship (Roussou et al., 2025; Abou-Senna and Radwan, 2013).

2.3 Integrated assessment of safety and environmental impacts

In recent years, increasing attention has been given to integrated approaches that evaluate multiple transport impacts simultaneously, including safety, environment, mobility, and economic performance. These approaches are often used in cost–benefit analysis and sustainable urban mobility planning, where decision-makers must evaluate trade-offs between different objectives (Elvik, 2012).

One of the main challenges in integrated assessment is that different impacts are measured in different units, such as crashes, emissions, travel time, and cost. For this reason, normalized indicators, ratios, and impact factors are often used to express changes relative to baseline conditions and allow comparisons between different scenarios and indicators. Impact factors and before-and-after comparison methods are widely used in road safety evaluation and transport policy analysis to estimate the effect of interventions relative to existing conditions (Roussou et al., 2025; Elvik, 2012).

Several studies have examined transport assessment approaches combining safety, environmental, operational, or socio-economic indicators within multi-criteria analysis, normalization techniques, or cost-benefit analyses (Paliotto et al., 2024). They have significantly contributed to supporting transport policy evaluation and sustainable mobility planning. However, many existing frameworks remain difficult to transfer between different urban contexts due to variations in data availability, modelling assumptions, indicator scales, and local traffic conditions.

Within this context, the concept of Impact Modification Factors can be used as a simple and consistent way to express changes in safety and environmental indicators between different scenarios. By expressing the relative change between baseline and intervention scenarios, the IMF approach allows different indicators to be compared on a common scale and supports the evaluation of trade-offs between safety and environmental performance.

3. Methodology

This section presents the methodology used to evaluate the impact of infrastructure and traffic management interventions on both road safety and environmental performance. The methodology combines traffic simulation outputs, emission estimates, and road safety indicators at road segment level. The analysis is based on the comparison of different scenarios using Impact Modification Factors, which express the relative change between baseline and intervention conditions.

3.1 Integrated assessment of safety and environmental impacts

The study was conducted on selected road segments of the urban road network of Athens, Greece. The analysed network includes arterial roads and urban streets with different geometric and operational characteristics, such as the number of lanes, lane width, speed limits, intersection types, and traffic volumes. The road segments were analysed individually in order to evaluate how different types of roads respond to infrastructure and traffic management interventions in terms of safety and environmental performance.

Each road segment was assigned a unique identifier, allowing the integration of traffic simulation results, emission estimates, and road safety indicators into a unified database. This segment-based approach allows the comparison of results across different road types and facilitates the identification of segments where interventions produce improvements or deteriorations in safety and environmental performance.

3.2 Simulation Scenarios and Simulation Outputs

Traffic simulation was conducted using the Aimsun Next microscopic simulation platform. Three scenarios were analysed in this study. Baseline scenario, representing existing traffic conditions and infrastructure characteristics. Then, the Infrastructure intervention scenario, including changes in road geometry, lane configuration, and traffic management measures, and last the Infrastructure and speed management scenario, including infrastructure changes combined with a zonal speed limit reduction to 30 km/h in selected areas.

The purpose of the scenario analysis was to evaluate how infrastructure changes and speed management measures affect traffic conditions, emissions, and road safety indicators at the road segment level. Traffic simulation was performed for each scenario, and traffic performance indicators such as traffic flow, speed, and travel time were extracted for each road segment. The baseline model was calibrated and validated using observed field traffic data, including traffic volumes, speeds, travel times, and turning movements collected from the study network.

Additional calibration adjustments were performed to ensure realistic representation of vehicle interactions, traffic signal operations, and vulnerable road user movements within the simulation environment. These outputs were then used for emission estimation and safety analysis.

Traffic simulation was used to estimate traffic conditions under each scenario. For each road segment and scenario, the simulation provided traffic indicators and more precisely traffic flow, average speed, travel time, traffic density. These indicators were used as input variables for emission estimation models and were also used to interpret the effects of infrastructure and speed management measures on traffic conditions. The simulation results were exported at road segment level and organized in a database structure where each road segment had separate values for each scenario.

