Sustainable Smart Cities: A Comprehensive Framework for Sustainability Assessment of Intelligent Transport Systems

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Abstract. This paper is an extended version of a previously published paper [22], which proposes a framework for assessing the sustainability impact of intelligent transport systems (ITS). Building on this research, this paper shows the practical application of the framework by assessing three exemplary ITS projects and discussing potential future use. Due to the increasing relevance of ITS to improve the efficiency of transport in highly congested areas, this framework has high practical relevance for smart mobility initiatives and (future) smart cities. Municipalities increasingly recognize their responsibility for creating a sustainable environment for citizens in the face of challenges like overpopulation, land shortage, and climate change. Nevertheless, many ITS initiatives still mainly focus on technical solutions and overlook their impact on sustainability despite the relevance for the environment, society, and economy. This paper bridges the gap between technical applications and their impact on sustainability by proposing a framework for assessing the sustainability of ITS applications and initiatives. It discusses and analyzes different perspectives on the complex concepts of sustainability and ITS to derive a set of Sustainable Development Goals (SDGs) that can be targeted by ITS in one central framework. Besides this theoretical contribution, this paper focuses on demonstrating the practical use of the framework with a diverse set of projects. Hence, this work bridges two fundamental perspectives for further research and supports decision-makers in choosing ITS initiatives that contribute to both smart mobility and sustainability.

Keywords: Smart City · Smart Mobility · Smart Traffic Management · Intelligent Transport Systems · Sustainability

1 Introduction

This article is an extension of work originally presented in the Proceedings of the 18th Conference on Computer Science and Intelligence Systems [22].

Smart mobility refers to a wide range of data-driven concepts that help move individuals, groups, or objects across different locations, shaping both our present and future

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[10]. Considering the complex challenges of the current decade, such as overpopulation, demographic change, globalization, space shortage, and dense traffic, cities aim to stay attractive to their citizens and provide a livable environment [5, 23]. With over 50% of the global population living in urban areas, their citizens can especially profit from the opportunities of smart traffic management and the management of high traffic volume in congested environments [9]. Simultaneously, the environmental and social challenges driven by climate change raise the need for municipalities to take responsibility and counteract the negative aspects of these challenges on their citizens. Consequently, more cities aim to use the advances of digitalization to create value for smart and sustainable mobility of citizens [2, 3, 18, 24]. Some researchers even point out that cities cannot become smart without being sustainable, making sustainability an important factor in smart city projects [34].

Intelligent transport systems (ITS) provide a set of technical applications and aim to provide innovative services for different modes of transport and traffic management [8, 10, 19]. They empower citizens to make better decisions regarding their mobility and enable safer and better-coordinated transport networks. Since road traffic is responsible for about 65% of the CO2 emissions in cities and is likely to increase in the future, ITS promise to mitigate the negative effects of traffic on the environment [4]. However, while sustainability is a key factor in smart mobility initiatives, many ITS projects are still mainly focused on technical criteria and measures and do not seem to analyze their impact on sustainability [7, 20, 27].

Therefore, we target the intersection of sustainability and ITS in this paper. We analyze the Sustainable Development Goals (SDGs) defined by the United Nations (UN) to determine which goals, targets, and indicators have implications for the development of ITS in the context of smart mobility towards a sustainable smart city. Specifically, we explore different perspectives on ITS and relate them to the SDGs to answer the following question:

Which Sustainable Development Goals, targets, and indicators are relevant for assessing the sustainability of intelligent transport systems?

To answer this question, we review the relevant literature and combine it with international agreements and resolutions to derive a framework for assessing the effectiveness of ITS strategies on sustainability. Further, we demonstrate the practical use of this framework by assessing three exemplary German ITS projects. This paper is structured as follows. First, we define the term intelligent transport systems and set it into the context of smart cities and sustainability. We then develop our framework based on the literature, demonstrate its use, and describe the implications for further research and practice.

With our research, we contribute to the research fields of sustainable smart cities and mobility while also providing practical implications for sustainable ITS. Through our findings, we aim to inspire municipal decision-makers and technical leaders to consider sustainability factors to build data-driven solutions that have a positive impact on society and nature. In fact, we are currently facing this specific challenge in a project for data-driven traffic management funded by the German Federal Ministry for Digital and

Transport[1]. Hence, we want to share our approach to support other cities considering or planning ITS projects.

2 Theoretical Background

2.1 Smart Cities and Smart Mobility

With the trend of urbanization and population growth, cities become increasingly populated while space and resources are limited. Urban areas will face challenges in meeting the needs of their growing populations in many sectors, such as housing, transportation, energy systems, education, and healthcare. These challenges lead to the need for sustainable development [11]. The concept of smart cities has been evolving in the last decade. It aims to enhance quality of life in urban areas by using the opportunities of information and communication technologies (ICT), hardware, algorithms, and data to create a positive impact on life in cities [24].

