

Developing Goals and Indicators for the Design of Sustainable and Integrated Transport Infrastructure and Urban Spaces

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Abstract: This paper aims to provide a framework for policy-makers and transportation and urban design professionals to evaluate alternative urban plans and infrastructure design, allowing them to select a set of locally relevant indicators to help assess scenarios considering sustainable development and overall system performance improvement in line with specific project goals. Using methods of systematic review, content analysis, multi-criteria analysis, and expert consultation, a three-level goal system is proposed, leading to the generation of 64 Key Performance Indicators (KPIs), both qualitative and quantitative, and an indicator set of 227 items. To allow stakeholders to apply their own set of indicators, the approaches and tools of measuring these indicators as well as the ways of using this indicator set are presented to assist decision-makers in evaluating and choosing optimal plans and designs.

Keywords: transport system; urban spaces; sustainable design; evaluation; indicator system

1. Introduction

The set of United Nations (UN) Sustainable Development Goals (SDG), particularly SDG Goal 11 to “make cities inclusive, safe, resilient and sustainable”, provide structure and objectives for a more sustainable future for all, anywhere on the planet [1]. To link these overarching goals to local decision-making processes, clear, project-oriented goals and operational objectives are needed. Guidelines or frameworks allow decision-makers to develop their own goals in specific socio-economic contexts and under certain project requirements. In transport and urban planning discourses, goals and evaluation are also paramount steps in the decision-making process. For example, in order to make a rational decision on an urban plan, it is necessary to accurately and systematically describe the urban system under study, to assess the advantages and disadvantages of the proposals, and to estimate system changes over time as a result of their implementation [2].

In the urban transport sector, transportation infrastructure has been constructed without serious consideration of the potential negative impact on cities’ public spaces, its users, and the environment during the past decades [3]. For instance, railways divide the surrounding urban fabric into fractured, inaccessible, and unfriendly areas, which has a negative impact on individual daily commutes, quality of life, and the natural environment. Studies on sustainable and integrated design of transport infrastructure and urban spaces, which prioritise the needs of people, ecology, and better places over mobility enhancement, have attracted widespread interest [4,5]. Yang et al. [6] stated that transport, spaces, and humans interact with each other and form an integral system that is interplaying with its

surrounding policy and the natural environment. Based on a state-of-the-art review, they highlighted the need for a systematic and thorough “evaluation of integrated transport–spaces–humans plans”. The selection of relevant indicators to help with this evaluation is, in the end, the responsibility of the key problem owner, and it is essential that the selected indicators are selected through a structured and transparent process.

Of note is that the issue of transportation and urban spaces integration has been studied at different scales and by scholars from diverse disciplines (see Figure 1). At the macrospatial level, transport and urban planners commonly approach the urban spaces system through the prism of urban spatial structures and urban forms, where land-use planning is a powerful tool [7–9]. At the microspatial scale, urban designers and architects explore the integrated design of transport infrastructure lines, stations, and public spaces that directly impacts citizens and users [10–12]. While the evaluation of the integrated plans in the macro-level scope has been extensively explored [8,13], this research focuses on the assessment of the integrated designs at the micro level, i.e., the interface between transport and public spaces where denizens interact. Because the quality of high-level urban area planning will determine the design condition of low-level public spaces, and in return, microscale environments can give insights for the macroscale strategic planning, evaluation of the macroscale spaces (e.g., land uses) should be taken into account when identifying microscale indicators [12]. In this case, this paper considers urban spaces at both scales to maintain consistency of goals and evaluation criteria.

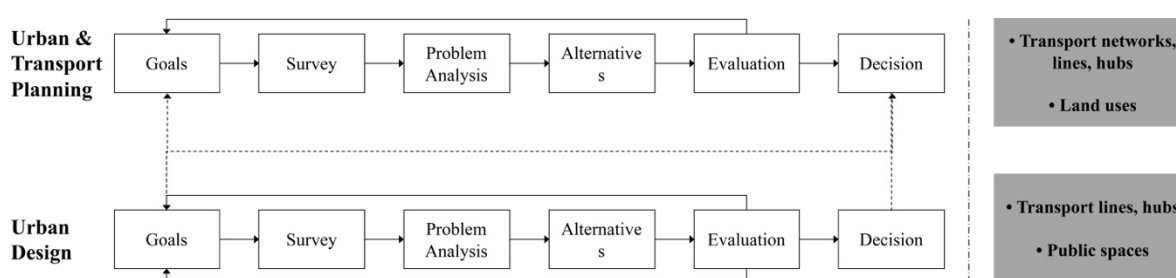


Figure 1. Different stages of transport and urban planning and urban design. The words in grey boxes explain the meanings of the transport system and the urban spaces system at macro and micro scales. Adapted partly based on [14], p. 19.

A transport system in the context of this paper refers to the land transport system in cities, including rail and road transport. The former could be categorised into intra-city rail transit (e.g., railways) and inner-city rail transit (e.g., tramways), while the latter includes roads and highways. In general, urban spaces can be classified into private, semi-public, and public spaces according to their ownerships. Following the definition given by Lévy [15], a public spaces system, in this study, denotes the urban areas that are socially owned and accessible for all, including streets, open spaces, and public amenities. Finally, the humans system in this research implies the behaviour of humans, including active travel (e.g., walking, cycling), recreational activity, social interactions, and behaviour regarding choice of travel mode.

Despite the growing awareness of building integrated transport–spaces–humans plans and the numerous investigations on transport and urban planning evaluation, more work is needed to provide interdisciplinary support for evaluating the performance of such integrated plans considering sustainability goals. Assessment of the baseline and the planned system performances in line with their sustainability benefits are of paramount significance to support rational decision-making as well as public consultations and building support for new plans. To this end, we first ask the following questions, motivated by the Jing-Zhang high-speed rail project in Beijing, which is currently in the stage of evaluating and implementing the masterplan. The government needs an appropriate framework to support decision-making. Discussions with several key stakeholders and local experts (see Acknowledgements) have shaped these questions:

- Q-1: What kinds of goals and objectives should be set up for integrated transport–spaces design?
- Q-2: Which Key Performance Indicators (KPIs) should be used for evaluation?

- Q-3: What kind of indicator system is capable of supporting scientific and interdisciplinary evaluation?

To answer these questions, this paper aims to first provide a benchmark for generating goals in different projects and then to propose an indicator set for evaluating the performance and sustainability of integrated transport infrastructure and urban spaces design. Such a transparent goal system is beneficial in interdisciplinary (or even transdisciplinary) transportation research where professionals, decision-makers, and the public are involved in developing the goals and strategies collectively [16]. The indicators presented here are not specific for any particular case study, but this paper provides a framework of indicators that can be relevant for any individual project, though the specifics will have to be aligned based on local individual circumstances. The authors attempt to promote progress in addressing transportation and urban spaces system sustainability in research, practice, and education. Such decision frameworks are directly applicable to project managers, but the overview presented in this paper could also be applied by educators to provide students with example indicators to be considered in their coursework or student projects, or to evaluate real-world example scenarios from a systems perspective.

The paper is organized as follows. In Section 2, we first build on the literature, reviewing relevant literature in urban planning and design evaluation and indicators selection. Next, Section 3 refines the research questions this paper attempts to address, proposes an overall framework for indicator set development, and details the approaches used in a systematic literature review. Section 4 presents the results of a goal system, a set of KPIs and a preliminary longlist of indicators, and the final indicator set, subsequently. Section 5 discusses the ways of applying such an indicator set and the appropriate methods of evaluating the qualitative and quantitative indicators outlined in the collection. Finally, the paper is concluded in Section 6, reflecting on how these indicators can be used to support decision-making.

2. Literature Review

To build upon the literature, we reviewed five parts of previous research: (1) goals set up for integrated transport infrastructure projects, (2) evaluation in urban planning, (3) transport and urban spaces systems assessment, (4) criteria of indicators selection, and (5) methods used in generating an indicator set.

2.1. Goals of Integration in Transportation Infrastructure Projects

Saidi et al. [17] divided the goals of infrastructure system integration into four levels: (1) high-level integration within an individual subsystem, (2) detailed-level integration within a specific subsystem, (3) high-level integration between multiple subsystems, and (4) detailed-level integration between various subsystems. For transportation infrastructure, Heeres et al. [18] proposed an instrumental matrix of integration, categorising a set of solution spaces (i.e., “the conceptual space in which possible solutions might be found” [19]) of integration. From a functional and spatial perspective, they identified three degrees of integration, including:

- No integration: Infrastructure projects are planned separately without coordination with urban spaces planning.
- Sector-internal integration: A multi-modal transport network is embedded in the transportation infrastructure that connects different urban areas.
- External integration: The focus is extended from merely improving the connectivity of the transportation system to integrating with other related urban systems, especially the integrated design of public spaces, natural systems, human behaviour, and land use. At the same time, the integrated design of this type of project is not only at the strategic level but also at the implementation and operation level.

These degrees can be used to accurately describe which (sub)systems need to be taken into account in the analysis.

2.2. Evaluation in Planning and Urban Design

In planning and urban design discourses, several evaluation paradigms have developed gradually to support the decision-making. Since the 1970s, scientific, systematic, and objective aspects have been emphasised in urban planning, the evaluation was aiming at “best plans” selection, and the cost-benefit analysis was widely used. In the following decades, social, environmental, and economic aspects of urban planning have gained increasing concern. Researchers and practitioners started using a series of tests to choose the solution that best meets the requirements outlined by project goals and evaluation criteria and using evaluation questions to judge the success of planning (for a review see [20]). Chadwick [2] demonstrated that evaluation and the formulation of goals and objectives are interdependent and interactive procedures in systematic planning. Assessment tasks include assessing project goals, baseline system performance, different plan scenarios, planned system performance, the impact of multiple policies, and the final decision.

In ex-ante and ongoing evaluations, “conformance-based” and “performance-based” views are adopted [20]. The former focuses on whether the implementation plan is consistent with the project’s proposals and goals; the latter expands assessment scope to the overall benefits to the city (e.g., sustainability), following the recognition of planning as a continuous decision-making process under uncertainty [8,21]. In such, performance-based evaluation, considering the emergence of complex changes in cities, holds promise for sustainable planning. Similarly, in the urban design field, conventional urban design uses morphological and aesthetic quality as the evaluation criteria. In contrast, contemporary urban design adopts multi-dimensional impact assessments to appraise design quality [22]. Among numerous assessment approaches, Environmental Impact Assessment (EIA) [23,24] and sustainability assessment [25–27] are of growing interests. Sustainability assessment that includes not only physical environment evaluation but also socio-economic-environmental evaluation is also called the third generation of impact assessment [28].