Emission estimations were derived from the simulation outputs using the London Emission Model (LEM), and were calculated for each road segment and scenario, and included pollutants such as carbon dioxide (CO_2) and nitrogen oxides (NOx). The emission estimation process used traffic simulation outputs such as traffic flow, speed, and travel time to estimate emissions at segment level. Emissions were calculated for each scenario and expressed in grams per road segment. This allowed the comparison of emissions between baseline and intervention scenarios and the evaluation of environmental performance at segment level.

3.3 Road Safety Assessment (iRAP)

Road safety assessment was conducted using the iRAP methodology which is based infrastructure safety indicators derived from road characteristics and traffic conditions. For each road segment, safety indicators were estimated based on infrastructure characteristics and specifically, number of lanes, lane width, speed limit, intersection quality, area type, traffic volume, operating speed, safety indicators included Star Rating Scores and Fatal and Serious Injury risk indicators for different road user groups, such as pedestrians, cyclists, motorcyclists, and vehicle occupants. These indicators were estimated for each scenario and road segment, allowing the comparison of safety performance between baseline and intervention scenarios. The analysed indicators were grouped according to road user category and intervention scenario in order to facilitate the comparison of safety performance across different road segments and infrastructure conditions.

3.4 Impact Modification Factors (IMF) Calculation

The Impact Modification Factors (IMF) was used to evaluate the effect of interventions on both safety and environmental indicators. The IMF expresses the relative change between an intervention scenario and the baseline scenario and is calculated as the ratio between the indicator value after the intervention and the corresponding baseline value: $IMF = \frac{Indicator_{after}}{Indicator_{before}}$ (1)

The above mentioned ratio-based formulation was selected in order to enable direct comparison between indicators expressed in different units and scales, such as emissions and safety-related indicators. The IMF provides a normalized comparison between the intervention and baseline scenarios as IMF > 1 indicates an increase relative to the baseline scenario, IMF < 1 indicates a decrease relative to the baseline scenario and IMF = 1 indicates no change between scenarios.

The interpretation of improvement or deterioration depends on the meaning of each analysed indicator. That is why the IMF was calculated separately for emissions and safety indicators for each road segment and scenario. For emission indicators, an IMF greater than 1 indicates an increase in emissions (negative environmental impact), while an IMF lower than 1 indicates a reduction in emissions (positive environmental impact). For risk-related safety indicators, such as Fatal and Serious Injury (FSI) estimates, IMF values lower than 1 indicate an improvement in safety performance, as they correspond to reduced risk levels compared with the baseline scenario, whereas IMF values greater than 1 indicate deterioration. Using the IMF allows different indicators, measured in different units, to be expressed on a common relative scale, facilitating comparison between safety and environmental performance. For example, if a road segment presents 100 units of NO_x emissions under baseline conditions and 80 units after the intervention, the resulting IMF equals 0.80, indicating a 20% reduction in emissions relative to the baseline scenario.

All datasets were integrated at road segment level using a common segment identifier. The integrated dataset included traffic simulation outputs, emissions estimates, road safety indicators and impact modification factors for each indicator. The analysis was conducted at road segment level and also aggregated by road type, such as number of lanes and road category. This allowed the identification of road types where interventions resulted in improvements or deteriorations in safety and environmental performance. The results were analysed by comparing the distribution of IMF values across road segments and road types, and by identifying segments where both safety and environmental performance improved or deteriorated.

4. Results

4.1. Network-level results

The results were analysed at network level by comparing safety and environmental indicators across the three scenarios: baseline, infrastructure intervention, and infrastructure combined with speed management. The comparison included indicators such as fatalities and serious injuries, percentage of network above safety thresholds, and average road safety risk for different road user groups.