Smart cities are characterized by the six areas *smart economy, smart people, smart governance, smart environment, smart living,* and *smart mobility,* which are all interlinked [13]. Smart mobility is an especially relevant building block of smart cities. The improvement of mobility with technical advances can save resources, increase efficiency, and provide accessibility [9]. More specifically, smart mobility is defined as "a set of coordinated actions addressed at improving the efficiency, the effectiveness and the environmental sustainability in cities," which is characterized by transport and the use of information and communication technology [2]. It further consists of local accessibility, (inter-)national accessibility, availability of ICT infrastructure, and sustainable, innovative and safe transport systems [13]. Smart mobility has direct implications for fulfilling the Sustainable Development Goals defined by the UN and will contribute to the future of city planning and logistics [25]. However, research still shows gaps regarding the consideration of potential sustainability factors that directly affect citizens, e.g., air quality [31]. The field of smart mobility therefore holds significant potential for future research aimed at creating more sustainable cities.

2.2 Smart Traffic Management and Intelligent Transport Systems

Various terms are employed to denote the technical applications, data-driven services, and conceptual advances for data-driven traffic management. The most frequently used terms are intelligent transport systems, smart traffic management, transport/travel demand management, and smart mobility management. Though not completely congruent, these terms are used interchangeably and exhibit a high semantic overlap. In this paper, we consistently use the term intelligent transport systems (ITS) since it has been researched for more than two decades [1] and is used by the UN and European Parliament [8].

[1] This research is in part funded by the German Federal Ministry for Digital and Transport in the context of the "VLUID" project, an Abbreviation for the German term "traffic management solutions for complex reconstruction scenarios based on intelligent data analysis".

ITS are defined as all technical solutions and construction concepts related to traffic [10]. The UN Economic Commission for Europe (UNECE) further describes them as "a set of procedures, systems and devices that enable (a) improvements in the mobility of people and transportation of passengers and goods, through the collection, communication, processing and distribution of information and (b) the acquisition of feedback on experience and a quantification of the results gathered" [32]. The European Parliament defines ITS in a slightly more generalized manner as communication systems that provide services related to different modes of transport and traffic management. These systems support a safer, more coordinated, and smarter use of transport networks for users [8]. All definitions, however, share the common goal of technology-based and data-driven traffic management, aiming to improve mobility. ITS further consist of various tools based on information and communication technology and support the concept of smart mobility [19]. Examples for specific applications are traffic light control systems or analytical tools that influence transport management.

In addition to various definitions, several perspectives on ITS focus on different means and needs. In Fig. 1, we summarize four of the most prominent perspectives and definitions. In the following, we describe them in more detail for a broad understanding of the concept.

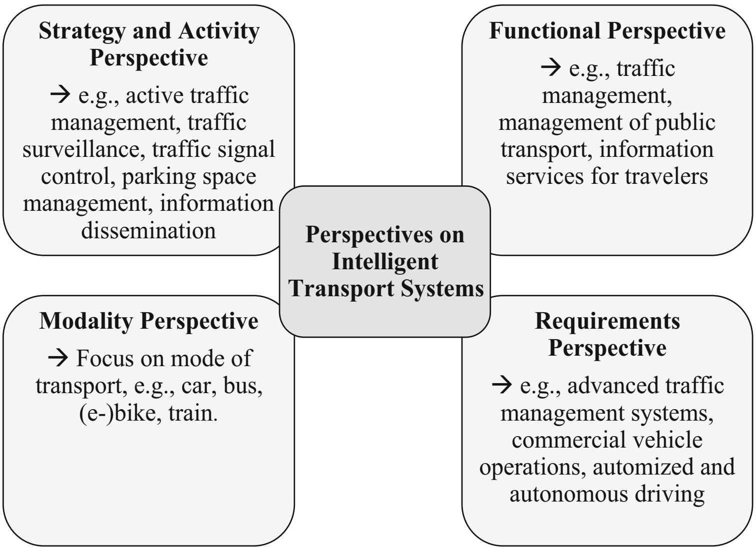

Fig. 1. Perspectives on intelligent transport systems, own illustration derived from [6, 10, 14, 19, 32].

