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Developing Transportation Livability-Related Indicators for Green Urban Road Rating System in Taiwan

Nam Hoai Tran [1], Shih-Hsien Yang [1,*], Calista Y. Tsai [2], Nien Chia Yang [1] and Chih-Ming Chang [3]

[1] Department of Civil Engineering, National Cheng Kung University, No.1 University Road, Tainan 70101, Taiwan; n68067076@gs.ncku.edu.tw (N.H.T.); n66074580@gs.ncku.edu.tw (N.C.Y.)
[2] Department of Hydraulic and Ocean Engineering, National Cheng Kung University, No.1 University Road, Tainan 70101, Taiwan; calista0523@gmail.com
[3] Construction and Planning Agency, Ministry of the Interior, R.O.C., No.342 Bade Road, Taipei City 105404, Taiwan; cm_chang@cpami.gov.tw
* Correspondence: shyang@mail.ncku.edu.tw

Abstract: Although indicators in rating systems have been initiated to measure and promote the sustainability performance of roadway projects in some developed countries, applying those indicators to other regions/countries may still be difficult. In response to the United Nations' sustainable development goals, local road agencies in Taiwan urgently need to establish systematic and quantifiable sustainable roadway strategies. As part of the project to develop a green urban road rating system in Taiwan, this study aims to develop transportation livability-related indicators (TLIs) and identify critical barriers to TLI application in Taiwan's urban road system. To this end, the research employed an adaptive approach that integrates top-down and bottom-up approaches. The top-down approach included the comprehensive literature review and panel discussion to derive four TLIs and 21 corresponding requirements, and nine potential barriers to hold the indicator adoption. Four TLIs are pedestrian facilities, universal design, multimodal transportation, and utility facilities. The bottom-up approach used the Analytic Hierarchy Process (AHP) to assign weights to proposed indicators/requirements. Four critical barriers were also investigated through the Weighted Sum Model (WSM) method, namely unfavorable in-situ conditions, lack of stakeholders' coordination, unsupported government policy and regulation, and limited budget and schedule. The findings can be beneficial to engineers and decisionmakers to enhance the livability standard of urban streets. The framework proposed in this research can be applied to other roadway characteristics aspects in different regions/countries.

Keywords: analytic hierarchy process; weighted sum model; adaptive approach; transportation livability; barrier

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1. Introduction

Road network is a critical infrastructure in cities. The growing automobile usage, especially in the densely populated urban areas, has deteriorated the urban environment and streets. Thus, in developed countries, the policies to promote green road/highway systems have been promulgated since the 1960s–70s [1]. Green roads/highways are constructional systems of roadway projects, which include five main aspects, i.e., (1) ecosystem conservation, (2) stormwater management, (3) life-cycle energy and emission reduction, (4) recycled, reused, and renewable materials, and (5) overall societal management [2]. In addition to topography, environment, and ecology, green roads demand considerations to societal benefits for the community, such as safety, equity, accessibility, and public health. These aspects are generally the main contributors to livable streets [3]. The livability transportation in this research emphasizes the physical aspects of livable urban roads (e.g., configuration, motorized and non-motorized traffic, traffic facilities, utilities) rather than livable streets' functional and social characteristics.

In conjunction with the accelerated development of urbanization in the Developing World, urban street construction and widening are critical to the urban infrastructure system and urban development. Hence, decisionmakers and scholars have advocated for developing urban streets towards the livability objective in developing countries [3]. For the sake of providing the living or general well-being of communities, transportation livability in urban streets focuses on managing the conflict among pedestrians and motor vehicles, building dedicated lanes and other facilities for public transit and bicycle modes [1]. Transportation livability also aims to create convenient accessibility and connectivity for all people, improve the transition to more environmentally sustainable modes of transport and equip street facilities and amenities [1].

Recent scholarly works argued the street planning should be more flexible to accommodate different street users to enhance the transportation livability characteristic of urban roads [3]. Tumlin [4] stressed the importance of adequate sidewalks and other supported facilities to create more favorable walking environments in the daily commute, such as pedestrian sidewalks, crossing, refuges, and countdown signals. According to Meyer [5], bicycle mode choice serves a vital role in sustainable transportation towards minimizing the usage of private motorized vehicles, offering a healthy lifestyle, reducing travel costs, and notably mitigating the environmental footprint from motorized vehicles. The most critical element to facilitate biking travel is the on-street bike lane. The integration of two of these active modes (i.e., active transportation) with public transportation indicates a potential strategy for urban transportation policies [6]. The accessibility and connectivity for these transit modes can be smooth and continuous by providing public transit stops and bicycle parking areas (i.e., Park and Ride) sufficiently and conveniently. As a design aspect in the equity category, the universal street principle requires all urban streets to be easily accessible to all users, notably paying attention to the most vulnerable peoples, e.g., disabled people, the elderly, and children [7]. In addition to typical pedestrian elements, the main components for universal accessibility can be pedestrian ramps and guidance for the visually impaired (e.g., tactile paving or detectable warning strips). Another essential aspect of urban roads' impact on the community is accommodating buried utility systems (e.g., electrical cable, telecommunication lines, sewers, and drain pipes) synergistically to avoid interference with urban street systems [8].