2.3. Assessment of Transportation and Urban Spaces Systems

In the transport sector, Arcdis [29] investigated mobility through the three pillars of sustainability and used 23 indicators for their sustainable cities mobility index. Based on 16 indicator initiatives developed in Europe, North America, and Oceania, Jeon et al. [30] summarized the frameworks and indicators for a transport sustainability assessment, arguing that system effectiveness, efficiency, and environmental impacts are fundamental metrics. Taking into account both sustainability assessment and economic returns, [31,32] presented an overview and an evaluation approach of the transport system evaluation. In the urban spaces sector, Yu et al. [33] appraised urban spatial development through a sustainability evaluation system.

Apart from the research on evaluating transport and spaces systems separately, numerous studies examined the mechanism of Land Use and Transport Integration (LUTI) as well as the prediction of their reciprocal impacts [7,9]. Methods of surveys, empirical studies, and mathematical and computational models have been widely used. One of the most influential works is the “transport land use feedback loop” initially proposed by Wegner [13] and adapted by Bertolini [8], which summarizes the relationship between land use, activities, transport systems, and accessibility. In [8,34], the necessity of educating students and professionals in integrated transport–land-use thinking and integrated modelling skills was emphasized. After critically reviewing all LUTI models, Acheampong [35] pointed out that the environmental impact considerations are still very limited in existing LUTI models. To this end, Yigitcanlar and Dur [36] developed a holistic Sustainable Infrastructure Land-use Environment and Transport Model (SILENT) that captures the interaction between demography, transport, land use and urban form, and the environment, with a spatial resolution of 100 × 100 m. Another example is the Wellington Integrated Land Use–Transport–Environment Model (WILUTE) which takes into account metrics of transport-related energy consumption and pollutants, public health benefits, the adaptive capacity to sea-level rise, and first-round socio-economic outcomes [37].

2.4. Indicator Types and Selection Criteria

To assist the aforementioned measurements and planning decisions, indicators are extensively used. They can be defined as statistical data that evaluate certain aspects of a particular research phenomenon and are a method for measuring abstract concepts [38]. Indicators can be divided into qualitative and quantitative components. The former is used to assess objective attributes, while the latter uses numerical values to measure the characteristics of objects. Typically, these two indicator types are adopted complementarily in the construction of an indicator system, which experiences a transition from a single indicator to a multi-dimensional and multi-scalar system. More specifically, to evaluate urban system performance, Key Performance Indicators (KPIs) (or performance indicators) are a powerful tool and of significance in sustainable planning [39].

The decision of indicators should follow a series of criteria. Coombes et al. [40] argued indicators need to (1) be supported by data, (2) have spatial meanings, (3) be operable, (4) be transformable and interpretable, and (5) consider time continuity and dynamic. Garau and Pavan [41] stated that indicators should feature (1) objectivity, i.e., be clear, easy to understand, and accurate; (2) relevance, measurability, and repeatability; (3) validity, i.e., can be verified, with high data quality; (4) representativeness; (5) comparability, i.e., are comparable at different space and time conditions; and (6) availability, i.e., data are easy to obtain. Also, the time and human resources required to evaluate the indicators should be considered to make the use of the indicators feasible and manageable. Under this prism, indicators should be as few as possible, though critical factors cannot be omitted [42].

2.5. Methods and Procedures of Indicator Set Generation

There are two fundamental ways to establish an indicator system: Delphi and Multi-Criteria Analysis (MCA). The Delphi method is based on experts' knowledge, experience, intuition, reasoning, preferences, values, application following steps of an expert panel formation, asking questions, experts commenting, feedback collection, judgment, and synthesis [43]. MCA, which is capable of taking account of multiple different criteria when constructing an evaluation system, is more objective, systematic, and time- and human resource-efficient in comparison with Delphi. The goals-achievement matrix is a significant multi-criteria decision method [44,45]. In doing this, researchers first define a set of goals, and then break them down into objectives and sub-objectives constantly until they can be measured by quantitative or qualitative indicators, after which an indicator set is formed. In general, goals refer to the long-term, high-level targets pursued by urban development, which may not be achievable at this stage due to certain conditions. Objectives are short-term, low-level steps for goal attainment, which are specific, measurable, achievable, realistic, and time bound. To support the development of indicator sets for the transport sector, Sdoukopoulos et al. [46] summarised a general iterative method, while Castillo and Pitfield [47] presented an Evaluative and Logical Approach to Sustainable Transport Indicator Compilation (ELASTIC) framework consisting of six procedures. In [41], a seven-step method grounded in MCA for measuring the overall sustainability of cities was proposed.

After reviewing the previous work, we found that the majority of the works simply collects a set of indicators, while the connection between the goals for transport and urban spaces planning projects and the indicator sets requires clarification. Furthermore, though some indicator sets introduce themes or categories for structuring indicators, the choice of these themes is problematic due to a lack of systematic underpinning. The sustainability assessment falls either in the transport sector and public spaces sector separately, or in the transport–land use interaction, while the interface of transport infrastructure–public spaces and the human users in this context still falls short.

3. Methodology

To address the research questions, the novelty of this paper lies in defining a system of benchmark goals and objectives, outlining a series of evidence-based themes and KPIs, and developing a systemic indicator set, which is classified and mapped corresponding to the goal system. The proposed indicator set can then help track progress in achieving the overall sustainability

goals of an integrated transport–spaces design. In spite of attempting to capture all the sustainability pillars (i.e., social, economic, and environmental) of the transport–spaces system, this paper focuses on the environmental aspect, that is, on environmental impact assessment.

3.1. A Three-Step Framework

This research applies the MCA method to generate a set of indicators. By synthesising and narrowing down the several steps presented in [41,46,47], we utilize a three-step framework to guide our research (see Figure 2) as follows:

- (1) A goal system construction: identifying goals and objectives.
- (2) Theme and KPI identification: first, conducting a systematic literature review; second, extracting themes by keyword and content analysis; and third, analysing and synthesising the findings, leading to KPI elicitation.
- (3) Indicator set development: first, forming a longlist of indicators based on the systematic review; second, shortlisting indicators in light of certain criteria; third, subdividing the indicators when necessary and describing, explaining, and standardising each indicator; fourth, consulting 10 experts in transport and urban planning about a draft of the indicator set; and last, finalising the overall indicator set.

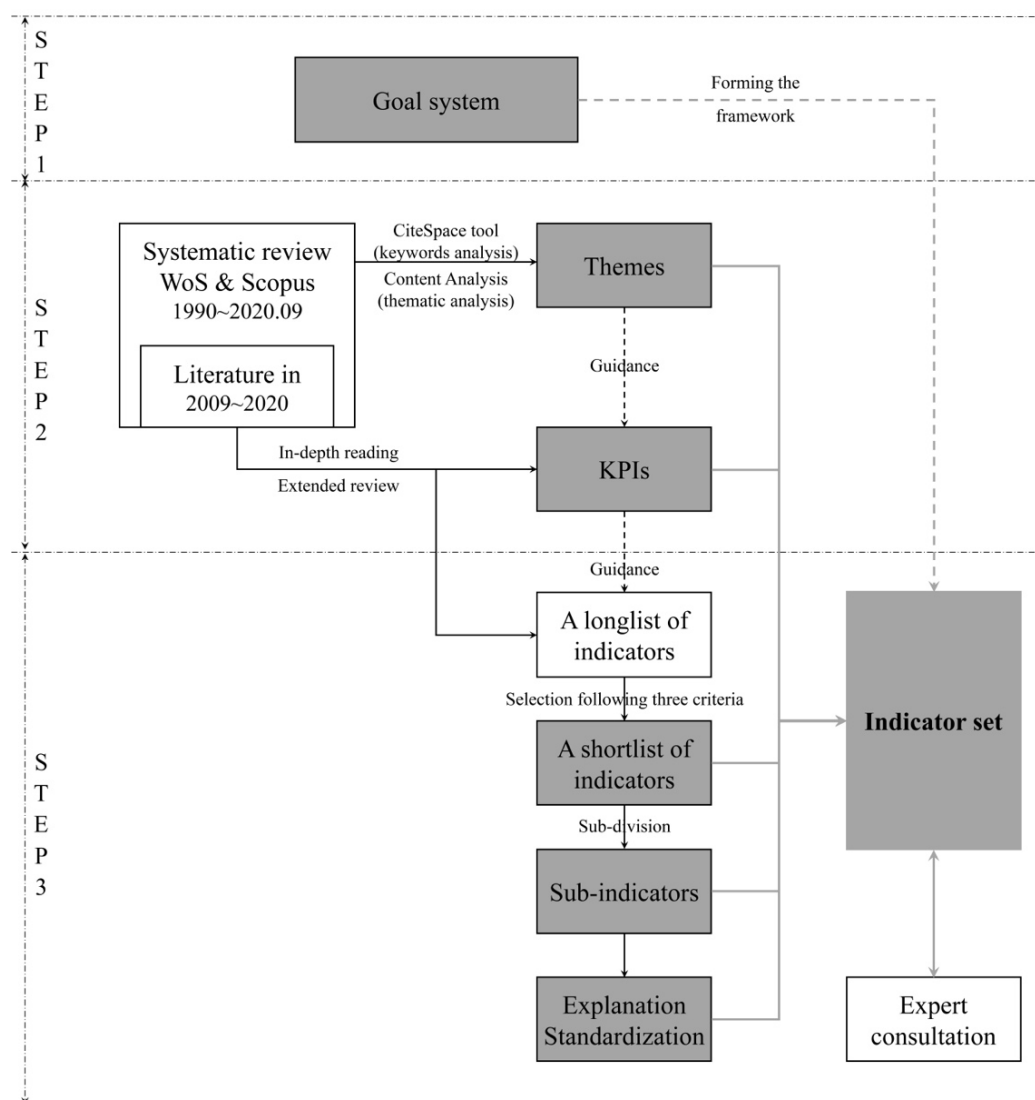


Figure 2. The three-step methodology used in this research.

