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DYNAMIC PROGRAMMING FOR ASSESSING THE EFFECTIVENESS OF INTELLIGENT TRANSPORT SYSTEMS IN ACHIEVING SUSTAINABLE DEVELOPMENT GOALS

Christina Nikolova, Marta Klisurova
University of National and World Economy, Sofia, Bulgaria

Abstract. In line with Goal 11 of the United Nations Sustainable Development Goals (SDGs), which seeks to ensure safe, accessible, and sustainable transportation systems for everyone by 2030, this study investigates the effect of Intelligent Transport Systems (ITS) on key indicators of sustainable urban development. The paper discusses the SDGs adopted by the UN in 2015, focusing on the social, economic, and environmental aspects of sustainability, especially Goal 11.

The research systematically identifies and classifies key indicators for sustainable transport, aligning each with Goal 11 of the United Nations' Sustainable Development Goals. It evaluates how different types of ITS influence these indicators, emphasizing their role in improving public welfare. A city-based case study is included, where a dynamic programming method is employed to optimize the outcomes of ITS implementation. The empirical results demonstrate the potential to achieve optimal results from various ITS solutions, as measured by impact coefficients related to each indicator.

The study concludes with a discussion of potential benefits related to ITS deployment, along with opportunities for future development within the broader context of sustainable urban mobility.

Keywords: intelligent transport systems; dynamic programming; sustainable development goals; sustainable transport indicators; optimization of ITS impacts

1. Introduction

With growing urbanization and increased traffic in cities, implementing Intelligent Transport Systems (ITS) is becoming crucial for sustainable transportation and mobility. These systems have great potential to help achieve the Sustainable Development Goals (SDGs), especially in urban areas, and to enhance public welfare. They can contribute to creating smarter, greener, and more inclusive cities. Their impacts can be viewed from various perspectives, including environmental, social, economic, and technological. In this context, implementing

ITS provides technological solutions that can optimize traffic flow, improve public transportation, and lower environmental impact [1]. The main aim of this report is to introduce a model based on dynamic programming that evaluates the impacts of different types of ITS on sustainable development.

2. Key components of intelligent transport systems

The main components of ITS include technologies, infrastructure, and software solutions that work together to enhance the efficiency, safety, and sustainability of transportation. The primary and most commonly used types of ITS in urban environments are:

– Adaptive traffic lights (Smart Traffic Lights);

– Real-time traffic management systems (RTMS) – including intelligent traffic light systems, adaptive intersection control systems, speed management systems, etc. [2];

– Intelligent public transport systems – include real-time tracking systems, information boards at stops, integrated tickets and payments, etc.;

– Passenger and driver information systems – include mobile applications, in-vehicle navigation systems, dynamic electronic displays, etc.;

– Geolocation and sensor technologies – include GPS/GNSS, cameras and radars, road surface sensors, etc.;

– Automated toll collection systems;

– Communication technologies (V2X) – include V2V (vehicle-to-vehicle communication), V2I (vehicle-to-infrastructure interaction), V2P (detection and protection of pedestrians through sensors and mobile devices);

– Data management and analysis centers – including traffic control centers, big data analysis systems, artificial intelligence, and machine learning [3];

– Cybersecurity and data protection, etc. [4, 5];

ITS integrates various components into a connected, intelligent system that promotes sustainable and safe mobility. The core of their effectiveness lies in the combination of hardware (sensors, cameras), software (analysis and control), and communications (V2X) [6].

3. Key indicators for sustainable development

Key indicators for evaluating sustainable transport development include economic, environmental, and social factors. They are used to measure progress toward a transportation system that is efficient, accessible, safe, and environmentally friendly.

Leading groups of indicators and indicators for sustainable development:

● Environmental:

– Greenhouse gas (GHG) emissions – CO_2, CH_4, N_2O from the transport sector.

– Noise pollution – especially in urban and suburban areas.

– Energy consumption – total and by type (fossil fuels vs. renewable sources)
– Air quality – levels of NO_x, PM10, PM2.5, SO_2, ozone.
● Economic:
– Transport efficiency – energy consumption per passenger or tonne-kilometer.
– Levels of intermodality – integration between different modes of transport.
– Investments in transport infrastructure, as a share of GDP or per capita.
– Internal and external costs – maintenance costs, delays, pollution, accidents.
● Social:
– Transport accessibility – to ensure access to public services, jobs, and education.
– Transport safety – number and severity of traffic accidents, injuries, and fatalities.
– Social justice – equal access for vulnerable groups (older adults, people with disabilities, low-income households).
– Quality of transport services – reliability, frequency, comfort.
– Travel time – average time spent traveling to work or services.
Behavior and mobility indicators:
– Share of trips by mode of transport – public, car, bicycle, walking.
– Number of vehicles per 1,000 people – an indicator of motorization.
– Development of cycling and walking infrastructure – network length and convenience.