The strategy and activity perspective on ITS [6, 14] is defined by the US Department of Transportation and provides the broadest and most granular perspective. It is focused on ITS strategies and details them in activities. Depending on the publication, 16 to 26 related activities are defined. The strategies and sample activities are:

- Traffic management and operations (e.g., traffic surveillance, traffic signal control, speed and intersection warning systems, and bicycle and pedestrian crossing enhancements),
- Road weather management operations (e.g., road weather information systems, winter roadway operations),
- Maintenance and construction management (e.g., coordination activities for construction management, work zone management),
- Incident and energy management (e.g., emergency management, emergency vehicle routing), and
- Public transportation management (e.g., electronic fare collection and integration, multimodal travel connections, transit surveillance).

The functional perspective [19] on ITS describes functions of ITS, such as management or information provision, consisting of:

- Traffic management,
- Management of public transport,
- Management of cargo transport and fleet of vehicles,
- Traffic safety management and monitoring systems for violation of regulations,
- Management of road incidents and emergency services,
- Information services for travelers and electronic payment services, and
- Electronic systems for collecting tolls for road use.

Some of these functions also overlap with the activities from the strategy and activity perspective, indicating the lack of a clear separation of the different perspectives. According to this definition, ITS operation is particularly focused on information collection from different systems, processing of this information, and the provision of related recommendations.

The requirements perspective [10] focuses on requirements profiles, and specific technical systems. Again, there are overlaps to both the strategic and functional perspectives. The related systems are:

- Advanced Traffic Management (ATMS),
- Advanced Traveler Information (ATIS),
- Advanced Vehicle Control (AVCS),
- Commercial Vehicle Operations (CVO),
- Advanced Public Transportation (APTS),
- Rural Transportation (ARTS),
- Automized and Autonomous Driving,
- Intelligent Traffic Data (Smart Traffic), and
- Vehicle Networks (Connected Vehicles).

These systems have a direct impact on activities such as emergency management, information management, and innovation management.

While the previous perspectives provide a more generic view, ITS can also be categorized according to the modes of transport they address. That leads to the modality perspective [10], comprising:

- (Motor) car traffic,

- Public transport (bus, train, city train, subway),
- (e-)Bike,
- Motorcycle,
- Plane, or
- Vessel.

The modal split is especially important in relation to sustainable solutions. However, unlike the previous ones, this perspective does not present activities or strategies. In summary, every perspective provides a slightly different view on ITS, with a common focus on more efficient, safe, and sustainable intelligent traffic management and consideration of the modal split.

2.3 Sustainability and the SDGs

Sustainability is a broad concept that is not easily defined, yet it is becoming an increasingly important research field. Previous research has found that researchers use four key concepts of sustainability:

1) a set of social and ecological criteria that guide human action,
2) a vision which is realized through a particular (social and ecological) reference system,
3) an object, thing or phenomenon that happens in certain social-ecological systems, and
4) an approach to include social and ecological variables in an activity, process, or human product [28].

All four concepts align in the social and ecological aspects in the definition of sustainability. In the context of software engineering, sustainability it can be defined as the "creation and upkeep of software systems in a way that is ethical and morally righteous, commercially viable, and technologically practicable" [15]. This includes effects on the environment, society, and economy. Other researchers have constructed sustainability with 16 variables that contribute to the four components of ecological, economic, socio-cultural, and political sustainability in the context of enterprises [35].

In the process of formulating a broad but also specific definition of sustainability, the Sustainable Development Goals provide more general guidance. In 2015 the UN formally acknowledged the need for transformative change towards sustainability and defined 17 sustainable development goals (SDGs). The resulting resolution defines sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" by considering environmental concerns, social aspects, and economic development [11]. According to this definition, sustainability encourages growth and technological progress by focusing on people's needs while also ensuring that choices in the present do not exhaust resources needed in the future. All 17 goals are interdependent, and they are defined by a total of 169 targets. The progress for achieving these targets can be tracked by 231 unique indicators (ibid). The goals are set to be achieved by 2030 and have universal relevance, as they have been aligned between all 191 UN member nations and thus represent a collective understanding of sustainability.

Current research further highlights the complex relationship between ICT and sustainability while showing that it is important to measure the impacts of ICT on sustainability. Especially challenging in this context is the alignment between the concepts of digitalization, ICT, digital sustainability, and digital transformation [16]. In general, previous research has found a positive association between ICT use and sustainable development, defined as contributing to social, economic, and environmental aspects. However, such research focused on the country-level sustainability impacts and not on how individual ICT can contribute to sustainability, especially in cities [17].