3.2. A Systematic Literature Review

The approach and process adopted in this literature review are inspired by [31,48]. Initially, to select accurate themes, KPIs, and a longlist of indicators for evaluating transportation infrastructure and public spaces systems, we conducted a database search on Web of Science (WoS, Core Collection) and Scopus for all years (until 30 September, 2020). They complement each other and archive the academic literature from a broad range of disciplines by connecting different databases, thus providing references from across the spectrum of expertise related to transport and planning (and other related disciplines) for the selected keywords [49]. The first set of search words used for exploring transport infrastructure assessment research was (Transport* Infrastructure AND Evaluation AND Indicator), and the second set used for investigating public spaces appraisal studies was ((“Public Space” OR “Urban Space”) AND Evaluation AND Indicator). In the first set, “transport*” was used to retrieve words of transport and transportation, which are always interchangeable. In the second set, both “public space” and “urban space” were contained to engage alternative terms and different spatial scales of the transport–spaces plan. These terms were used to search the field of Topic in Web of Science and applied to the fields of Article title, Abstract, and Keywords when searching in Scopus. As a result, Web of Science returned 249 (transport evaluation) and 357 (spaces evaluation) sources of literature and Scopus returned 333 (transport evaluation) and 98 (spaces evaluation) results. After removing the duplicates, the result was 435 (transport evaluation) and 424 (spaces evaluation) records.

In order to extract themes from these publications, the CiteSpace technique and content analysis were applied. CiteSpace is a literature analytical tool to visualise trends and patterns in the literature, such as about the growth of specific fields over time and their geographic spread, and is particularly powerful for conducting computerised analysis of keywords [50]. This study used CiteSpace to investigate keywords appearing in the study of transportation infrastructure assessment and public (and urban) spaces assessment. Content analysis is a useful research method for the objective and systematic investigation of documents, especially for coding the texts in accordance with certain subjects and themes [51].

Furthermore, literature published in 2009–2020 (more than 90% of the indexed literature found was from this period) was reviewed thoroughly to first determine KPIs. After an overview of their titles and abstracts, 57 relevant documents were selected for in-depth reading. In addition to these sources, we reviewed the references they cited and the references in which they were mentioned to reach literature not captured from the Web of Science and Scopus keyword searches but that is influential in the topics of sustainability assessment, liveability assessment, public space quality evaluation, and community severance. This extended review led to a total of 27 books and journal articles. After selecting the KPIs, we sorted and synthesised the indicators reported in these documents, leading to a longlist of indicators. The longlist was then screened based on three criteria, which resulted in a shortlist of indicators:

- Relevance to the theme: Indicators for assessing the quality of underground urban spaces and the impacts of surrounding areas (e.g., building facades) on public spaces are not considered in this research. Although the longlist involves all sustainable indicators, i.e., social, economic, and environmental factors, this article focuses on the natural environment aspect, so only indicators relevant to the environment are retained.
- Integration of similar indicators: To assure the independence between indicators and avoid duplication and overlap, related items are merged into a single indicator where possible.
- Necessary evaluation items inclusion: Elements in the analysed system are not independent, so the impact on other aspects needs to be taken into account. The evaluation of public spaces systems takes account of the factors of adjacent transportation structures. For example, when public space is surrounded by elevated railways, the shadowing effect of the latter should be considered.

4. Results

This section describes the outcomes of the process described above, first presenting the goal system, then the longlist of KPIs, and finally the selected indicator system for integrated and sustainable transportation infrastructure and urban spaces design.

4.1. Goal System for Evaluating Transport and Spaces Systems

4.1.1. Hierarchy of the Goal System

In line with [17,18], an integrated transportation infrastructure system should achieve both sector-internal integration and external integration with other sectors. Furthermore, according to complex systems theory, system integration aims to coordinate not only the interrelationships among internal elements of a subsystem but also the relation between the subsystems and with the external environment. In such, the human-made transport–spaces system needs to be coordinated with human and ecological systems. In this regard, we present a multi-level solution space to assess the integration degree of a status quo system or a designed system, as illustrated in Figure 3:

- Integration of the subsystems (the transport system and the spaces system) considering human behaviour;
- Integration between two subsystems (transport–spaces–humans system) themselves;
- Integration between the transport–spaces–humans system and the (external) natural environment system considering social and economic impacts.

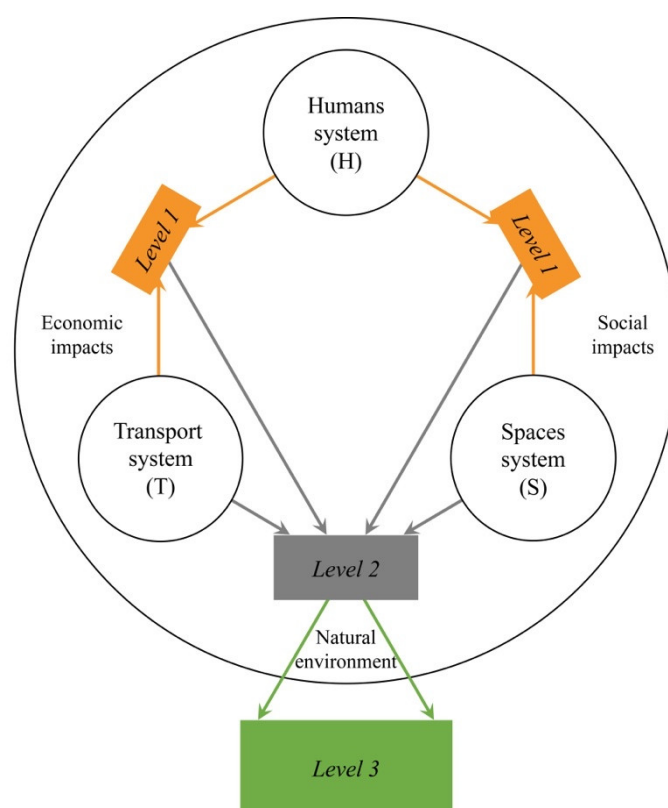


Figure 3. Illustration of a goal system.

4.1.2. Goals

Following this multi-level solution space, the overall goals of transportation and urban area planning projects can be defined. From a long-term perspective, the integration of transport and spaces needs to meet basic human needs and external ecosystem needs, achieve a balance between liveability and mobility, follow the principles of sustainable development, and contribute to building eco-, healthy, and intelligent cities. Therefore, goals consist of three levels:

- Level 1: Interdependence between the elements of the transportation infrastructure system and the urban spaces system are coordinated to achieve a synergy. In parallel, basic human needs are fulfilled through short, medium, and long-term people-oriented infrastructure development.
- Level 2: Mutual reciprocity between transportation systems and urban spaces systems is generated at elemental, spatial, and regional scales. Needs for mobility and liveability are balanced while people's healthy behaviour is promoted [5,52].
- Level 3: Reciprocity between the transport-spaces system and the external environment is obtained. Material, energy, and information exchanges between transport-spaces systems and ecosystems (as well as social and economic systems) are optimised while satisfying both human and ecological needs in pursuit of overall sustainability.

4.1.3. Objectives

Based on these high-level goals, three groups of objectives are derived. Note that for realistic transportation infrastructure (re)development projects, the formulation of objectives should also recognise and balance the project constraints, which are external conditions and typical features of a site that restrain the planning and construction process. For instance, time constraints, budget, local policies, social issues and customs, cultural backgrounds, and available land are significant factors (a full list of project constraints can be found in [53]).

- Level 1: Synergy between internal elements of the transport system and the urban spaces systems are created to meet the human needs of mobility and liveability.

To satisfy mobility demands, it is necessary to (1) configure connected and accessible transportation networks and nodes for each transport mode, (2) build an efficient connection between different transport modes, and (3) make public transport and active travel the dominant transport modes. To satisfy liveability demands, the design of transportation and spaces systems should accomplish objectives of: (1) a sense of place, (2) mixed-use, (3) density, (4) design for the use of the vulnerable population, (5) high environmental quality, (6) green infrastructure provision, (7) safety, and (8) public health [54].

- Level 2: Mutual reciprocity between transport and spaces systems is developed, with mobility and liveability needs balanced and healthy behaviour stimulated.

In an attempt to achieve integration of transport infrastructures and affiliated urban spaces, the two systems should be designed holistically from visual, spatial, functional, and psychological perspectives. To balance the two human needs, the accessibility and connectivity of active transport networks should be increased in the transport system; the quality and continuity of public spaces ought to be enhanced in the spaces system.

- Level 3: Reciprocity between the transport-spaces system and the external environment is stimulated, leading to an improvement of overall sustainability in cities.

In this respect, sustainable planning and design strategies are needed. Sustainable transport infrastructure planning should avoid, reduce, and compensate for the negative impacts of infrastructure construction on individuals, communities, and ecosystems [55]. Sustainable urban spaces design should provide a healthy environment for residents by adjusting the factors of solar, wind, air quality, temperature, rain, sound, and noise [56]. Furthermore, the construction, maintenance, and abolishment of transportation and public spaces infrastructure should adopt the "circular economy" concept, that is, reducing the usage, improving the reuse, and enhancing the recycling of raw materials [57]. Other considerations include the promotion of economic efficiency, public health, social justice, cultural heritage protection, and social satisfaction.

4.2. Descriptive Data Analysis

4.2.1. Temporal Dimension

Research on “transport evaluation indicator” and “public (OR urban) spaces evaluation indicator” recorded on Web of Science and Scopus mostly appeared after the year of 2000, with only one and four publications before 2000 in transport and spaces domains, respectively. Figure 4 presents the results found in the new millennium.

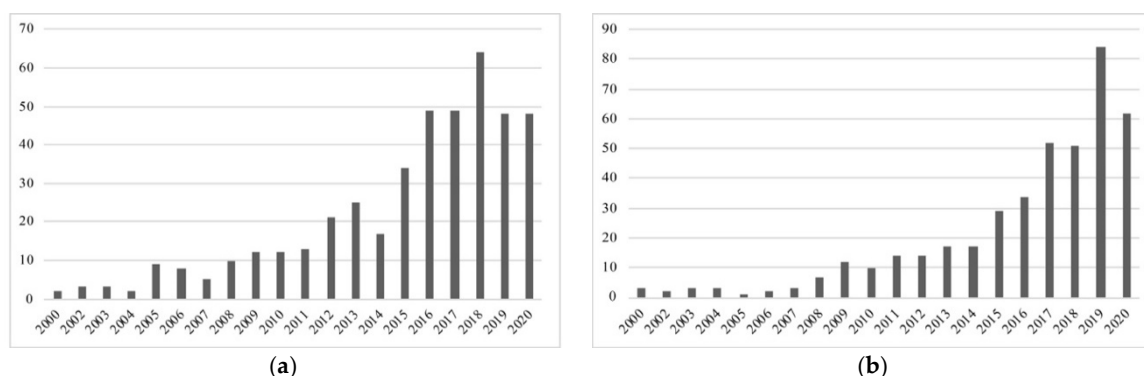


Figure 4. Search records from Web of Science and Scopus databases on the topics of (a) transport evaluation indicators and (b) public (OR urban) spaces evaluation indicators. Period: 2000–2020 (September).