Although these elements above can make urban roads more livable, their successful adoption is not guaranteed in specific conditions. Scholars have reported different barriers to the transportation livability application to streets. Chang and Tsai [9] identified nine reasons/barriers to sustainable roadway design in Taiwan, such as limited budget and schedule, insufficient databases and information, etc. These barriers are also found and mentioned in other research, such as Banister [10] and Bardal et al. [11]. In order to overcome the barriers and stimulate the application of the transportation livability concept to urban streets, policy measures and strategies (e.g., sustainability rating systems) need to be implemented [12].

Sustainable transportation infrastructure rating systems have been developed over the past decade to assess and promote the sustainability performance of a transportation project. A rating system, such as Greenroads, INVEST, collects the number of best practices (a.k.a, indicators) that can measure sustainability roadway achievement in a quantitative and qualitative manner. Thus, rating systems can enable users to monitor the changes and development in sustainability [13]. Each indicator is assigned a particular point value based on a consensus of experts and related stakeholders in a group discussion when assessing their relevance, importance, and impact on sustainable development. However, this scoring approach arouses controversy over the subjectivity stemming from expert judgments [14]. Under each indicator, a set of requirements or instructions reflects the specific data, thresholds, and requests that a project must fulfill to obtain points [14]. However, a one-size-fits-all rating system is invalid for the following reasons. Firstly, sustainability is a context-sensitive approach because of the intrinsically complex nature of assessing sustainability in different regions/countries. The existing indicators developed for specific evaluation conditions usually do not fit other assessment contexts [15]. Secondly, transportation infrastructure projects have significant geographic footprints both explicitly with respect to the location of infrastructure and services and implicitly concerning impacts on human and physical systems (e.g., population density, land-use, and socioeconomic circumstance) [16]. Thirdly, the performance of transportation projects might fluctuate, adhering to respective project types. Apart from common characteristics, an urban road might accommodate utility facilities such as electric cables for street lighting and signal, communication cables, and other pipelines. The previous facts clarified the necessity for developing defined indicators in a particular rating system capturing the local context and specific road type.

Recent attempts towards the above adaptability have been made by developing indicators for sustainable roadway rating systems in particular countries. For example, Park and Ahn [17] recommended a green road rating system framework in South Korea, while Ibrahim and Shaker [18] developed a sustainability index for Egyptian highway construction projects. However, there are some limitations in those research which are seen as starting points to this study. First, the research proposed many indicators for the whole rating system rather than specific indicators. The requirements that guide users on quantifying project performance were not detailed under each indicator. Therefore, it can render policymakers and practitioners challenging to apply those indicators to an actual roadway project. Second, in the Analytic Hierarchy Process (AHP) method adopted in those research, scholars used expert judgments to capture the broad content of different categories of transportation infrastructure projects and thus may cause significant bias when making the pairwise comparison. According to Namini et al. [19], each respondent participating in the AHP method needs to emphasize their specific interests instead of the whole project concerns. Lastly, indicator applicability to specific projects varies between regions/countries and is likely hindered by different barriers. However, there are limited academic and industry efforts concerning the obstacles to TLI adoption. Hence, it is necessary to develop a systematic approach to identify indicators/requirements and barriers to adoption in the specific roadway conditions.

In response to the United Nations' sustainable development goals, the Construction and Planning Agency (CPA), in charge of Taiwan's urban road funding program, urgently needs to establish a systematic and quantifiable rating system to assess the sustainability level of urban street projects. This study presents the development of the indicators related to transportation livability characteristics of urban road projects, which is part of the Taiwan Green Urban Road (TGUR) Rating System. The contents of this paper were threefold: (1) the assembly of the transportation livability-related indicators (TLIs) and their corresponding requirements; (2) rationale to assign the specific points to each TLI and their requirements; (3) identify the critical barriers to TLI implementation in Taiwan urban streets. Although various indicators can be potentially defined in the TGUR rating system, this research only emphasizes TLIs. The other indicators may be identified in further works.

Following this introduction, Section 2 presents the status of transport livability for urban roadways in Taiwan. Next, we demonstrated how to develop and allocate the score to indicators/requirements for the TGUR rating system and examine the critical barriers in Sections 3 and 4. Section 5 introduces the results, followed by a detailed discussion of the TLIs, comparing their weights with other systems, and a barrier sensitivity analysis in Section 6. Section 7 concludes the significance of the work in this research.