Many of the SDGs build an important foundation for the progress towards smart mobility. The application of traffic-related technology and smart services in cities reflects the original idea of smart mobility. However, smart mobility also calls for a balance of technology with the needs of citizens that are reflected by the sustainability factors [29]. Recent research shows that there is a high potential for analyzing the contribution of smart cities to achieve sustainable development [30]. Some researchers even go as far as to point out that cities cannot become smart without being sustainable, making sustainability an important factor in smart city projects [33]. Further, researchers have covered ICT adoption for sustainable development in the industry context, highlighting the link between ICT and sustainability [36]. In contrast, while sustainability is considered an important aspect, researchers have found that it does not (yet) influence ICT infrastructure decision making in companies [26]. However, sustainability is especially important in smart city projects due to the global challenges in urban development. More specifically, smart cities a) usually aim to integrate technology to improve the quality of life and reduce the impact of urbanism on the environment [30] and b) are usually funded by state funds and are hence linked with a responsibility towards citizens as taxpayers and stakeholders. As pointed out, smart mobility especially has the potential to improve sustainability in cities.

In summary, the presented literature shows that sustainability is important for smart mobility in smart cities. While there are many perspectives on sustainability, the Sustainable Development Goals provide a broad view while being aligned between the countries of the UN. Therefore, we aim to provide a framework of the important SDGs that relate to ITS in order to assess related projects and support decision-making in smart mobility initiatives.

3 Research Methodology

3.1 Method Overview

In the previous section, we showed the need for ITS that are not only smart but also sustainable. However, to our knowledge, no frameworks exist to help researchers and decision-makers assess whether and how smart traffic management measures contribute to sustainability. Therefore, we dedicate this research to analyzing the various perspectives on ITS and bringing them into the context of the SDGs. To answer our research question, we combine the Sustainable Development Goals, their targets, and related indicators in a framework that shows the sustainability factors ITS can influence. Based on the relevant literature on sustainability, smart mobility, and ITS, we conduct conceptual development in our study. Besides scientific literature, we also include international agreements and recommendations regarding development for several reasons: First, UN resolutions can be seen as universally relevant because 191 states from the world community have committed to their achievement. Recommendations by the UNECE are similarly relevant and, while not legally binding, provide a more detailed view than the resolutions. While other conceptualizations of sustainability are discussed in the literature section of this article, the SDGs provide the most detailed view, encompassing various social, economic, political, and ecological perspectives. Second, we aim to ground our framework on existing work while developing a new concept through the combination of several perspectives. An exploration of the literature can provide different views and serve as a foundation for developing a unified understanding. Third, combining scientific literature with international agreements allows for both rigorous and relevant contributions. The detailed process of the framework development is described in the following section.

3.2 Framework Development

In the following, we detail the process of our framework development and explain how we combined the SDGs with perspectives from ITS, filtered and refined them across different stages, and finally brought them together for a central view. Figure 2 summarizes this process and shows how both strands are first considered individually and then merged into the final framework.

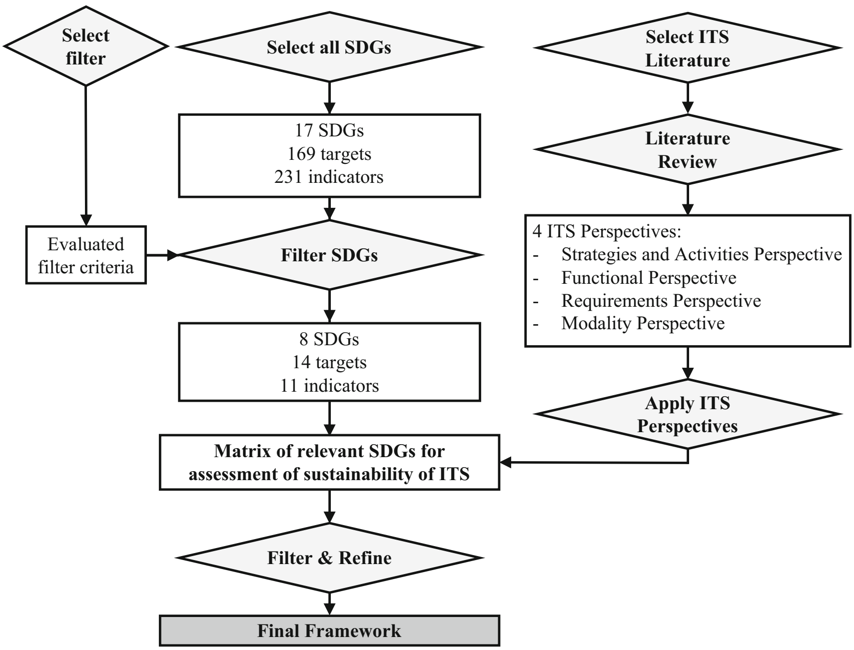

Fig. 2. Method of Framework Development (Own Illustration)

3.3 Determination of Relevant Sustainable Development Goals

To determine the relevant SDGs for our framework and their relation to ITS, we searched for key terms in the resolutions A/RES/70/1 as the original 2030 Agenda for Sustainable Development and A/RES/71/313, which additionally contains the later-adopted indicators to the goals [11, 12]. We began with all 17 goals, 169 targets, and 231 indicators (248 indicators including duplicates) and filtered them according to the terms in Table 1. We determined the terms according to the perspectives of ITS described in the previous section and used collective terms, e.g., "transport," for all related terms. We added terms that focus on cities since we used them as the application context of our study. Additionally, we added the pollution perspective as a result of traffic and as one goal of ITS. The detailed rationale behind the terms can also be found in Table 1.