These indicators and metrics are sourced from data provided by the UN – UN Sustainable Development Goals (SDG Indicators), Eurostat – Sustainable Development Indicators (EU SDIs), the National Statistical Institute (NSI) – Sustainable Development Section, European Environment Agency – Environmental Indicators, ITU & UNECE – Smart Sustainable Cities Indicators, and other organizations.

4. Sustainable Development Goals

In 2015, the UN adopted its Sustainable Development Agenda for the period up to 2030. It includes 17 Sustainable Development Goals (SDGs) and 169 sub-goals, with progress tracked through 232 indicators. The agenda seeks to promote sustainable social, economic, and environmental development worldwide by 2030. This report highlights the opportunities to use intelligent transport systems to achieve Goal 11 – Sustainable Cities and Communities, which aims to ensure safe, accessible, and sustainable transportation for all in urban areas.

To achieve SDG 11, cities and other settlements need to be renewed and planned in ways that ensure equal access to basic services, energy, housing, transportation, and green public spaces, while also reducing resource consumption and environmental impact.

Monitoring SDG 11 within the EU transport policy context involves analyzing changes in urban and community quality of life, efforts to promote sustainable mobility, and the environmental impacts of transport. Current EU assessments indicate moderate progress toward SDG 11 over the past five years [7]. While there have been improvements in urban and community quality of life, trends in sustainable mobility remain somewhat unfavorable. The environmental impact outlook is mixed, with both sustainable and unsustainable developments noted [7].

Each country's advancement toward this goal is tracked with the following indicators:

● **Population living in households that consider themselves to be affected by noise, by poverty status**

The Environmental Noise Directive is the EU's key tool for identifying and addressing noise pollution [8]. It focuses on three main areas: assessing exposure to environmental noise, providing the public with access to information about environmental noise and its effects, preventing and reducing environmental noise where needed – especially where exposure could harm human health – and maintaining the quality of environmental noise where it is beneficial. The indicator tracks the percentage of the population that reports being affected by noise from transportation or other sources. In 2023, 18.2% of the EU population experienced noise disturbance [7].

● **Road fatalities by type of road**

The indicator tracks the number of deaths caused by road accidents, including those involving road users – drivers, passengers of motor vehicles, bicycles, and pedestrians. People who die within 30 days of a traffic accident are counted as traffic-related deaths. In 2023, 20,380 people died in traffic accidents across the EU [7].

● **Premature death due to exposure to particulate matter**

This indicator estimates the number of premature deaths caused by long-term exposure to PM2.5 levels above five μg/m³ (the World Health Organization's recommended level). Two hundred thirty-nine thousand people in the EU died prematurely in 2022 due to PM2.5 exposure [7].

● **Share of rail and inland waterways in domestic freight transport**

Transport should be organized to minimize environmental impact. This indicator shows the share of buses and trains within total inland passenger transport, measured in passenger-kilometers (pkm). According to the Eurostat database, 16.6 % of passenger traffic in passenger-kilometers was carried out by buses and trains in 2022. The share of cars in passenger traffic accounts for 83.4 % which put them in a dominant position on the passenger market [7].

5. Link between the leading indicators for sustainable transport and Sustainable Development Goal 11.

The following table assesses the impact of various intelligent transport systems on sustainable transport indicators, emphasizing their role in improving public welfare. Based on this table, a judgment can be made about the significance of each ITS system's effect in achieving a specific goal.