2. Transportation Livability for Urban Streets in Taiwan

Based on the first official document, i.e., The Agenda 21 of Taiwan: the Guidelines for the National Sustainable Development Strategy, the Taiwan Government proved many efforts in developing sustainable transportation, notably incorporating livability standards into the transportation policy decision-making [20]. The Public Transportation Development Act released in May 2002 was a critical policy in developing public transit in urban areas in Taiwan [21]. The Taiwan Sports Affairs Council launched the Planning and Establishment of a Bikeway System in Taiwan to build a safe and comfortable bikeway network for the growing biking movement around Taiwan [22]. In Taiwan, a bike-shared system has been developed to support the accessibility among travel modes, reduce private transportation selection, and provide a positive contribution to the urban environment, such as YouBike in Taipei and T-Bike in Tainan cities [23].

One of the significant barriers preventing bicycle trips in Taiwan urban areas is the lack of connectivity between bicycle paths and public transport networks [22]. In addition, the lack of laws governing the use of bicycles and the supporting infrastructures has caused traffic accidents related to cyclists [23]. Notably, the existing road infrastructure conditions in many areas in Taiwan are not suitable for bicycles when a small portion of roads nationwide allocate separated lanes for cycling [24]. These mentioned facts raise the necessity of incorporating transportation livability standards into urban road projects in Taiwan. Hence, proposing TLIs in a TGUR rating system facilitates promoting related best practices and evaluating the transportation livability performance of urban streets in Taiwan. Such a sustainability rating system can be perceived as a form of decision support tool for transportation public agencies in Taiwan.

3. Research Methodology

This research carried out an adaptive approach (a.k.a., integrated or hybrid approach), merging the top-down and bottom-up approaches. This integrated approach employed in developing indicators can increase effectiveness and applicability in a specific local context. Thus, this approach makes the current research more referential and possibly generalizable to other regions/countries worldwide. This overall process is depicted in Figure 1 and presented explicitly in the following sections.

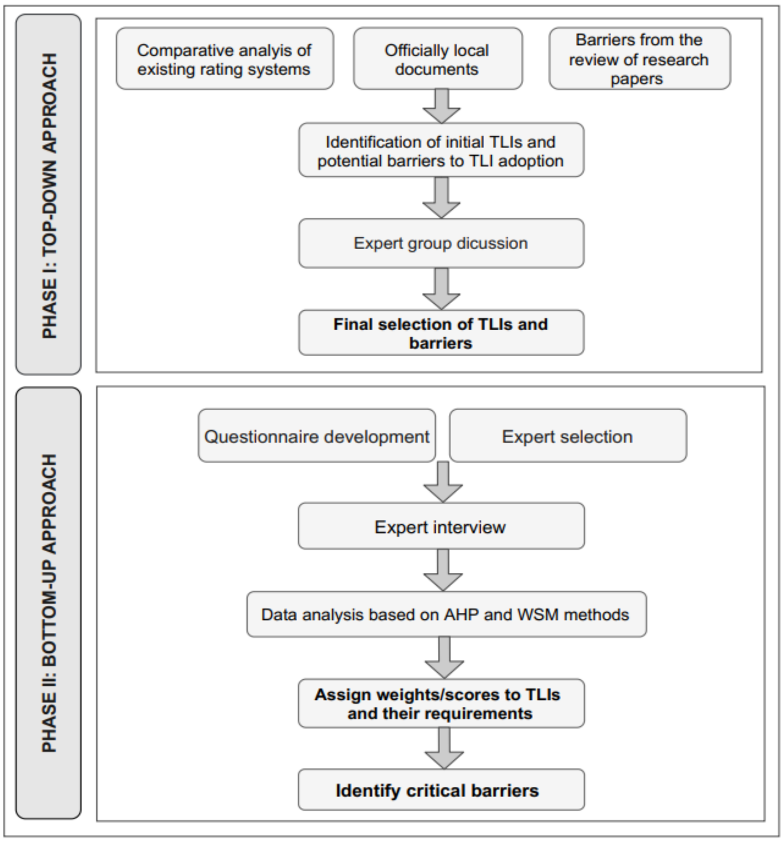

Figure 1. Adaptive approach flowchart.

3.1. Top-Down Approach

This method aims to derive TLIs applicable to urban street projects in Taiwan and identify potential barriers to their implementation. To this end, the review process for indicators and obstacles centers around three sources, i.e., existing rating systems, local documents, and academic papers. Subsequently, an expert group discussion was held to finalize TLIs and barriers.

3.1.1. Significant Indicators from Existing Rating Systems

Oltean-Dumbrava et al. [25] recommended that developing indicators need to begin with a comprehensive review of existing rating systems. These pre-selected indicators stemming from this process can be the baseline to establish the new indicators or refine the existing ones adaptable to the specific conditions. TLIs in the review process can fulfill an international agreement or be approved by a competent international body as recommended by the International Standards Organization (ISO) [26]. Furthermore, these indicators inherently described in existing systems will satisfy the essential criteria for selecting indicators, e.g., reliability, independence, and comparability [27].