As shown in Figure 4a, the number of papers relating to transport evaluation research was simply two in the year 2000 but peaked at 64 in the year 2018. More than 87% of publications were after 2010 and in the last five years more than 48 papers were published annually. From Figure 4b it can be found that interest in the research topic of urban and spaces assessment has increased remarkably; in the year 2019 alone, 84 papers were recorded.

By comparing the number of publications on both topics in different time periods, Figure 5 indicates that evaluation indicator studies in the transport sector burgeoned earlier than those in the urban spaces sector, but that the latter have gained much more attention since 2016. More specifically, research in the topic of transportation evaluation saw a remarkable increase after 2005 and the research on urban/public spaces appraisal started to attract increasing attention three years later, as illustrated in Figure 4. Similarly, both threads of studies were documented mainly in the last five years, with 59.3% of transport assessment literature and 66.8% of urban spaces appraisal literature occurred in this period.

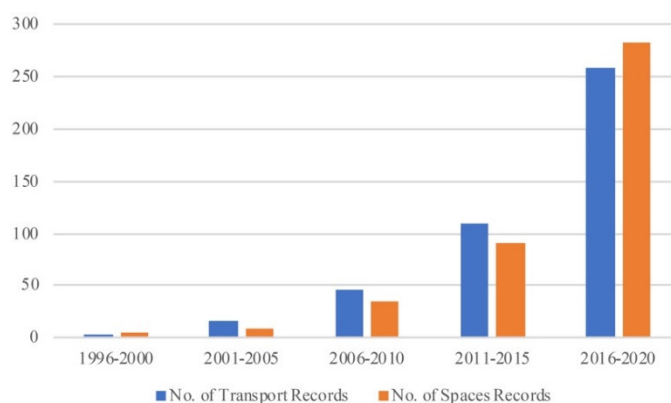


Figure 5. Search records from the Web of Science and Scopus databases on the topics of transport evaluation indicators and public (OR urban) spaces evaluation indicators in different time periods from 2000 to 2020 (September).

4.2.2. Geographic Dimension

The geographical distribution of all articles (the address of all authors) is explored, as presented on the maps in Figures 6–9.

Papers that investigated the evaluation indicators of the transport system were predominantly authored by European researchers (73.4%), as shown in Figure 6, followed by Asian (28.0%) and North American scholars (13.7%). In Europe, the top five productive countries were Italy, Spain, Lithuania, Russia, France, and the United Kingdom of Great Britain and Northern Ireland (UK). The Asian countries of China and India and the American countries of the United States of America (USA), Canada, and Brazil paid the most attention to transport sector assessment. Australia and South Africa led the research in Oceania and African countries. Globally, as depicted in Figure 7, following China (14.1% of the total), the USA (8.1%), Italy (10.6%), Spain (5.7%), and Lithuania (5.5%) published the most literature on transport system evaluation.

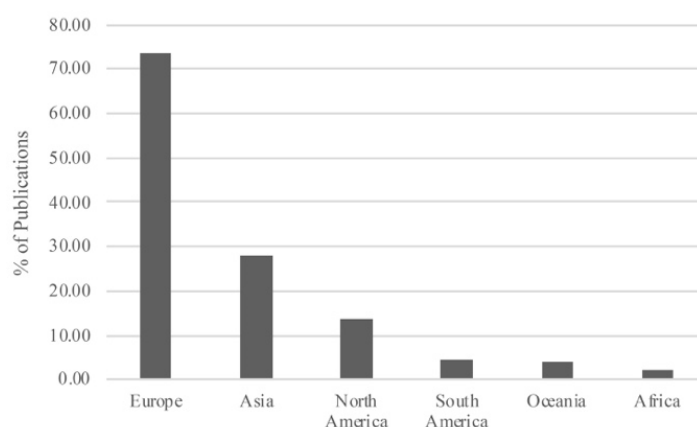


Figure 6. Geographical distribution of research on the topic of transport evaluation indicators (metadata extracted from the address of authors from the records returned from the Web of Science and Scopus databases. Period: 2000–2020 (September)). The number represents the percent of documents published by each continent.

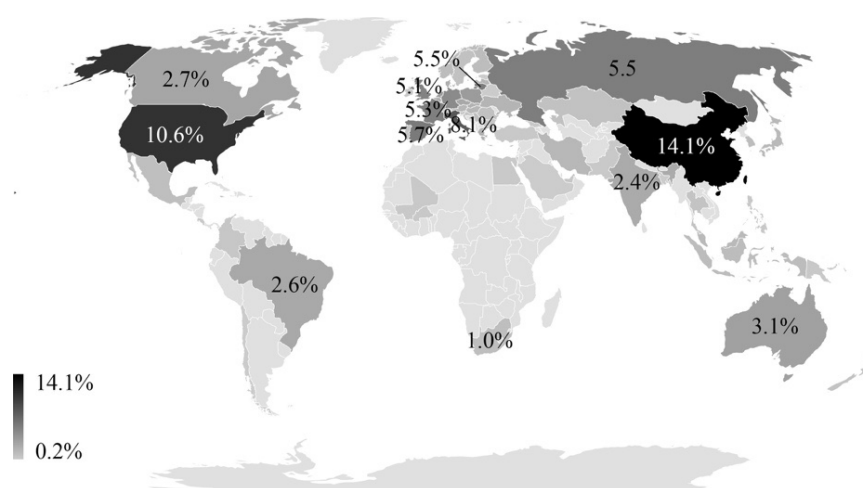


Figure 7. Geographical distribution of research on the topic of transport evaluation indicators (metadata extracted from the address of authors of the records returned from the Web of Science and Scopus databases. Period: 2000–2020 (September)). The number represents the percent of documents published by each country.

Research on evaluation indicators of the public/urban spaces system was mostly reported by European and Asian authors, with 56.5% and 43.7% of the total records, respectively (see Figure 8). Italy, the UK, Spain, Germany, and Russia were the most productive European countries, while China,

Iran, Turkey, Japan, and South Korea were the most fruitful in Asia. The USA and Brazil produced many more papers than other American countries. On the continents of Oceania and Africa, Australia and South Africa were the main research bodies. Figure 9 maps the dominant countries in examining the indicators for urban and public spaces systems. Among others, China (28.3%), Italy (8.9%), Spain (6.5%), the USA (6.3%), and Brazil (5.7%) rank in the top five.

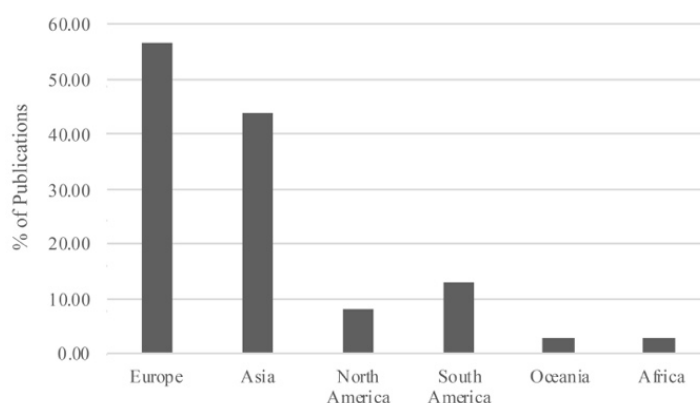


Figure 8. Geographical distribution of research on the topic of public (OR urban) spaces evaluation indicators (metadata extracted from the address of authors from the records returned from the Web of Science and Scopus databases. Period: 2000–2020 (September)). The number represents the percent of documents published by each continent.

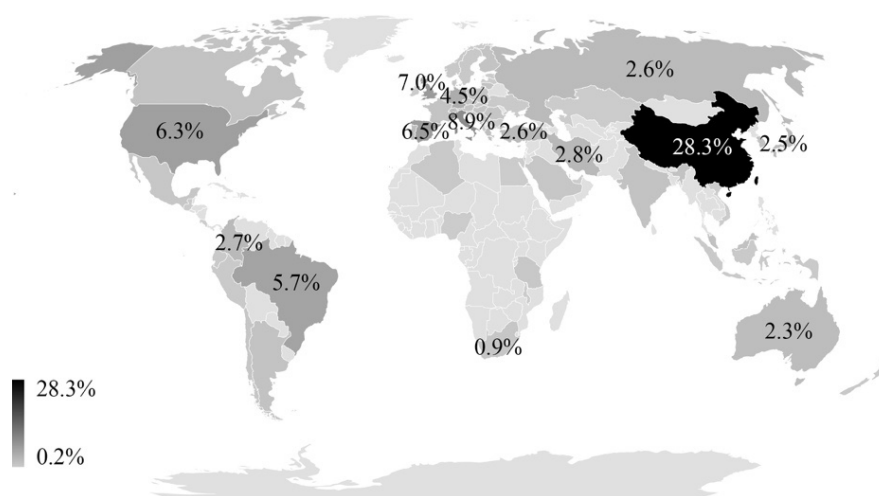


Figure 9. Geographical distribution of research on the topic of public (OR urban) spaces evaluation indicators (metadata extracted from the address of authors from the records returned from the Web of Science and Scopus databases. Period: 2000–2020 (September)). The number represents the percent of documents published by each country.

4.3. KPI Selection and Indicator Longlisting

4.3.1. Keywords and Thematic Data Analysis

In this work, the frequency of keywords in the study of transport infrastructure and public spaces assessment were analysed and are presented as word clouds in Figures 10a and 11a. These figures also indicate the centrality of each word. Node centrality is a graphical property that quantifies the significance of a point's position in a network, which is usually measured by the betweenness centrality metric. The betweenness centrality of each node is determined by calculating the proportion of total numbers of the shortest paths in a network linking to the node [58]. To further investigate the most common terms used for transport and spaces system evaluation, Figures 10b

and 11b were generated. Here, we excluded any combination of the words used in search strings, i.e., “transport, transportation, infrastructure, evaluation, indicator”, which occur repeatedly but are not helpful for extracting themes.