Table 1. Assessment of the impact of different types of ITS on sustainable transport indicators related to Goal 11

Sustainable Development Goals	Indicator measuring progress	Impact of ITS (benefits)	
		Type of system (product or service)	Contribution/Effect
GOAL 11 – Sustainable cities and communities	Population living in households that consider themselves to be affected by noise, by poverty level	Reactive traffic management and control	Smooth travel for all, leading to reduced noise levels Direct and targeted information to road users, leading to informed travel choices. Internal and external costs Social equity **Economic effect** **Social effect** **Environmental impact**
		Predictive traffic management and control	
		Information for travelers	
		Parking management and information	
		Road user charging	
		Fleet management systems	
		Demand-responsive transport	
		Mobility as a service	
	Road traffic fatalities by type of road – Number of fatalities in road traffic accidents	Automatic number plate recognition system (ANPR, CCTV)	Reduction in road accidents and number of fatalities (in %) Transport safety Quality of transport services Reduced internal and external costs **Economic effect** **Social impact**
		Reactive traffic management and control	
		Predictive traffic management and control	
		Priority for public transport and emergency vehicles	
		Mobility as a service	
		Traveler information	
		Red light running and parking enforcement	
		Dynamic route guidance	
		Road user charging	
		Electronic tickets	
		Electronic payment	

Sustainable Development Goals	Premature deaths due to exposure to fine particulate matter	Reactive traffic management and control	Improved air quality Improved transport efficiency Reduced internal and external costs Social equity **Economic effect** **Social impact** **Environmental impact**
GOAL 11 – Sustainable cities and communities		Predictive traffic management and control	
		Information for travelers	
		Parking management and information	
		Red light running and parking enforcement	
		Dynamic route guidance	
		Road user charging	
		Fleet management systems	
		Demand-responsive transport	
		Electronic payment	
		Mobility as a service	
	Share of rail and inland waterways in domestic freight transport	Real-time traffic management systems (RTMS)	Reduction in delays (in %) Increase in public transport use (in %) Accessibility of transport Quality of transport services Travel time Transport efficiency Levels of intermodality **Economic impact** **Social impact** **Environmental impact**
		Information for travelers	
		Electronic tickets	
		Electronic payment	
		Transportation that meets demand	
		Fleet management systems	
		Mobility as a service	

Source: Systematization of authors based on the EU Strategies and Policies (https://commission.europa.eu/strategy-and-policy/sustainable-development-goals/eu-and-united-nations-common-goals-sustainable-future_bg) [9]

6. Dynamic programming approach and its application in transport

Dynamic programming (optimization) relies on the principle of optimality, introduced by Richard Bellman in 1962: "A policy is optimal if, for a given stage, regardless of decisions made earlier, the decisions to be made form an optimal policy, considering the results of previous stages." [10] These methods are extensively used in transport planning. Their practical application often results in significant economic benefits. A key feature of dynamic programming problems is the strict need to observe the sequence of individual operations due to the time factor [11]. Solving such problems involves a multi-stage decision-making process, where identifying the optimal choice is divided into several sub-stages. In this approach, the goal is not to find isolated optimal solutions for each subtask but to determine the overall optimal solution that minimizes costs over the entire period. The implementation of the dynamic programming approach involves two stages:

– Conditional optimization (moving from step to step);

– Actual optimization (moving from step 1 to step n).

The principles of dynamic programming can also be used to solve problems that are not multi-stage but rely on the decision-making process itself [12].

7. Practical application of the dynamic programming approach to optimize the effects of ITS implementation

To demonstrate the capabilities of the dynamic programming approach in assessing the impact of implementing intelligent transport systems in an urban environment on achieving Sustainable Development Goal 11, an example has been developed featuring four systems: the implementation of smart traffic lights, video surveillance at intersections, shared mobility as a service, and electronic toll collection. For the model, it is assumed that the budget needed for implementing these systems is BGN 50 million, distributed among the four selected systems. The costs must be equal to or less than this budget.

(1) $C(x) \leq B$,

where:

x – configuration of selected ITS;

C(x) – value/cost of implementing x;

B – budget.

The empirical assessment of the impact (coefficients) of the systems is performed based on a method for obtaining the sustainable value, using a linear regression model for effects:

(2) $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon$

(3) $Y = \Sigma(\beta i \cdot Xi)$

where:

Y – sustainable value (aggregate effect);

Xi – level of implementation of ITS i;

Bi – impact coefficient;

ϵ – model error.

The impact coefficients (β) for indicators such as reduction in traffic accidents, decrease in CO_2, reduction in travel time, and increase in demand for public transport (PT) are not arbitrary; they are based on empirical data and statistical analysis.

Data can be collected from various sources, including the Sofia Municipality, the traffic police, the National Statistical Institute, the Bulgarian Academy of Sciences, the Ministry of Regional Development and Public Works, as well as European Commission reports.