Tran et al. [7] presented a comprehensive review and systematic screening process on existing rating systems to select six potential TLIs because of their essential contribution to the sustainability performance of roadway projects. They are (1) pedestrian path and sidewalks, (2) bicycle facility, (3) transit facilities, (4) public transportation, (5) traffic safety management, and (6) road alignment.

3.1.2. Official Documents Related to Transportation Livability Standards

According to Anderson et al. [28], sustainable indicators should incorporate practices beyond current standard requirements. Thus, referring to local documents (e.g., technical standards and specifications) can help avoid double-counting in selecting TLIs/requirements defined in those standards. Hence, this study reviewed three documents relevant for transportation livability design and management of urban roads in Taiwan. They are (1) the Design Code for Urban Roads and Auxiliary Works developed by the Ministry of the Interior released in 2015, (2) the Urban Humanistic Transportation Planning and Design Manual launched by the Ministry of the Interior released in 2017, and (3) the Tainan City Urban Design Review Principles released in 2017. The present research identified similar works between six potential TLIs and three of those documents through content analysis. As a result, two indicators (i.e., traffic safety management, road alignment) were defined explicitly in these references and thereby excluded from the proposed TLIs for the TGUR rating system in Taiwan.

3.1.3. Barriers to Adopting TLIs

Although applying TLIs can yield various sustainability benefits, the TLI application has not been smooth in many parts of the world. Accordingly, there is a need to identify the possible barriers to TLI application in Taiwan during the policymaking process. Understanding these constraints can potentially pave the way for Taiwanese policymakers to provide incentives or policies to promote sustainable urban roads.

Many publications have mentioned the barriers associated with the application of transportation livability practices to roadway projects. Thus, this research conducted an extensive literature review of scholarly studies in various countries to establish initial barriers. As a result, nine barriers were identified based mainly on Chang and Tsai's research [9], as listed in Table 1.

Table 1. Barriers to applying TLIs to Taiwan urban roads.

No.	Barriers	Description	References
B1	Unsupported owner requirement, government policy, and regulation	A lack of proper incentives from related programs, policies, and legislation that support and promote the innovative design and construction in urban street projects.	[9–11,29]
B2	Unfavorable in-situ condition	The green design has strong geographic footprints regarding natural preconditions at the project site, e.g., topography, project location, weather condition, and available land.	[9,10]
B3	Limited budget, schedule	A lack of financial investment and longer schedule in transportation livability practices for urban streets. Applying those practices might consume higher costs and time than conventional standards.	[9–11,29]
B4	Insufficient databases and information	A lack of a green road database and information will limit TLI adoption. Some indicators of green road design need sufficient and long-term data to make design reliable.	[9,11]
B5	Lack of specifications and standards	Existing specifications and standards in the roadway sector do not address TLI practices and thus can not compel stakeholders to employ them.	[9]
B6	Lack of professional knowledge and expertise	Limited experience and knowledge will hinder the willingness to apply TLIs to urban roadways. Green technologies are most complicated, and their application needs some technical considerations.	[9,10,29]
B7	Unavailable resources and techniques	Unavailability of resources (e.g., materials, energy, and workforces) or techniques (e.g., tools and methodologies)	[9,10,29]
B8	Absence of constructability, operability, and maintainability	Some sustainable practices in the design phase can lose their function without suitable construction and maintenance activities due to a lack of construction and maintenance reality understanding.	[9]
B9	Lack of interface coordination among stakeholders	An absence of lack of communication between the designers, little coordination of the design inputs, and unclear divisions of responsibility	[9,11,29]

3.1.4. Group Discussion

In order to make indicators adaptable to local conditions, local experts can help filter the potential TLIs and barriers identified through previous stages on their local relevance. This discussion was conducted by meeting three experts with more than 20 to 30 years of experience in highway research, design, and construction. Accordingly, the nine barriers reached consensus among experts and kept the same with previous identification.

With respect to TLIs, experts selected four TLIs, including pedestrian facilities (TL1), universal design (TL2), multimodal transportation (TL3), and utility facilities (TL4). Each indicator represents a function or a relevant aspect of livability characteristics of urban road projects. Those indicators can be structured into two layers, i.e., sub-indicator and requirements. The requirement level presents the thresholds or descriptive criteria that projects must achieve for each indicator goal. The detailed descriptions of four indicators and their 21 corresponding requirements are presented in Table 2. It is worth noting that some requirements were designed as optional selections. It means that the project team only needs to fulfill one of those requirements that fit the project's characteristics. For example, in TL1 indicators, requirements TL 1.1.1 and TL 1.1.2 are such above cases.

Table 2. The final TLIs and their corresponding requirements.