It is evident from Figure 10 that the word “sustainability” dominates, appearing 35 times in the publications. “Sustainable development”, “investment”, “decision making”, “public transport”, “accessibility”, “roads and street”, “model”, “transportation planning”, “economics”, “transportation system”, “railroad transportation”, “urban transportation”, “impact”, “railroad”, “cost”, and “green infrastructure” (GI) were utilised frequently (no less than 15 times) in research on transport infrastructure evaluation indicators. In the study on public and urban spaces evaluation indicators (visualised in Figure 11), the terms “city”, “urban planning”, “sustainability”, “sustainable development”, “health”, “impact”, “land use”, “quality”, “ecosystem service”, “green infrastructure” (GI), and “accessibility” each appeared no less than 15 times. This list of keywords is a reference standard for deciding on KPIs. By comparing the two threads of research, we also found that “sustainability (sustainable development)”, “accessibility”, “impact”, and “green infrastructure” are common words utilised in studies of transport and urban spaces evaluation.

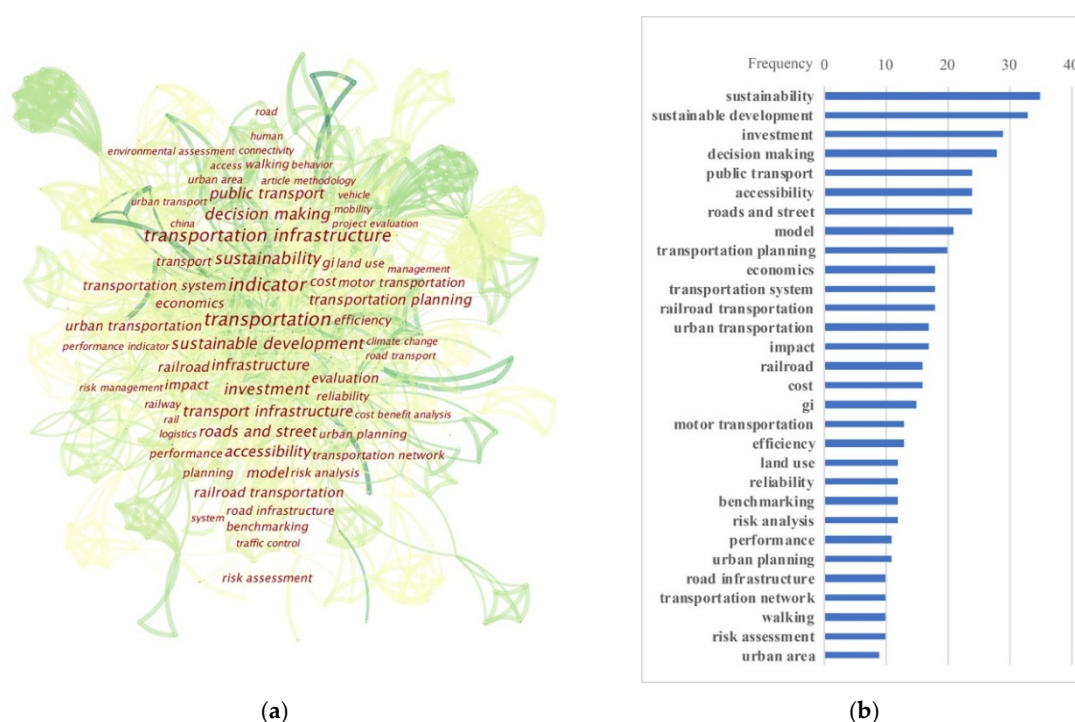


Figure 10. Frequency analysis of keywords used in research on transport infrastructure evaluation indicators: (a) The bigger the words, the higher the frequency, only showing those occurring more than seven times and (b) the 30 most common words, excluding any combination of the terms in search strings.

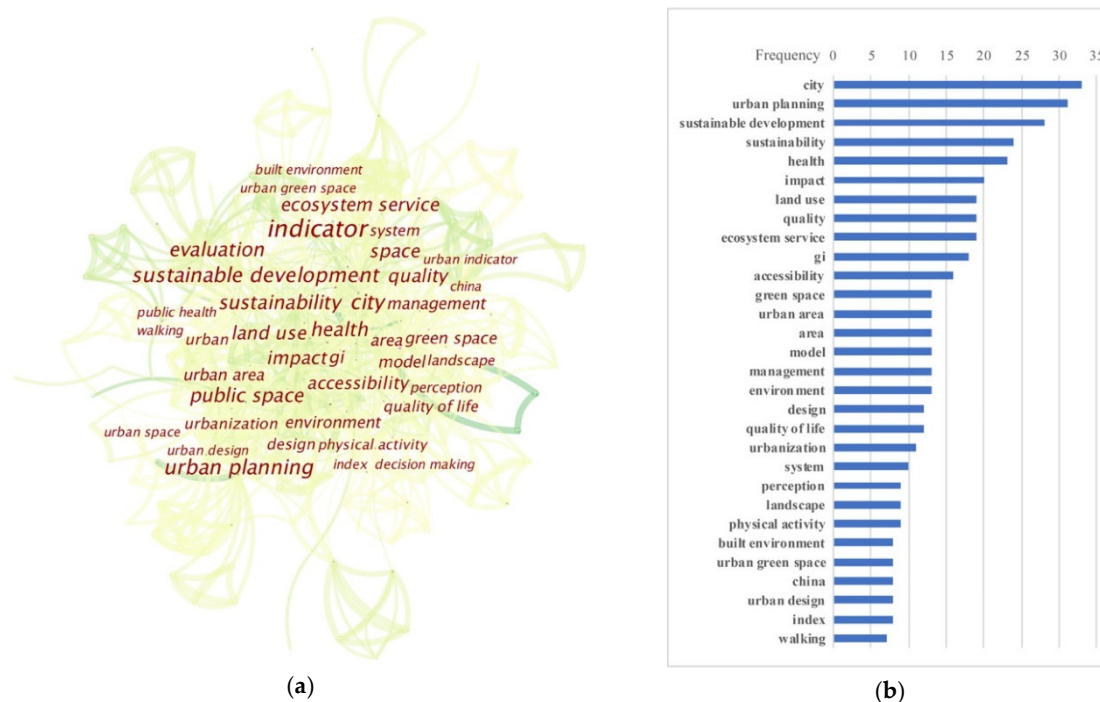


Figure 11. Frequency analysis of keywords used in research on public/urban spaces evaluation indicators: (a) The bigger the words, the higher the frequency, only showing those occurring more than seven times and (b) the 30 most common words, excluding any combination of the terms in search strings.

Taking into account the list of keywords and the results of the literature content analysis, we chose 22 themes for transportation system evaluation and 15 topics for spaces system evaluation.

4.3.2. KPIs and Longlisting Indicators Synthesis

After performing an in-depth review of the documents published since 2009 and an expanded review of influential literature, we completed a meta-analysis, with the results summarised in Table S1 provided in the Supplementary Materials. In consideration of the themes extracted from the previous step, we selected 64 KPIs for assessing transport and spaces systems. Afterwards, a longlist of 124 indicators was chosen for transportation system evaluation, while 113 longlist indicators were decided for spaces system evaluation. Following the goal system of transport–spaces development, the findings were classified into six types:

- (1) Transportation and spaces systems self-performance considering human behaviour;
- (2) Transportation and spaces systems performance related to the counterpart system, i.e., where there is a direct interaction between the two systems;
- (3) Complementary environmental impacts of the two systems;
- (4) Other natural environmental impacts of transportation and spaces systems;
- (5) Social impacts; and
- (6) Economic impacts.

Figure 12 and Table 1 frame the selected themes and KPIs according to the goal system. Note, however, that the selection and addition of KPIs in realistic projects need to be adjusted regarding certain conditions.