Table 2. Impact coefficients (example values from empirical studies)

ITS	Coefficient for road accidents (β_1)	Coefficient for CO_2 (β_2)	Coefficient for time (β_3)	Coefficient for public transport (β_4)
Intelligent traffic lights	-0.05	-0.10	-0.15	0
Traffic accident cameras	-0.20	0	-0.05	0
Shared mobility as a service	0	-0.05	-0.10	+0.25
Electronic charging	0	-0.20	0	+0.10

Source: Authors' calculations

To provide input data for the model, the effects of reducing road traffic accidents, lowering CO_2 emissions, saving time, and decreasing the use of private motor vehicles are also presented, along with the associated social, economic, or environmental benefits.

Table 3. Input data for the model (example values)

ITS solution	Cost (million BGN)	Effect on road accidents	Effect on CO_2	Effect on time	Effect on vehicle use
Smart traffic lights	15	5% ↓	10%	15	0
Traffic accident cameras	10	20% ↓	0	5% ↓	0
Shared mobility as a service	25	0	5% ↓	10	25% ↑
Electronic charging	20	0	20% ↓	0	10% ↑

Source: Authors' calculations

A key requirement for using the dynamic programming approach is defining an optimal substructure. This involves selecting and combining the most effective solutions to the minor problems that comprise the main issue. These optimal substructures are described recursively. The purpose of the equation below is to illustrate how the overall effect is achieved when different intelligent transport systems are added to the model incrementally.

The recursive equation is:

(4) $E_n = E_{n-1} + (\alpha_1 \cdot P_{1n} + \alpha_2 \cdot P_{2n} + \alpha_3 \cdot P_{3n} + \alpha_4 \cdot P_{4n})$

where:

E_n is the cumulative effect after the implementation of the n-th ITS system;

α_i are the weights of the indicators (e.g., Acc = 0.3, CO_2 = 0.3, time = 0.2, public transport PT = 0.2);

P_{in} is the value of the respective indicator in the n-th ITS system.

Table 4. Accumulation of sustainable effects with the gradual addition of ITS to the model

ITS System	↓ Acc (%)	↓ CO_2 (%)	↓ Time (%)	↑ PT (%)	Single effect	Cumulative effect
Smart traffic lights	5	10	15	0	7.5	7.5
Traffic accident cameras	20	0	5	0	7.0	14.5
Shared mobility as a service	0	5	10	25	8.5	23.0
Electronic charging	0	20	5	10	9.0	32.0

Source: Authors' calculations

The single effect column (F) in Table 4 displays the effect of each ITS system. The cumulative effect column (G) illustrates how the recurrence equation is implemented by adding the value from the previous row:

(5) $G_n = G_{n-1} + F_n$

To simulate the effects of various ITS strategies in an optimization scenario for the city of Sofia, the function is maximized as follows:

(6)

$$U = \alpha 1 \cdot (\Delta Acc) + \alpha 2 \cdot (\Delta CO2) + \alpha 3 \cdot (\Delta time) + \alpha 4 \cdot (\Delta public\ transport)$$

Where α are priority weights. For example:

– $\alpha_1 = 0.3$ (Acc);
– $\alpha_2 = 0.3$ (CO_2);
– $\alpha_3 = 0.2$ (time);
– $\alpha_4 = 0.2$ (public transport).

When executing a scenario that includes the selection of smart traffic lights (BGN 15 million), traffic accident cameras (BGN 10 million), and shared mobility as a service (BGN 25 million) within a BGN 50 million budget, an overall impact is achieved, as shown in Table 5.

Table 5. Calculations of the aggregate effect of implementing the four systems

Indicator	Amount of effect	Weight	Contribution
Acc	5% + 20% = **25%** ↓	0.3	7.5
CO_2	10% + 5% = **15%** ↓	0.3	4.5
Time	15% + 5% + 10% = **30%** ↓	0.2	6.0
Public transport	0 + 0 + 25% = **25%** ↑	0.2	5.0

Source: Authors' calculations

Based on the calculation of the overall effect of implementing the four systems, a total sustainable value (Y) of 23 conditional units is established.

To identify the most effective values for reducing traffic accidents using various ITS systems within the available budget, we follow a step-by-step approach. The results of the calculations are shown in Table 6 below.