Indicators	Sub-Indicators	Requirements	
TL 1. Pedestrian facilities	TL 1.1 Sidewalk facilities	TL 1.1.1	o If the urban road width is ≥ 18 m, at least 2.5 m of sidewalk width on both sides.
		TL 1.1.2	o If the road width is < 18 m, at least 1.5 m of sidewalk width on both sides.
		TL 1.1.3	o Install new street furniture and other amenities or improve existing ones for pedestrians.
	TL 1.2. Intersection facilities	TL 1.2.1	o Install safety facilities for pedestrians at intersections, such as crosswalks, curb extensions, signal timing, pushbuttons, refuge islands.
		TL 1.2.2	o Providing a grade-separated pedestrian crossing (i.e., overpass or tunnel) at intersections.
TL 2. Universal Design	TL 2.1. Park and Ride	TL 2.1.1	o Provide bicycle parking spaces at or close to public transit stops or stations.
		TL 2.1.2	o Reserve areas for vehicle sharing services (i.e., shared bicycles, motorcycles) in the future.
	TL 2.2. Accessibility for disability	TL 2.2.1	o Provide facilities for disabled people's movements, such as proper gradients of footway for manual wheelchair users, tactile paving and audible signals, and seating.

Table 2. *Cont.*

Indicators	Sub-Indicators		Requirements
TL 3. Multimodal transportation	TL 3.1 Dedicated bus lanes	TL 3.1.1	o Implement physical or constructed changes to the existing roadway structure to provide dedicated lanes for public transit.
		TL 3.1.2	o Developed new continuous dedicated lanes for public transit, e.g., on-street bus lane, shoulder-running bus.
		TL 3.1.3	o Reserve rooms, such as using median strips, for future dedicated bus lane development.
	TL 3.2 Public transit stops	TL 3.2.1	o A minimum of 50% of public transportation stops are equipped with amenities, such as bus turnouts, lighting, stop signage, seating, itinerary, and timetable information.
		TL 3.2.2	o Provide enclosed shelters at least 50% of the public transit stops.
	TL 3.3 Bicycle facilities	TL 3.3.1	o Develop continuous and dedicated bicycle lanes placed on the sidewalk or shoulders.
		TL 3.3.2	o Adjusting existing street structures for dedicated bike lanes, such as removing parking space on one side to set bicycle lanes.
		TL 3.3.3	o Provide facilities for bikeways, e.g., differentiate bicycle lanes in different colors, colored bike facility, colored pavement, bike route wayfinding signage, and markings system.

Table 2. *Cont.*

Indicators	Sub-Indicators		Requirements
TL 4. Utility facilities	TL 4.1 Utility conflict	TL 4.1.1	o Investigate all existing utility facilities within the project boundary and put forward a test excavation implementation plan if necessary.
		TL 4.1.2	o Explain the utility conflict within the planned roads and propose solutions to conflicts between the pipeline facilities.
	TL 4.2 Multi-utility tunnels (MUTs)	TL 4.2.1	o Develop a MUT integrating all utilities along with a new road project in new urban areas.
		TL 4.2.2	o Develop a MUT for road projects in inner urban areas or developed areas.
	TL 4.3 Utility management	TL 4.3.1	o Having a management system to manage and maintain the utility network.

3.2. Bottom-Up Approach

This approach aims to assign weightings/scores to TLIs and identify critical barriers to their implementation. Among Multi-Criteria Decision Making (MCDM) tools for obtaining the weighting system and selecting the best alternatives, the AHP and Weighted Sum Model (WSM) methods are the leading methods and most widely used in green buildings and sustainable transportation infrastructure projects [30,31].

3.2.1. Method Selection

The AHP method was developed by Saaty in the 1970s to assign a weighting to alternatives in the decision-making process [32]. Based on these weights, decisionmakers can select the best attribute among several ones. By constructing the hierarchical structure of attributes, the AHP method allows users to break down a complicated decision problem into sublevels that easily understand, quantify, and compare the relative importance [33]. This method assembles the experts' judgments on pairwise comparisons on the relative importance over another attribute by applying a linguistic variable with a 9-point scale [32]. For a group of experts, the comparison matrix in the AHP can be made by integrating the various judgments under each expert through a geometric mean or arithmetic mean [34]. Therefore, the AHP is reliable and straightforward in allocating relative weights to indicators in sustainability assessment tools [31,35,36].

In order to identify critical barriers to TLI adoption, the WSM (a.k.a., simple additive weighting) was used. It is a common and effective method to assist in deciding the best alternatives in the MCDM methods [31]. The WSM method shows the advantage of a proportional linear transformation of the raw data [30]. In the current research, the WSM method is based on a total criticality score of each barrier. It was calculated by multiplying the average criticality scores provided to that barrier with different indicator weights directly calculated by the AHP, then by summing the products for all indicators. For the sake of data collection for the AHP and WSM analysis, the questionnaire was established, as described in the following subsection.

3.2.2. Questionnaire Development and Data Collection

The questionnaire form was first produced in English and then translated into Taiwanese to enable more involvement from the local experts, who may not be well-versed in English. The questionnaire collects expert judgments about the relative importance based on pairwise comparisons among indicators or requirements through Saaty's 9-point scale. Moreover, interviewees were asked to indicate how critical each of the nine barriers is to each indicator implementation in the Taiwan urban condition based on Likert's five scales from 1 = not critical to 5 = very critical. The questionnaire draft was piloted to test and refine data collection methods, content validity before full-scale implementation. The pilot study includes a professor and two graduate students who had extensive experience in sustainable road development.