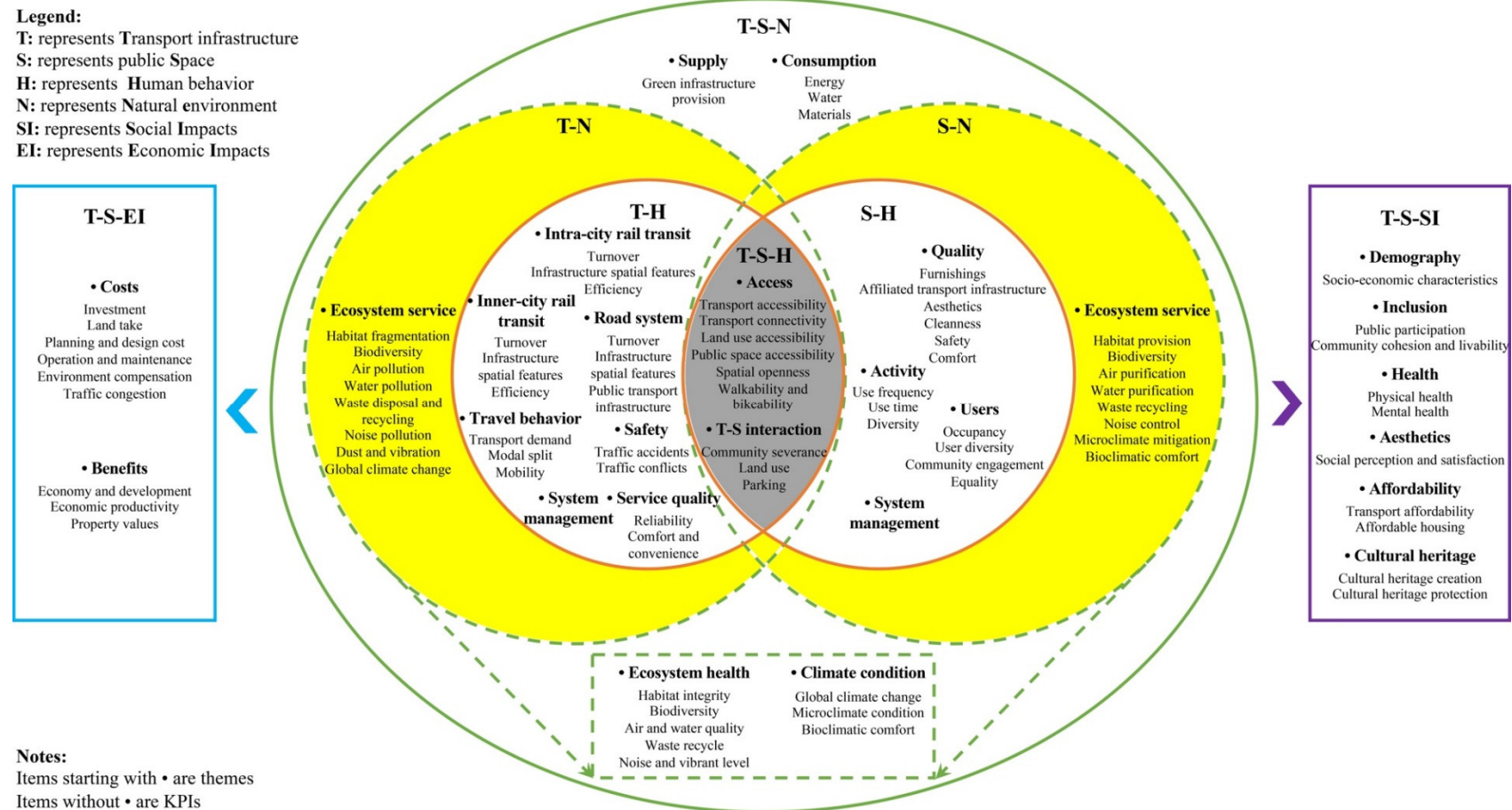


Figure 12. Themes and Key Performance Indicators (KPIs) used in evaluating the transport infrastructure and urban spaces systems.

Table 1. The 64 Key Performance Indicators (KPIs) of the transport–spaces system.

Hierarchy of the Goal System			Key Performance Indicators (KPIs)	
Level 1	Level 2	Level 3		
Transport system performance considering human behaviour		(1) Intra-city rail transit: turnover, infrastructure spatial features, efficiency	(4) Transport demand	
		(2) Inner-city rail transit: turnover, infrastructure spatial features, efficiency	(5) Modal split	
		(3) Road system: turnover, infrastructure spatial features, public transport infrastructure	(6) Mobility	
Spaces system performance considering human behaviour			(7) Safety: traffic accidents and conflicts	
			(8) Service quality: reliability, comfort, convenience	
			(9) System management	
Transport–spaces system performance considering human behaviour		(10) Furnishings	(17) Use time	
		(11) Affiliated transport infrastructure	(18) Diversity	
		(12) Aesthetics	(19) Occupancy	
		(13) Cleanliness	(20) User diversity	
		(14) Safety	(21) Community engagement	
		(15) Comfort	(22) Equality	
		(16) Use frequency	(23) System management	
		(24) Transport accessibility	(29) Walkability and bikeability	
		(25) Transport connectivity	(30) Community severance	
		(26) Land-use accessibility	(31) Land use	
		(27) Public space accessibility	(32) Parking	
		(28) Spatial openness		
		(33) Habitat integrity		
		(34) Biodiversity		
		(35) Air and water quality	(40) Bioclimatic comfort	
		(36) Waste recycling	(41) Green infrastructure provision	
		(37) Noise and vibration impacts of land transport projects	(42) Energy consumption	
		(38) Global climate change	(43) Water consumption	
		(39) Microclimate condition	(44) Materials consumption	
		(45) Socio-economic characteristics	(51) Social perception and satisfaction	
		(46) Social equity	(52) Transport affordability	
		(47) Public participation	(53) Affordable housing	
		(48) Community cohesion and liveability	(54) Cultural heritage creation	
		(49) Physical health	(55) Cultural heritage protection	
		(50) Mental health		
		(56) Investment	(60) Environment compensation	
		(57) Land take	(61) Traffic congestion	
		(58) Planning and design cost	(62) Economy and development	
		(59) Operation and maintenance	(63) Economic productivity	
			(64) Property values	

4.4. Indicator Set Development

After screening, a total of 117 indicators for transportation infrastructure and 116 indicators for urban spaces systems were selected. Figure 13 maps the number of themes, KPIs, and shortlist indicators introduced to the evaluation of each subsystem.

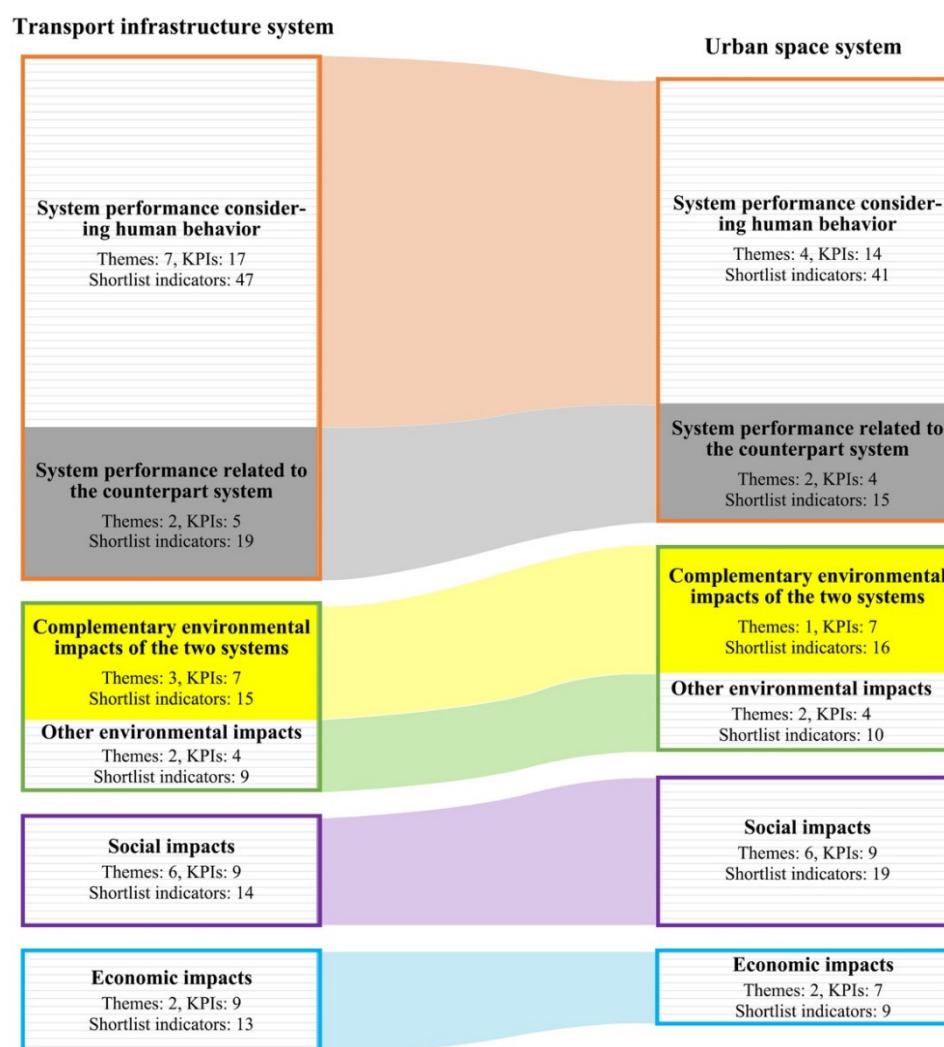


Figure 13. The number of themes, KPIs, and shortlist indicators for different evaluation dimensions. This is a high-level framework of Tables 2–6 and the meaning of the different colours remains the same as in Figure 12.

In addition, specific explanations and standardisations were performed for each of the selected indicators. For quantitative indicators, the most common units were derived from the literature. Qualitative indicators were marked in the indicator set as well. Afterwards, an initial indicator set was shown to 10 experts in transportation planning, transportation control systems, urban planning, and urban design to collect their comments on each KPI and indicator. We then modified the items and formed the ultimate indicator set for transportation and spaces systems assessment, as shown in Tables 2–6. The indicator system consists of five parts: Part 1 presents the transportation and spaces systems self-performance indicators considering human behaviour, Part 2 shows the performance indicators of transportation and spaces systems that correspond to the counterpart system, and Part 3 lists the environmental impacts of transportation and spaces systems in which the complementary effects of the two systems were highlighted. Part 4 and Part 5 denote the social and economic impacts of the systems. Note that the Explanations column in these figures either describes the meaning of an indicator (by providing a definition, illustrating the evaluation objective, or giving an example) or demonstrates a common way to measure an indicator.

Table 2. An indicator set for evaluating the transport and spaces systems—Part 1: The transportation and spaces systems self-performance indicators considering human behaviour (further details see the Supplementary Materials).

Transport infrastructure system					Urban space system				
Theme	KPI	Indicator	Explanation	Unit	Theme	KPI	Indicator	Explanation	Unit
Intra-city rail transit system (railway)	Turnover	Number of passengers		million people/d	Furnishings		Pavement materials quality		Qual
		Number of goods		tons/d			Share of vandal-proof materials usage		
		Length of operational rail lines		km			Bike racks provision		racks
		Network density		km/km ²			Seating furniture provision		seats
	Infrastructure spatial features	Network extension		%	Affiliated transport infrastructure		Quality of the structure of the transport infrastructure		Qual
		Population influenced		km/capita			Quality of materials of the transport infrastructure		Qual
		Ratio of electrified railways		%			Imageability		Qual
		Ratio of high-speed rail		%			Identity (or sense of belonging)		Qual
	Efficiency	Occupancy rate of vehicles		passengers/km	Aesthetics		Public art presence		Qual
		Frequency		trains/d			Landscape topography—spatial arrangement on different elevations		Qual
		Workers in this infrastructure		population			View value		Qual
		Number of locomotives		locomotives/y			Shadow	Average area of the shadow	m ²
Inner-city rail transit system	Turnover (by each mode)	Number of passengers		million people/d	Cleanness		Washing and sweeping		Qual