The resulting set contained eight goals, 16 targets, and 16 indicators. We then eliminated two further targets and five indicators. First, we ruled out target 14.1 because it is related to marine pollution, which falls outside the scope of our framework that focuses on traffic on land. We also excluded two indicators that contained the term "urban" as a description for the measurement process and therefore did not apply in terms of content (indicators 1.1.1., 4.5.1, 11.6.1). Finally, we also excluded goal 12.c and indicator 12.c.1 because they are related to subsidies that are not decided on the level of municipalities and therefore not in the scope of ITS in the context of smart cities. Afterward, we added the superordinated targets or goals related to targets or indicators since they would not apply to the search terms. Hence, we did not add indicators to related targets when they did not apply to the criteria, leaving some indicators blank. From these constraints, we derived eight goals, 14 targets, and 11 indicators that we applied to different perspectives on ITS.

Table 1. Filter Terms for Sustainable Development Goals, Targets, and Indicators

Term	Rationale
"traffic", "transport"	Direct relation to the traffic component of ITS
"air", "pollution", "air pollution", "greenhouse gas", "emission(s)"	Direct relation to the consequences of (motorized) traffic and traffic density as well as the goal of ITS to mitigate the effects on the environment with data-driven systems and technology
"urbanization", "urban", "urban planning", "city", "cities"	Application context of a (smart) city
"fuel", "fossil fuel"	Resources for motorized traffic, which is the dominant form of traffic in cities
"car", "bike", "bicycle", "public transport", "train", "pedestrian", "walk(ing)"	Relation to modes of transport on land that are part of ITS

3.4 Perspectives of Intelligent Transport Systems

After the preselection of relevant SDGs, we determined the relevant ITS dimensions. As presented in the literature review, multiple perspectives of ITS overlap and align in some parts but still provide different views and concepts. In general, we opted for the UNECE definition, which contains the aspects of improvements in the mobility of people, transportation of passengers and goods, and the collection, communication, processing, and distribution of information. Additionally, the definition includes the acquisition of feedback on experience and quantification of the gathered results. Based on this definition, we aimed to equally consider all four perspectives on ITS derived from the literature and presented in Fig. 1. We decided against choosing only one of the perspectives in order to include SDGs that are relevant but do not relate to all perspectives. By using several perspectives, we further aim for more transparency, a broader view, and stability in the evaluation to assess the SDGs for developing our final framework.

3.5 Combination of SDGs and ITS

After filtering the relevant SDGs and determining the ITS perspectives, we combined both dimensions in a matrix. By doing this, we analyzed how the measure of each of the ITS perspectives could contribute to sustainability targets and indicators. We distinguished the impact in direct contributions to a target or indicator and indirect contributions to indicate a lower relevance. After analyzing each relation, we summarized the findings in a central framework and determined whether ITS primarily or secondarily impacts a target or indicator.

4 Research Findings

4.1 Final Framework

From the analysis performed, we were able to determine six main sustainability indicators and eight targets that relate to a total of six Sustainable Development Goals and are primarily influenced by ITS. The remaining five indicators and five targets can be influenced by ITS but probably with lower intensity. Therefore, they were marked as indirectly influenced. The final framework is displayed in Tables 2 and 3.

While SDG 11, "Sustainable Cities and Communities," is the most represented goal in the framework with the highest number of related targets and indicators, the other goals are equally relevant. Our framework also highlights goals that do not relate directly to traffic, like SDG 7, "Affordable and Clean Energy," or SDG 6, "Clean Water and Sanitation" but still might have an impact on the SDGs. In general, the framework does not prioritize or weight certain SDGs.

Our framework provides an overall view of the most important SDGs as a recommendation for researchers and practitioners to consider when developing intelligent transport systems. It further emphasizes that there is not only one perspective on sustainability and that ITS solutions could target sustainability in multiple areas. Some measures might also contribute to multiple SDGs at the same time, e.g., targeting indicator 9.4.1, "CO2 emission per unit of value added," might also have a positive impact on indicator 13.2.2, "Total greenhouse gas emissions per year," due to the general reduction of emissions.