In order to reflect the local condition in developing sustainable urban road projects, local experts were invited rather than public participation. Rating indicator importance level and barrier criticality would place undue demands onto a random population and probably overtax their competence in technical issues. Several criteria for selecting experts consist of (1) at least 15 years of experience working in local road projects; and (2) extensive knowledge in the field of transportation planning; or (3) extensive knowledge in the field of infrastructure design and management. Finally, 12 experts agreed to participate in individual interviews first, followed by a half-day meeting. The experts work in CPA, local public work agencies, local transportation planning agencies, and consultants in Taiwan. The large sample size in the AHP application is unnecessary because it may give arbitrary responses, thereby rendering a high degree of inconsistency [37]. Several previous researchers conducted the AHP methods with under 12 experts involved in the questionnaire survey. For example, Kamaruzzaman et al. [38] invited ten experts for establishing a weighting set of the refurbishment building rating tool in Malaysia, while Alwaer et al. [39] gathered 11 experts for AHP utilization to investigate the key indicators for sustainability intelligent buildings. Therefore, the sample size in this research can be acceptable in the AHP method focusing on specific aspects to provide valuable judgments into an empirical inquiry.

4. Data Analysis

4.1. AHP-Based Calculation

This study employed a five-step AHP calculation to assign weights to TLIs for a green urban road rating system in Taiwan, as shown in Figure 2.

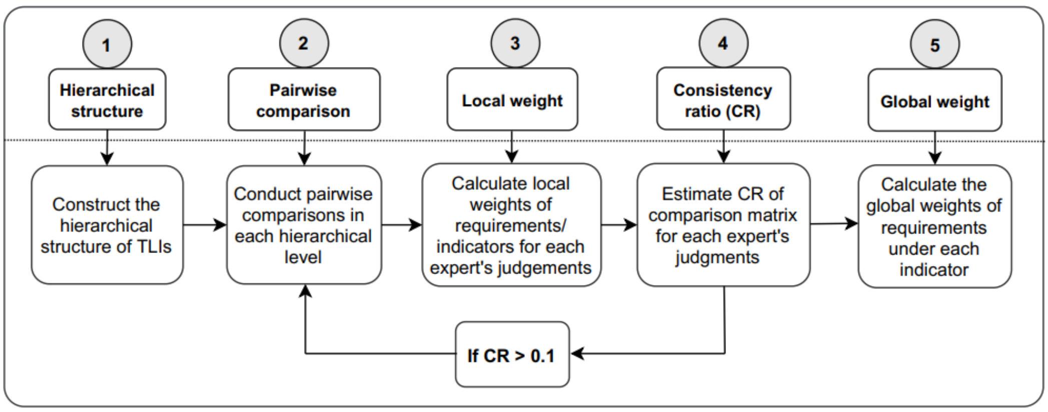

Figure 2. Five steps of the AHP-based calculation.

Step 1: Construct the hierarchical structure

The AHP is typically used to decompose complex problems (higher levels) into manageable elements (lower levels) presented in hierarchical levels. In this research, the hierarchical structure includes three levels (Figure 3): Level 1, the decision problem goal/objective (in the top-level); Level 2, the indicator; and Level 3, requirements. At the first level, the objective is to maximize the sustainability performance of urban road projects in terms of transportation livability characteristics. There were four indicators at level 2. At level 3, requirements can be classified into different groups (a.k.a., sub-indicators). It should be noted that the attribute number for each level can be acceptable for the AHP method since Saaty [40] stated that the number of attributes, in general, should be seven or less to minimize inconsistency in making pairwise comparisons.

Step 2: Establish pairwise comparison matrices

Once the hierarchical structure was constructed, pairwise comparison matrices were established at each hierarchy level (see Equation 1). For each of these matrices, pairwise comparisons were conducted between every two attributes (i.e., indicators, sub-indicators, requirements), using the converted 9-point scale, as shown in Table 3. There was a total of 13 matrices, including one 4 × 4 matrix, five 3 × 3 matrices, and seven 2 × 2 matrices:

At level 2: weights of indicators with one 4 × 4 matrix among four TLIs are determined.

At level 3: the weights of sub-indicators/requirements within each indicator are determined. For example, under TL1, the matrices include the comparison in pairs among (1) TL 1.1.1 vs. TL 1.1.2, (2) TL 1.1.1, TL 1.1.2, vs. TL 1.1.3, and (3) TL 1.2.1 vs. TL 1.2.2.