The results showed that infrastructure interventions alone led to noticeable improvements in road safety indicators across the network. The combined scenario including infrastructure changes and a 30 km/h speed limit resulted in even greater safety improvements. In particular, reductions in pedestrian and cyclist risk were observed, indicating that speed management measures significantly improve safety conditions for vulnerable road users. Overall, the results indicate that combining infrastructure changes with speed reduction policies provides the greatest improvement in safety performance across the network.

4.2. Emission results

Emission results were estimated using traffic simulation outputs and the London Emission Model. Emissions of CO_2 and NOx were calculated for each road segment and scenario, and Impact Modification Factors were estimated to evaluate the relative change between scenarios.

The results showed that emission impacts varied depending on road type and traffic conditions. Some arterial roads showed increased emissions due to increased travel times and reduced speeds, while other segments showed emission reductions due to smoother traffic flow and reduced congestion. The IMF results indicated that infrastructure interventions alone produced mixed environmental results, whereas the combined infrastructure and speed management scenario showed more consistent emission reductions in several road segments. These findings suggest that the relationship between infrastructure interventions and emissions is complex and depends on traffic flow conditions, speed changes, and congestion levels.

Table 1. Emission Results.

	eid	nox_before	nox_after1	nox_after2	co2_before	co2_after1	co2_after2	IMF1_nox	IMF2_nox	IMF1_co2	IMF2_co2
Ardittou	7083	72,046	92,974	182,779	238915,59	339540,08	379088,07	1,290	1,966	1,42	1,12
Vas. Sofias	7008	607,825	652,873	781,081	434547,48	507233,26	524844,31	1,074	1,196	1,17	1,03
Akadimias	6979	205,054	486,500	630,596	234762,02	653716,71	809678,87	2,373	1,296	2,78	1,24

4.3. iRAP results

Road safety performance was evaluated using infrastructure-based safety indicators derived from the iRAP methodology, including Fatal and Serious Injury risk indicators for different road user groups. Impact Modification Factors were calculated for each road segment and scenario in order to evaluate safety improvements relative to baseline conditions.

The results showed that most road segments presented IMF values greater than one for safety indicators, indicating improvements in safety performance after the implementation of infrastructure interventions. The greatest safety improvements were observed in urban arterial roads where infrastructure modifications and speed reductions were applied. Vulnerable road users, particularly pedestrians and cyclists, showed the largest improvements in safety indicators.

However, some wider road sections and high-capacity roads showed smaller improvements or mixed results, indicating that infrastructure changes may have different effects depending on road type and traffic conditions.

Table 2. iRAP IMF Results.

	Part of Eleftheriou Venizelou					**Leof.Konstantinou**					**Sina**				
	Base line	**I1**	**I2**	**IMF1**	**IMF2**	**Baselin e**	**I1**	**I2**	**IMF 1**	**IMF 2**	**Baselin e**	**I1**	**I2**	**IMF 1**	**IMF 2**
Total-Bicyclists	606,06	657,19	122,6	1,084	0,187	60,44	53,92	8,37	0,892	0,155	15,82	15,82	9,26	1,000	0,585
Total – Motor cyclists	17,69	14,74	4,81	0,833	0,326	3,36	3,54	0,73	1,054	0,206	2,94	2,94	1,9	1,000	0,646
Total-Pedestrian	829,74	71,88	15,95	0,087	0,222	91,71	80,28	14,5	0,875	0,181	2,76	2,77	1,69	1,004	0,610
Total - Vehicle Occupants	15,9	13,15	4,46	0,827	0,339	2,92	3,08	0,73	1,055	0,237	2,68	2,68	1,78	1,000	0,664
Total-BIC-	606,06	657,19	122,6	1,084	0,187	60,44	53,92	8,37	0,892	0,155	15,82	15,82	9,26	1,000	0,585
Total MO-S	17,69	14,74	4,81	0,833	0,326	3,36	3,54	0,73	1,054	0,206	2,94	2,94	1,9	1,000	0,646
Total PED-S	829,74	71,88	15,95	0,087	0,222	91,71	80,28	14,5	0,875	0,181	2,76	2,77	1,69	1,004	0,610
Total VO-S	15,9	13,15	4,46	0,827	0,339	2,92	3,08	0,73	1,055	0,237	2,68	2,68	1,78	1,000	0,664

4.4. Integrated IMF analysis

By comparing IMF values for both safety and emissions, it was possible to identify road segments where interventions improved both safety and environmental performance, as well as segments where trade-offs occurred. In several urban road segments, both safety and emission indicators improved simultaneously, indicating that infrastructure and speed management measures can support both road safety and environmental sustainability objectives.