Table 6. Result of a step-by-step approach to determine optimal values for road accident reduction within a limited budget

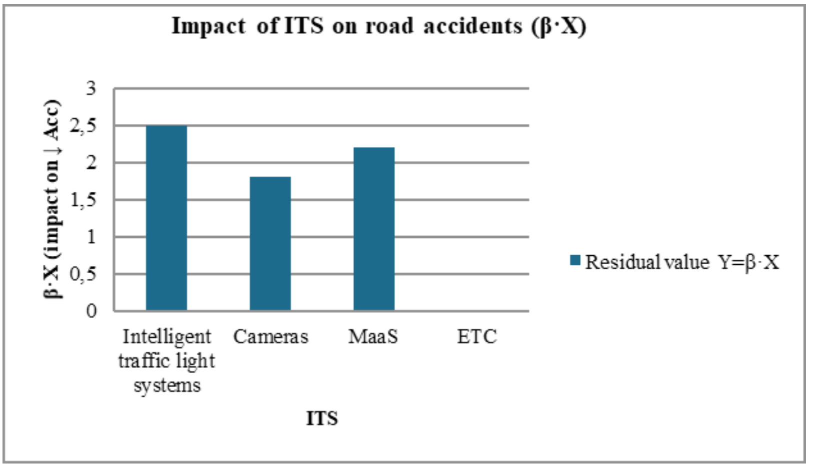
ITS system	Coefficient β	Level (0/1)-X	Budget (BGN)	Sustainable value Y=β·X	Expense
Smart traffic lights	2	1	15,000,000	2.5	15,000,000
Traffic accident cameras	1.8	1	10,000,000	1.8	10,000,000
Shared mobility as a service	2.2	1	25,000,000	2.2	25,000,000
Electronic charging	3	0	20,000,000	0	0
			Total expenditure:		50,000,000
			Total ↓ Acc:	6.5	

Source: Authors' calculations

The results from the calculations allow us to determine a total sustainable value (Y) of 6.5 conditional units.

Impact on sustainability indicators

The practical example demonstrating the application of the dynamic programming approach in evaluating the impact of implementing the four types of ITS in the scenario above shows that by using an optimal combination of intelligent traffic light systems, traffic accident cameras, and shared mobility as a service, a total reduction in traffic accidents of 6.5 (sustainable value) can be achieved within the specified budget constraint (see Figure 1). This way, it becomes possible to evaluate how ITS contributes to lowering the number of fatalities from traffic accidents, which aligns with SDGs 3 and 11.



Source: Based on authors' calculations

Figure 1. Impact of ITS on the road accidents

In summary, the results of testing the dynamic programming approach in evaluating the impact of ITS implementation on achieving sustainable development goals lead to the following conclusions:

– The dynamic programming model enables the simulation of scenarios with various combinations of ITSs within budget constraints.

– The optimal combo for Sofia in the example includes: smart traffic lights, traffic accident cameras, and shared mobility as a service.

– Using empirical impact coefficients enables quantitative evaluation and prioritization of investments to promote sustainable transport development.

Conclusions

The EU's sustainable transport system goals aim to create an intelligent, flexible, and adaptable system that responds to the ever-changing patterns and needs within the transport sector. It is based on technological advances to ensure seamless, safe, and secure connectivity for all European citizens. The results of the presented study and empirical testing confirm that dynamic programming can be used to optimize the effective selection and implementation of ITS in urban environments, even with budget constraints. The effectiveness of this methodology demonstrates that dynamic programming is a powerful tool for sustainable urban planning. Future research and development directions include calibrating the model with real data from sources such as the NSI, Sofia Municipality, and the Traffic Police, as well as adding GIS analysis for spatial assessments. Municipalities across the country can also utilize this model for planning and making informed decisions related to transport planning, policy development, and operational adjustments. The use of data from ITS enables the development of a follow-up model based on the real effects of system application over time, clearly demonstrating the achievement of sustainable development goals, especially Goal 11.

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✉ **Prof. Dr. Christina Nikolova**
ORCID iD: 0000-0002-0966-5872
Department of Transport and Energy Economics
University of National and World Economy
19, Osmi Dekemvri St.
Sofia, Bulgaria
E-mail: hrnikolova@unwe.bg

✉ **Marta Klisurova, PhD student**
ORCID iD: 0009-0009-5346-4777
Department of Transport and Energy Economics
University of National and World Economy
19, Osmi Dekemvri St.
Sofia, Bulgaria
E-mail: marta.klisurova@unwe.bg