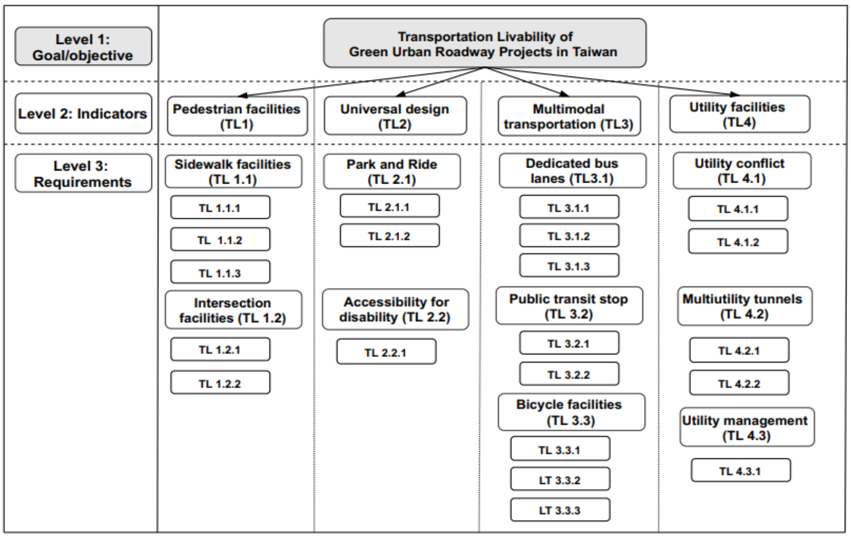

Figure 3. AHP hierarchy for TLIs.

$$A_e = \begin{pmatrix} a^e_{11}, & a^e_{12}, & \ldots, & a^e_{1m} \\ a^e_{21}, & a^e_{22}, & \ldots, & a^e_{2m} \\ \vdots & \vdots & & \vdots \\ a^e_{m1}, & a^e_{m2}, & \ldots, & a^e_{mm} \end{pmatrix} \quad (1)$$

where A_e is the individual comparison matrix among m attributes from Expert "e", a^e_{ij} is the relative importance between attributes "i" and "j" based on the judgment of expert "e", $i, j = 1, 2, \ldots, m$. $a^e_{ij} = 1/a^e_{ji}$ and $a_{ij} = 1$ when $i = j$.

Table 3. Saaty's 1–9 scale of pairwise comparison [32].

Weight	Definition	Explanation
1	Equal importance	Two indicators/requirements (Is/Rs) contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one I/R over another
5	Essential or strong importance	Experience and judgment strongly favor one I/R over another
7	Very strong importance	An I/R is strongly favored, and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one I/R over another is the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is necessary

Note: If the relative importance of an attribute "*i*" to "*j*" is equal to *k*, then the relative importance of "*j*" to "*i*" is 1/*k*.

Step 3: Local weight calculation

Due to the pairwise comparison derived from different experts, it is necessary to aggregate various pairwise comparison judgments into a single comparison matrix [34]. Among available methods (i.e., harmonic mean, geometric mean (GM), arithmetic mean), a single comparison matrix established by GM would be consistent if all individual comparison matrices have acceptable consistency [41]. Thus, it is suitable for handling group decision-making problems [36]. This research utilized GM to aggregate the different 12 experts' judgments, as shown in Equation (2).

$$A = \begin{pmatrix} \sqrt[n]{a_{11}^1 \times a_{11}^2 \times \ldots \times a_{11}^n}, \sqrt[n]{a_{12}^1 \times a_{12}^2 \times \ldots \times a_{12}^n}, \ldots, \sqrt[n]{a_{1m}^1 \times a_{1m}^2 \times \ldots \times a_{1m}^n} \\ \sqrt[n]{a_{21}^1 \times a_{21}^2 \times \ldots \times a_{21}^n}, \sqrt[n]{a_{22}^1 \times a_{22}^2 \times \ldots \times a_{22}^n}, \ldots, \sqrt[n]{a_{2m}^1 \times a_{2m}^2 \times \ldots \times a_{2m}^n} \\ \vdots \\ \sqrt[n]{a_{m1}^1 \times a_{m1}^2 \times \ldots \times a_{m1}^n}, \sqrt[n]{a_{m2}^1 \times a_{m2}^2 \times \ldots \times a_{m2}^n}, \ldots, \sqrt[n]{a_{mm}^1 \times a_{mm}^2 \times \ldots \times a_{mm}^n} \end{pmatrix} \quad (2)$$

where, 'n' is the number of experts (n = 12), see Equation 1 for a_{ij}^e.

After getting the single matrix of different experts' judgments, the weight of indicators/requirements can be calculated. Figure 4 presents a single matrix using GM from 12 experts to calculate a standardized matrix and the weights of four TLIs. Following this process for other comparison matrices, the local weights of all requirements in the TLI hierarchy were determined. Prior to the synthesizing procedure, the pairwise comparison matrices of each expert must meet the accepted consistency ratios that were demonstrated in the next step.