Table 2. Final Assessment Framework: Primary impact of ITS on relevant SD goals, targets, and indicators

SDG	SDG Target/Indicator
Goal 3: Good Health and Well-Being	3.6 Halve the number of global deaths and injuries from road traffic accidents 3.6.1 Death rate due to road traffic injuries 3.9 Substantially reduce the number of deaths and illnesses from hazardous chemicals and pollution and contamination 3.9.1 Mortality rate attributed to household and ambient air pollution
Goal 6: Clean Water and Sanitation	6.3 Improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials
Goal 7: Affordable and Clean Energy	7.1 Ensure universal access to affordable, reliable, and modern energy services 7.1.2 Proportion of population with primary reliance on clean fuels and technology
Goal 9: Industry, Innovation and Infrastructure	9.4 Upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes 9.4.1 CO2 emission per unit of value added
Goal 11: Sustainable Cities and Communities	11.2 Provide access to safe, affordable, accessible, and sustainable transport systems for all, improving road safety, notably by expanding public transport 11.2.1 Proportion of population that has convenient access to public transport, by sex, age, and persons with disabilities 11.6 Reduce the adverse per capita environmental impact of cities; special attention to air quality 11.6.2 Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted) 11.b Increase the number of cities/settlements adopting and implementing policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement (…) holistic disaster risk management at all levels
Goal 12: Responsible Consumption and Production	12.4 Environmentally sound management of chemicals and all wastes and reduce their release to air, water, and soil

4.2 Using the Framework

Researchers and practitioners can use our framework to reflect upon projects and initiatives related to intelligent transport systems and sustainability. While it might not be

Table 3. Final Assessment Framework: Secondary impact of ITS on relevant SD goals, targets, and indicators

SDG	SDG Target/Indicator
Goal 11: Sustainable Cities and Communities	11.3 Enhance inclusive and sustainable urbanization and capacity for participatory, integrated, and sustainable human settlement planning and management 11.3.2 Proportion of cities with a direct participation structure of civil society in urban planning and management 11.7 Provide universal access to safe, inclusive, and accessible green and public spaces 11.7.1 Average share of the built-up area of cities that is open space for public use for all, by sex, age, and persons with disabilities 11.a Support positive economic, social and environmental links between urban, peri-urban, and rural areas by strengthening development planning 11.a1 Number of countries that have national urban policies or regional development plans that respond to population dynamics and ensure balanced territorial development
Goal 13: Climate Action	13.2 Integrate climate change measures into national policies, strategies, and planning 13.2.2 Total greenhouse gas emissions per year
Goal 16: Peace, Justice, and Strong Institutions	16.1 Significantly reduce all forms of violence and related death rates everywhere 16.1.4 Proportion of population that feel safe walking alone around the area they live after dark

possible to consider every factor equally, the framework serves as a starting point to create awareness of sustainability targets and indicators in the context of ITS.

Derived from one of our current ITS projects in cooperation with the German city of Wetzlar, Fig. 3 shows the different phases in which our framework can be used to assess the contribution of ITS projects to sustainability. We recommend using it as a checklist to determine whether at least one of the goals, targets, or indicators is addressed with the planned initiative. The framework is best used in the planning phase of new ITS projects to determine possible sustainability goals, targets, and indicators that might play a role in the related projects. Nevertheless, practitioners can also use the framework along the project to assess whether the individual solution approaches still fit the SDGs or to conduct a final evaluation that compares the contribution in relation to the initial strategy. Throughout initiatives, the framework can help in make the general assessment of the contribution to the sustainability of software solutions more transparent and provide a more complete view at different stages.

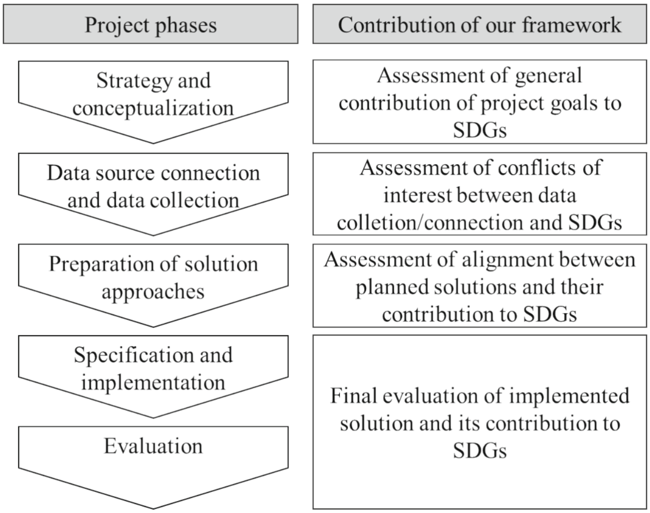

Fig. 3. Use of the framework in different project phases (Own Illustration)