However, in some cases, safety improvements were associated with increased emissions due to lower speeds and increased travel times. These results highlight the importance of integrated assessment approaches that consider both safety and environmental impacts simultaneously rather than evaluating them separately.

5. Conclusions

This research proposed and implemented a new methodology, namely Impact Modification Factor (IMF), which can be used to assess the impact of interventions in both road safety and environmental performance. The methodology implemented in this research integrated simulation results, emission calculations, and infrastructure-based road safety measures. The results of this research indicated that interventions in infrastructure resulted in improvements in road safety measures for most road segments, especially for vulnerable road users.

The integration of these measures in speed management further enhanced road safety measures, which highlighted the significance of incorporating speed reduction measures in achieving Safe System concepts. The results revealed mixed results in terms of environmental impacts, where there were road segments with improved emissions and road segments with deteriorating emissions, depending on traffic flows and changes in travel times.

The integrated methodology provided a tool to identify road segments where both road safety and environmental impacts were improved, as well as where trade-offs were identified. Generally, the Impact Modification Factor proved to be a useful tool in integrated assessment of road safety and environmental impacts, where different indicators were compared on a similar scale, thus supporting decision-making in urban transport planning.

The IMF framework has the potential to support the transferability of results to similar road networks, where similar scenarios are implemented. Future research should focus on applying the IMF methodology to larger networks and additional impact categories such as travel time, accessibility, and economic impacts, in order to support integrated transport policy evaluation. Additionally, extending the proposed framework through more detailed statistical comparisons, sensitivity analyses, and typology-based assessment of road segments is a mandatory need to further investigate the observed trade-offs between safety and environmental performance.

Acknowledgements

The present research was carried out within the research project "PHOEBE - Predictive Approaches for Safer Urban Environment", which has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101076963.

References

Abou-Senna, H., & Radwan, E. (2013). VISSIM/MOVES integration to investigate the effect of major key parameters on CO2 emissions. Transportation Research Part D: Transport and Environment, 21, 39-46.

Elvik, R. (2012). Analytic choices in road safety evaluation: Exploring second-best approaches. Accident Analysis & Prevention, 45, 173-179.

FHWA, Crash Modification Factors (CMFs), https://highways.dot.gov/sites/fhwa.dot.gov/files/2022-06/cmf.pdf

Holló, P., Eksler, V., & Zukowska, J. (2010). Road safety performance indicators and their explanatory value: A critical view based on the experience of Central European countries. Safety science, 48(9), 1142-1150.

The International Road Assessment Programme (iRAP), https://irap.org/rap-tools/infrastructure-ratings/star-ratings/

Paliotto, A. (2024). Development of a Network-Level Road Safety Assessment Procedure Based on Human Factors. Infrastructures, 9(2), 35.

Papadimitriou, E., & Yannis, G. (2013). Is road safety management linked to road safety performance?. Accident Analysis & Prevention, 59, 593-603.

Roussou, S., Petraki, V., Deliali, K., Kontaxi, A., & Yannis, G. (2024). Cost benefit analysis of reducing speed limits in Athens to 30 Km/h. Case Studies on Transport Policy, 18, 101289.

Tarko, A. P. (2012). Use of crash surrogates and exceedance statistics to estimate road safety. Accident Analysis & Prevention, 45, 230-240.

Wegman, F., & Schepers, P. (2024). Safe System approach for cyclists in the Netherlands: Towards zero fatalities and serious injuries?. Accident Analysis & Prevention, 195, 107396.