(light rail and tram)	Infrastructure spatial features (by each mode)	Length of total operational rail lines	km	Safety	Garbage disposal		Qual
		Network density	km/km ²		The ratio of the number of buildings with graffiti		%
		Network extension	%		Effective and correct lighting		Qual
		Population influenced	km/capita		Use at all hours of the day		h/d
	Efficiency (of each mode)	Occupancy rate of vehicles	passengers/km		The average number of passers-by		passers-by
		Frequency	trains/d		The presence of policies/CCTVs on a street		policies (OR CCTVs)
		Workers in this infrastructure	population		Protection against vehicular traffic	e.g., Traffic speed reducers provision	Qual
					Protection against unpleasant sensory experiences		Qual
	Turnover	Number of passengers	million people/d		Number of crimes per year		crimes/y
		Number of goods	tons/d		Emergency plans		Qual
Road system	Infrastructure spatial features	Length of total operational roads	km	Comfort	Security protection for crowd cluster		Qual
		Ratio of modern roadways	%		Protection from natural disaster		Qual
		Network density	km/km ²		Feeling of psychological comfort of users		Qual
		Public transport stops	Further measured by passenger shelter, cleanness, seats, lighting, CCTV, timetable, real-time display, Wi-Fi, etc.		Connections with devices such as ramps, elevators, etc.		--
	Public transport infrastructure	Public transport route network	Further measured by multimodal compatibility, the system of ticket sale and distribution,				
	Turnover	Number of passengers	million people/d				
		Number of goods	tons/d				

		distance to a bus stop, etc.							
		Public transport efficiency	Occupancy rate of buses	%	Use frequency	Average time occupied by users within a day, a week	h/d (OR h/week)		
Travel behaviour	Transport demand	Non-motorized transport demand		passenger-km travelled	Usage	Use time	Time used for medium or vigorous physical activity per day	h/d	
		Motorized transport demand		vehicle-km travelled			Density of public services within all area	services/m²	
	Modal split	Personal travel mode split	Share of non-motorized, automobile, public transport	--	Diversity		Variety of activity types	--	
		Freight mode split	Share of truck, rail, ship, air	--					
	Mobility	Average person-miles or trips per day or per year		person-km/d (OR person-trips/y)	Occupancy		Number of users	users	
							Concentration of residents and their financial status within 15-min walking, cycling, and car-driving	population	
		Average commute travel time		h/d			Mix of different household income users	--	
		Average transport speed		km/h			Mix of users from different educational attainment	--	
	Safety	Traffic accidents	Annual number of traffic crashes and fatalities per 100,000 residents		accidents/100,000 residents	Users		Mix of users from different races and ethnicities	--
			Share of population feeling safe from violations and other relevant		Qual			Community engagement	Degree to which the public is involved in public space design process

	Traffic conflicts	incidents during traveling	collisions	Equality	Degree to which vulnerable people's needs are considered in public space design	Qual
		Number of collisions between motor vehicles and non-motorized travellers				
Service quality	Reliability	Number of collisions between pedestrians and vehicles	collisions	System management	Degree to which used by specific social groups (homeless etc.)	Qual
					Degree of multi-stakeholder cooperation	Qual
	Comfort and convenience	Integration of different transport modes	Qual		Maintenance of public space	Qual
		Quality of non-automobile modes relative to automobile travel	Qual			
		Quality of transport for vulnerable people	Qual			
System management	Traffic management	Traffic regulation management	Qual	Public space management		
		Intelligent transportation system	Qual			
		Traffic facilities	Further measured by traffic signals, traffic signs, road marking			

Table 3. An indicator set for evaluating the transport and spaces systems—Part 2: The transportation and spaces systems performance indicators related to the counterpart system (further details see the Supplementary Materials).

Transport Infrastructure System					Urban Space System				
Theme	KPI	Indicator	Explanation	Unit	Theme	KPI	Indicator	Explanation	Unit
Accessibility	Transport accessibility	Share of population living within 300–500 m from public transport stations		population	Access	Public space accessibility	Accessibility by walking		— —
		Ratio between number of stations and the reference territory surface		stations/km ²			Accessibility by cycling		— —
	Transport connectivity	Connected Node Ratio (CNR)		%			Accessibility to public transport station		— —
	Land use accessibility	Number of public spaces within 10-min walk		spaces			Accessibility by car-driving		— —
		Travel time to the nearest regional centre		min			Accessibility for emergence rescue		Qual
Transport—Spaces interaction	Community severance	Number of residents within isochrones 30-min to markets		population		Spatial openness	The number of entrances of visibility along the street		entrances/m
		Accessibility to specific sites of historical, architectural, and cultural importance		— —		Walkability and bikeability	Overall width of sidewalk and cycling lanes		m
		Number of job opportunities within 30-min commute of residents	To evaluate accessibility to jobs	jobs			Effective width of the sidewalk and cycling lanes		m
		Barrier Effect Index (BEI) = Barrier x Crossing need	To measure physical severance (Anciaes et al. 2014)	— —			Number of sidewalk and cycling lanes		lanes
		Cognitive severance	By conducting surveys	Qual			Number of formal crossings per length of the road	To measure crossability	crossings/m

	Visual severance	By conducting surveys	Qual		Type of crossing facilities	Qual
Land use	Total land devoted to transport facilities (e.g., Roads, parking)		m ² /capita		Quality of crossing facilities	Qual
	Ratio of agriculture land used for transport facilities to total land take		%		Pedestrian oriented traffic lights	Qual
	Ratio of green spaces used for transport facilities to total land take		%		Formal parking facilities provision	m ²
	Land use compactness	Equals to the percentages of built up areas within urban growth boundaries (Thinh et al. 2002)	%	Transport— Spaces interaction	The ratio of the number of sidewalks with parking fully occupied	%
	Population density		population/m ²			
	Development location		Qual			
	Regeneration of brownfield sites		Qual			
	Preservation of specific sites of historical, architectural, and cultural importance		Qual			

Table 4. An indicator set for evaluating the transport and spaces systems—Part 3: Items highlighted in yellow denote the complementary impacts of the two systems, while other items illustrate the other natural environmental impacts of the systems (further details see the Supplementary Materials).

Transport Infrastructure System					Urban Space System				
Theme	KPI	Indicator	Explanation	Unit	Theme	KPI	Indicator	Explanation	Unit
Eco-system health	Habitat integrity	Habitat Connectivity Index (CI)	To measure habitat fragmentation degree (Hanski 1994)	— —	Eco-system health	Habitat integrity	Habitat animals	Provision of living space that support species richness for animals	m ²
		Annual number of collisions with wildlife		collisions			Habitat plants	Provision of living space that support species richness for plants	m ²
		Biodiversity	Species loss rate	Variation of species richness overtime	— —		Plant pollination	Provision of plant pollination	Qual
		Number of endangered species		— —		Biodiversity	Species richness. Menhinick's index D = number of different species/total number of individual organisms in the sample		%
	Air and water pollution	Traffic air pollutant emissions	To measure traffic-related air pollution	µg/capita			Protection of endangered species		Qual
		Concentration of air pollutant emissions		µg/m ³		Air and water quality	Concentration of air pollutant emissions (NOx, CO, PM, etc.)	To measure air purification effectiveness	µg/m ³
		pH; temperature; chlorophyll fluorescence; total solids; conductivity and alkalinity; dissolved oxygen levels; total hardness	To measure transport-related water pollution	— —			pH; temperature; chlorophyll fluorescence; total solids; conductivity and alkalinity; dissolved oxygen levels; total hardness	To measure water purification effectiveness	— —
		Transport infrastructure impervious area per capita	To measure water run-off	m ² /capita		Waste recycling	Waste decomposition effectiveness		— —

	Waste disposal and recycling	Transport solid waste per capita	kg/capita	Construction waste reused or recycle in-situ in respect to total waste production				kg/m ²
		Recycling rate for end-of-life vehicles	%	Noise and vibrant control	Noise levels			dB
	Noise pollution	Traffic noise pollution	decibel	Climate condition	Microclimate mitigation	Air temperature		°C
	Dust and vibration impacts	Vibration impacts of land transport projects	Hz			Mean radiation temperature		°C
		Dust pollution	— —			Wind speed		m/s
Climate condition	Global climate change	GHG emissions	kg/capita		Bioclimatic comfort	Thermal comfort	Spatial distribution of daytime thermal comfort on a summer day	% and °C
		Electromagnetic radiation	milligauss (mG)				Annual frequency of thermal comfort for the point with worst microclimatic conditions	% and °C
		Number of trees, grasslands, hedges, flower/vegetation beds, water surfaces provided	— —				Annual frequency of thermal comfort for the main functions	% and °C
Supply	Green infrastructure provision	Size of trees, grasslands, hedges, flower/vegetation beds, water surfaces provided	m ²			Number of trees, grasslands, hedges, flower/vegetation beds, water surfaces provided		— —
		Quality of trees, grasslands, hedges, flower/vegetation beds, water surfaces provided	Qual	Supply	Green infrastructure provision	Size of trees, grasslands, hedges, flower/vegetation beds, water surfaces provided		m ²
Consumption	Energy	Fossil fuels consumption	kg/capita			Quality of trees, grasslands, hedges, flower/vegetation beds,		Qual

[illegible]

Table 5. An indicator set for evaluating the transport and spaces systems—Part 4: The transportation and spaces systems impacts on social sectors (further details see the Supplementary Materials).