To demonstrate the use of our framework, we chose three exemplary projects to assess their contribution to sustainability. All three projects are part of the "Emmett" network, which connects projects funded by the German Federal Ministry for Digital and Transport. We decided on this platform as a source for exemplary projects since the author's project is also associated with this funding and initiative. All three projects are already completed and were listed in the category of "sustainable" projects by the Emmett network. In the following, we will briefly discuss the projects "PAMIR," "SAUBER," and "ECOSense," which all differ in their target goal as well as in their contributions to sustainability, demonstrating the need for a broad framework (Table 4). We explicitly do not evaluate or rate the projects but rather show a qualitative representation of our framework.

The PAMIR project installed a system for reserving parking spots in advance at selected park-and-ride car parks to improve the planning of multimodal travel routes and promote the use of public transport as part of such a route [37]. Although the project is listed as "contributing to sustainability" on the related project page, there is no description or explanation included as to how it does this. Applying the project description and closing report to our framework, we concluded that it contributes to SDG 11.2 by providing safe and accessible access to (sustainable) transport systems, e.g. public transport like trains. Additionally, it aligns with 11.2.1 by facilitating easier route planning, thereby increasing the population with access to such options. Further, the project indirectly contributes to SDGs 11.6 and 13.2.2 by promoting the use of public transport and eventually reducing the environmental impact of individual transport in cities. In sum, the project contributes to several sustainability goals, targets, and indicators and can hence be considered as being sustainable.

The second exemplary project is SAUBER which targets pollution in cities by collecting current environmental data and using artificial intelligence to predict future air quality [38]. By doing this, the project aims to identify polluted areas early to mitigate or even prevent negative environmental impacts. This project clearly contributes to SDGs 3.9 and 3.9.1 by mitigating pollution and its effects on health and well-being. It further contributes to indicator 13.2.2 by aiming to reduce emissions in highly polluted areas. It also could indirectly contribute to targets 6.3 and 12.4, depending on the links between the pollution evaluated and its links to clean water and production.

Table 4. Exemplary application of the framework

Project	Relation to SDG Target/Indicator	Contribution to SDG Target/Indicator
PAMIR	11.2 Provide access to safe, affordable, accessible, and sustainable transport systems for all, improving road safety, notably by expanding public transport 11.2.1 Proportion of population that has convenient access to public transport, by sex, age, and persons with disabilities 11.6 Reduce the adverse per capita environmental impact of cities; special attention to air quality 13.2.2 Total greenhouse gas emissions per year	The solution provides safe and accessible access to public transport for more citizens The solution promotes and supports the use of public transport and makes it more convenient, therefore helping to reduce total emissions
SAUBER	3.9 Substantially reduce number of deaths and illnesses from hazardous chemicals and pollution and contamination 3.9.1 Mortality rate attributed to household and ambient air pollution 13.2.2 Total greenhouse gas emissions per year 6.3 Improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials 12.4 Environmentally sound management of chemicals and all wastes and reduce their release to air, water, and soil	The solution mitigates pollution in general and predicts future air quality to prevent highly polluted areas
ECOSense	3.6 Halve the number of global deaths and injuries from road traffic accidents 3.6.1 Death rate due to road traffic injuries 11.2 Provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport	The solution helps to identify and mitigate potential threats on bike roads The solution promotes and supports more sustainable mode of transport

The third project ECOSense aimed to develop and evaluate a platform to collect data on bicycle usage [39]. Through the collection and analysis of cyclists' data, they wanted to help city planners to gain a better understanding of the needs of cyclists, thereby enabling more effective planning of the bicycle infrastructure within cities. Such data includes information on infrastructure, road safety and the environment. This project contributes to SDGs 3.6 and 3.6.1 by identifying potential threats for cyclists, helping cities make their roads safer. It further indirectly contributes to SDG 11.2 by improving road safety and promoting a sustainable mode of transport. Summarizing those three examples, we can say that sustainable ITS solutions could contribute to multiple SDGs.

5 Discussion of Findings

Our framework targets the gap between the development of ITS applications and concerns regarding sustainability. While sustainability is a broadly defined term, we narrowed it down in the literature review and specified it further in the development process of our evaluation framework. Furthermore, while there are already guidelines on how to measure the achievement of SDGs on a global level (e.g., per country), there are no guidelines for measuring them on an individual level. With our final framework, we were able to answer our research question: Which Sustainable Development Goals, targets, and indicators are relevant for assessing the sustainability of intelligent transport systems?

The specific contributions to sustainability can still vary between initiatives which makes a broad and more general framework like ours a necessity. For now, we decided against weighting individual SDGs because of this span and variety between contributions. However, we advocate for the requirement that initiatives, which claim to contribute to sustainability must specify precisely how their projects contribute to SDGs. Of course, initiatives can never fully fit all sustainability criteria, but projects and ITS solutions should at least contribute to one of the SDGs if they claim to be sustainable. This would foster transparency and communicate the contributions of such projects more clearly. Since many ITS projects are funded by public funds, they further have a responsibility to consider sustainability factors. Governments are funded by taxpayers, who are citizens of cities and therefore central stakeholders of such projects.

This framework can serve as a starting point for assessments of sustainability and certainly allows for extension. One aspect will be to prioritize contributions to sustainability and expand the framework to an instrument for decision-making.

6 Conclusion

In this paper, we described the need for more sustainable actions in the mobility sector and pointed out that previous ITS projects and research seemed to lack the consideration of sustainability factors. We further argued that municipalities have a particular responsibility towards sustainability, given their role as decision-makers for their citizens, who, eventually, should benefit from ITS solutions. We developed a framework that considers both different ITS perspectives and sustainability factors. This framework determined which Sustainable Development Goals, targets, and indicators are relevant for assessing the sustainability of intelligent transport systems, and it should be considered when developing ITS strategies. We further showed how our framework can be used to assess the sustainability impact along different project phases and assessed three exemplary German ITS projects.

In summary, our research contributes to the research fields of sustainable smart cities and smart mobility in the practical context of sustainable ITS. For practitioners, we provide an easy-to-use framework that can be adjusted to individual needs. We further showed the practical use of the framework as a blueprint for further assessments. With this, we aim to enable decision-makers to assess the sustainability impact of individual ITS projects or measures. This research employs an interdisciplinary approach, combining technical considerations and sustainability aspects while identifying avenues for further investigation. We advocate considering the impacts of sustainability in future ICT research.

While we aimed for a broad and deep analysis in the creation of our framework, we would like to address some limitations in the approach and implications for future work.

First, one challenge of a literature review is including both relevant and novel literature as well as considering established "basic" literature. Despite our diligence in the selection process, we cannot claim to have a complete overview. Further, we recognize that other researchers might choose different publications. Additionally, the selection of the four perspectives on ITS might be influenced by subjective perception. As discussed in the literature review, there are many different terms for and perspectives on ITS. One reason might be the interdisciplinary character of ITS, where different perspectives from traffic engineering, traffic planning, business administration, and information systems intersect. We see the potential for future work in attempting to find one definition of ITS that includes all perspectives, thereby fostering a common transdisciplinary understanding.

Second, the inclusion and exclusion criteria of the relevant Sustainable Development Goals were chosen with the application context in mind but are nevertheless subjective and offer room for discussion. Using various search terms could produce diverse result sets and potentially influence the composition of the final matrix. Further, there might be additional SDGs that do not have a direct relation to ITS but might still be considered when developing such systems. For example, SDG target 16.7 calls for ensuring responsive, inclusive, participatory, and representative decision-making at all levels. From a more social perspective, inclusive decision-making in choosing and developing ITS measures, e.g., by including citizens, could also contribute to this target. While we do not consider the development process of the applications or social factors in our analysis, our framework is easily adjustable and could include these factors in the future or be enhanced for projects with special emphasis on these dimensions.

Third, we recognize that the assessment of each SDG in relation to ITS might be subjective. We conducted the assessment to the best of our knowledge and based it on the descriptions of each SDG, target, and goal. However, other researchers might have rated the criteria differently. In future work, the rating could be enhanced with more expertise by including more researchers.

Fourth, our framework shows the criteria for assessing ITS from a qualitative perspective but does not provide quantitative measurement criteria. The UN does provide some implications for measurement in its definition of indicators. However, they are on a rather high level and need to be adjusted to and detailed for the specific context. Therefore, we suggest a follow-up study on developing a specific measurement for assessing ITS quantitatively. A central index that incorporates and balances all indicators would facilitate comparability between projects and measures. Furthermore, we aim to combine the results from this framework with our previously developed instrument to evaluate data-driven traffic management applications [21]. In this work, we included criteria to evaluate sustainability, e.g., on an environmental level. By combining both approaches we aim to develop a more robust and extensive evaluation instrument.

To summarize, our framework can support decision-makers in municipalities by providing an approach to assess their selected or planned ITS initiatives regarding sustainability factors. This could help policymakers, planners, and citizens make more conscious decisions towards a higher quality of living in cities and contribute to the economy, society, and nature at the same time. Hence, we call for municipal traffic management that is not only smart but also sustainable to contribute to a livable future.

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