Transport Infrastructure System					Urban Space System				
Theme	KPI	Indicator	Explanation	Unit	Theme	KPI	Indicator	Explanation	Unit
Demography	Socio-economic characteristics	GDP per capita		\$/capita	Demography	Socio-economic characteristics	GDP per capita		\$/capita
		Employment rate		%			Employment rate		%
Equity	Social equity	Share of different groups of people exposed to air pollution	To measure the equity/justice of exposure to air pollution emissions	%	Equity	Social equity	Share of different groups of people exposed to air pollution	To measure the equity/justice of exposure to air pollution emissions	%
		Degree to which vulnerable people's needs are considered in transport planning		Qual			Degree to which vulnerable people's needs are considered in public space planning		Qual
		Degree to which public is involved in transport planning process		Qual			Degree to which public is involved in public space design process		Qual
Inclusion	Community cohesion and liveability	Quality of interactions among neighbours		Qual	Inclusion	Community cohesion and liveability	Quality of interactions among neighbours		Qual
		Community liveability ratings		Qual			Community liveability ratings		Qual
		Population exposure	Share of population exposed to noise and pollution levels above the statutory threshold	%			Physical health	Total time of doing physical activity within a day (or a week)	h/d· capita
Health	Physical health	Illness and mortality	Number of chronic respiratory illnesses, respiratory restricted activity days and premature deaths due to air pollution	population	Health	Physical health	Physical health	Average times of doing physical activity within a day (or a week)	times/d· capita
		Physical activity	Portion of residents who walk or bicycle 15-min or more daily	%				Duration of medium or	h/d· capita

					vigorous physical activity per day					
		Portion of children walking or cycling to school		%			Mental health	Mental health benefits	Qual	
		Mental health	Mental health benefits	Qual						
		Social perception and satisfaction	Landscape visual injures	Qual	Aesthetics		Social perception and satisfaction	The public’s perceived beauty	By conducting surveys	Qual
Aesthetics		Social perception and satisfaction	Landscape visual injures	Qual				Satisfaction of the public spaces	By conducting surveys	Qual
		Transport affordability	Share of household budgets devoted to transport	Expenditures to vehicles	\$			Cultural heritage creation	Creating cultural trails	Qual
				Expenditures to parking	\$				Protection archaeological heritage	Qual
				Expenditures to transit services	\$				Protection UNESCO sites	Qual
Affordability		Affordable housing	Housing affordability in accessible locations	\$	Cultural heritage		Cultural heritage protection	Protection viewpoints	Qual	
								Protection places of Taste	Qual	
								Protection places of heterotopic	Qual	
								Protection places of events	Qual	
								Protection places of personality	Qual	

Table 6. An indicator set for evaluating the transport and spaces systems—Part 5: The transportation and spaces systems impacts on economic sectors (further details see the Supplementary Materials).

Transport Infrastructure System					Urban Space System				
Theme	KPI	Indicator	Explanation	Unit	Theme	KPI	Indicator	Explanation	Unit
Costs	Investment	Public expenditures and subsidies to transport system		\$	Costs	Investment	Public expenditures and subsidies to transport system		\$
		Private capital to transport system		\$			Intervention costs		\$
		Marginal costs of public funds		\$			Land take	Land take cost	\$
	Land take	Land take cost		\$		Planning and design cost	Investigation, planning, designing cost in public space design		\$
	Planning and design cost	Investigation, planning, designing cost in transport planning		\$		Operation and maintenance	Maintenance costs and taxes		\$/m ²
	Operation and maintenance	Fuel prices and taxes		\$		Economy and development	Share of GDP contributed by public spaces		%
	Environment compensation	Compensation for ecological effects and replacement of environmental assets		\$		Economic productivity	Ratio of public spaces revenues to the respective maintenance and operation cost		%
	Traffic congestion	Traffic congestion cost		\$/capita		Property values	Public amenity land values		\$
		Average time spent traveling under congested conditions per year per capita		h/y·capita			Adjacent property values		\$
Benefits	Economy and development	Share of GDP contributed by transport sector/share of GVA generated by transport sector		%	Benefits	Property values	Adjacent property values		\$
	Economic productivity	Ratio of public transport revenues to the respective maintenance and operation cost		%					
	Property values	Transport facility land values		\$					
		Adjacent property values		\$					

5. Discussion

This section takes these results and discusses the application of the indicator system in planning and research practices and the evaluation of the indicators. Our indicator set can be applied to a wide range of applications of transportation and spaces system integration. Primarily, it is necessary to investigate conflicts and to raise questions using fieldwork, survey, data analysis, and literature review, followed by an appraisal of the status quo systems through the prism of the indicator set. Afterwards, designers, practitioners, and other decision-makers could draft plans to solve the problems, engage with stakeholders, mediate conflicts, and transform the systems by providing a set of plan alternatives. Finally, the indicators can be used to assess the planned systems for supporting decision-makers to choose the best solution that is most likely to achieve the goals and objectives of a project while considering specific constraints. This approach leads to a transparent and repeatable evaluation, which is particularly relevant for sustainability assessment given the scale of the global challenge and the urgency to act, while also acknowledging the local situation, economic and social development, and limited resources that have to be used in a way to maximise impact.

In the presented indicator system, both qualitative and quantitative indicators are included. Though 57 KPIs identified in Table 7 could be measured quantitatively, some others are difficult to be assessed by quantitative methods, e.g., quality of transportation services, transport system management, public participation, equity, open space management, quality of adjacent transport infrastructure, the aesthetic quality of public spaces, cleanliness, and comfort. These factors, however, could be measured by the following qualitative approaches:

- Designers and planners' observations, analyses, and subjective judgments based on their professional knowledge; among others, assessments of aesthetic quality, cleanliness of public spaces, and the quality of related transportation infrastructure are suitable for using this method.
- Users' expression of their feelings and experiences in transport infrastructures and public spaces by conducting questionnaires, interviews, etc.; for example, appraisal of the quality of transportation services, public participation, equity, aesthetics, and the comfort of public spaces are appropriate for this technique.
- Collective knowledge generated from a multidisciplinary team of experts through brainstorming sessions, Delphi, expert consultation, and other methods that are beneficial for making comprehensive judgments on complex issues. In theory, the qualitative assessment of the aforementioned factors could all be achieved by this method, especially the appraisal of service and management quality. However, due to the fact that the Delphi method usually consumes a lot of time, labour, and financial resources, it is only used when necessary (or in large projects).

It is worth noting that there are two types of qualitative research: One is pure qualitative research with a lack of quantitative analysis, and the other is a higher level of qualitative evaluation that is based on quantitative analysis. In general, quantitative research can start from qualitative judgment and then use data analysis, statistics, simulation, and other techniques to generate more objective and precise judgments. Sometimes, however, results of quantitative studies could be opposite to the previous qualitative conclusions. Consequently, after making a quantitative judgment, it is necessary to describe the results qualitatively, such as summarising the rules and identifying impact factors. In quantitative evaluation, the reliability, consistency, and transparency of measurements in line with the time frames used are crucial issues.

Finally, it should be noted that while the selection of indicators presented here could be generally applicable within the proposed scope, the weighting of individual indicators will not be universal and was therefore not incorporated in this paper. It is key to establish weighting factors or priorities given a specific application, ideally through engagement by the problem owner with other stakeholders and based on local policies and circumstances following political, economic, business, and societal priorities. In the end the indicator system and its application have to support specific goals under given circumstances. The local context always drives the final selection and weighting of

individual KPIs. In a future paper we will explore the role and application of these indicators in close collaboration with local stakeholders for the Jing-Zhang high-speed rail project in Beijing, which motivated this research, but the results presented here show that it is valuable to have an indicator system based on the literature in place before such discussions with any group of stakeholders.

6. Conclusions

Evaluation is a kind of value judgment behaviour that has a direct correlation with the goals and standards of projects. It includes the assessment of design goals, the baseline system, and the designed system. Initially, this article formulated a goal system and reviewed and synthesised the literature systematically to select themes and KPIs, all leading to the development of an indicator set that can be applied and support decision-making. The focus and main contribution of this paper is on the following themes: (1) integration of the transport system and the multi-level urban spaces system with an emphasis on microscale public spaces, (2) operational guidelines for generating and applying sustainability goals, and (3) to help track progress in achieving these goals by providing a systemic indicator set based on the goal system that can be applied to the interface of planning transport infrastructure, public spaces, and the impact of human behaviour in this context.

Regarding the goal system formulation, this study classified transportation and spaces system integration into three levels: internal integration, integration between subsystems, and integration between the system and the external environment. Under this hierarchy, three sets of goals and objectives are proposed for transport infrastructure redevelopment projects. On this basis, this study elicits themes and a longlist of indicators for transportation and spaces systems assessment based on a systematic literature review. According to the chosen selection criteria, 64 KPIs are suitable for quantitative and qualitative analysis of the integration degree of a baseline system or planned system. This work also provides evaluation indicators and subitems for each KPI. Among these KPIs, qualitative and quantitative items are distinguished, and conventional qualitative assessment methods are outlined.

Table 7. Quantifiable KPIs for transport and spaces systems evaluation (57 items).

Hierarchy of the Goal System			Key Performance Indicators (KPIs)
Level 1	Level 2	Level 3	
Transport system performance considering human behaviour		(1) Intra-city rail transit: turnover, infrastructure spatial features, efficiency	(4) Transport demand (5) Modal split (6) Mobility (7) Safety: traffic accidents and conflicts
		(2) Inner-city rail transit: turnover, infrastructure spatial features, efficiency	
		(3) Road system: turnover, infrastructure spatial features, public transport infrastructure	
Spaces system performance considering human behaviour		(8) Furnishings	(12) Use time (13) Diversity (14) Occupancy (15) User diversity
		(9) Affiliated transport infrastructure	
		(10) Safety	
		(11) Use frequency	
Transport–spaces system performance considering human behaviour		(16) Transport accessibility	(21) Walkability and bikeability (22) Community severance (23) Land use (24) Parking
		(17) Transport connectivity	
		(18) Land-use accessibility	
		(19) Public space accessibility	
		(20) Spatial openness	
	Transport–spaces system performance considering natural environment	(25) Habitat integrity	(32) Green infrastructure provision (33) Energy consumption (34) Water consumption (35) Materials consumption
		(26) Biodiversity	
		(27) Air and water quality	
		(28) Waste recycling	
		(29) Noise and vibration impacts of land transport projects	

(30) Microclimate condition (31) Bioclimatic comfort			
Transport-spaces system performance considering social impacts	(45) Socio-economic characteristics (46) Physical health	(47) Transport affordability (48) Affordable housing	
Transport-spaces system performance considering economic impacts	(49) Investment (50) Land take (51) Planning and design cost (52) Operation and maintenance (53) Environment compensation	(54) Traffic congestion (55) Economy and development (56) Economic productivity (57) Property values	

These indicators can support decision-makers in carefully evaluating their projects while considering the integration of multiple subsystems and can thus be part of public consultations as well as internal evaluation. Moreover, the proposed approach can be repeated in other sectors and used to select the relevant indicators from the literature systematically. A transparently designed and tailored indicator system can be used to inform the creation of evaluation tools, including simulation models, and provide a benchmark for consultation meetings. Finally, the use of the indicators post-construction is key to informing the design of surveys and implementing sensor systems to continue to monitor impact after a proposed plan has been turned into a physical intervention, from which further lessons can be shared and understood within the context of the selected indicators.

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/12/22/9677/s1, Table S1: Research scopes, scales, methods, number of themes, and indicators in key references (published before September 2020).

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