Step 4: Consistency ratio estimation

This step ensures the reliability and validity of each pairwise comparison matrix. The inconsistency may occur in the expert judgments, which can cause inaccurate weights. A typical example of inconsistency is that A is more important than B, and B is more important than C; however, when comparing A and C, C is measured as more important than A [42]. Thus, consistency checking represented by Consistency Ratio (*CR*) in the AHP is obligatory for comparison matrices among at least three attributes. The *CR* is acceptable if it is less than 0.10 [32]. If *CR* value exceeds 0.1, the pairwise matrix has some inconsistency in its comparisons. In such a case, the respondents were asked to re-review their pairwise comparisons during the interview.

Comparison matrix		TL1 Pedestrian facilities	TL2 Universal design	TL3 Multimodal transportation	TL4 Utility facilities	
TL1	Pedestrian facilities	**1.00**	2.45	0.44	1.06	
TL2	Universal design	0.41	**1.00**	0.26	0.46	
TL3	Multimodal transportation	2.29	3.81	**1.00**	2.29	
TL4	Utility facilities	0.94	2.18	0.44	**1.00**	
Sum		4.64	9.44	2.14	4.81	
Standardized matrix		Pedestrian facilities	Universal design	Multimodal transportation	Utility facilities	Weight (W)
TL1	Pedestrian facilities	1/4.64 = 0.22	2.45/9.44 = 0.26	0.44/2.14 = 0.20	1.06/4.81 = 0.22	(0.22+0.26+0.20 +0.22)/4 = **0.23**
TL2	Universal design	0.09	0.11	0.12	0.10	**0.10**
TL3	Multimodal transportation	0.49	0.40	0.47	0.48	**0.46**
TL4	Utility facilities	0.20	0.23	0.20	0.21	**0.21**
Sum		1.00	1.00	1.00	1.00	1.00

Figure 4. Synthesized pairwise comparison matrix and weight calculation for TLIs.

In order to calculate the *CR* value, three parameters, namely a Maximum Eigenvalue ($\lambda_{\max}$), Consistency Index (*CI*), and Random Indices (*RI*), were computed. Mathematically, as proposed by Saaty [32], the principal eigenvector of matrix A as the desired priority vector ω can be estimated by solving Equation (3), as follows:

$$A \times \omega = \lambda_{max} \times \omega \tag{3}$$

where, λ_{max} is the maximum eigenvalue of the matrix A and the corresponding eigenvector ω.

Then, λ_{max} is used as an essential parameter to calculate the consistency index (*CI*) for a matrix of m size by Equation (4):

$$CI = \frac{\lambda_{max} - m}{m - 1} \tag{4}$$

The consistency ratio (*CR*) is calculated by Equation (5). The random index (*RI*) of consistency is shown in Table 4.

$$CR = \frac{CI}{RI} \tag{5}$$

Table 4. The random index (*RI*) in the AHP for different *m* values [31].

m	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Figure 5 shows the calculation of *CR* value for the comparison matrix among four TLIs for Expert 1. This process was duplicated for other judgment matrices in this research. As a result, all the *CR* values for this research were less than the limitation of 0.10 recommended to demonstrate consistency using the AHP method. Hence, all expert judgments were employed for the AHP-based calculations.

	A	B	C	D	E	F	G	H	I
1			TL1	TL2	TL3	TL4			
2	**Comparison matrix**		Pedestrian facilities	Universal design	Multimodal transportation	Utility facilities			
3	TL1	Pedestrian facilities	1.00	2.00	0.50	2.00			
4	TL2	Universal design	0.50	1.00	0.33	1.00			
5	TL3	Multimodal transportation	2.00	3.00	1.00	3.00			
6	TL4	Utility facilities	0.50	1.00	0.33	1.00			
7	Sum		4.00	7.00	2.16	7.00			
8	**Standardized matrix**		Pedestrian facilities	Universal design	Multimodal transportation	Utility facilities	Weight (*W*)	Eigenvalue vector (*Ei*)	*Ei*/*W*
9	TL1	Pedestrian facilities	1/4=0.25	2/7=0.29	0.5/2.16=0.24	2/7=0.29	0.26	1.05	4.010
10	TL2	Universal design	0.13	0.14	0.15	0.14	0.14	0.57	4.006
11	TL3	Multimodal transportation	0.50	0.43	0.46	0.43	0.46	1.83	4.020
12	TL4	Utility facilities	0.13	0.14	0.15	0.14	0.14	0.57	4.006
13	**Note:**							λ_{max}	4.010
14	Weight (*W*): G9=Average (C9:F9) (C9, F9 are cells)				λ_{max} = Average (I9:I12)			*CI*	0.003
15	Eigenvalue vector (*Ei*) = MMULT (C3:F6,G9:G12) (Product of two matrices)				*CI* = (λ_{max} − *m*)/(*m* − 1) = (I13 − 4)/(4−1) (*m* is matrix size, *m* = 4)			***CR***	**0.004**
16	*Ei*/*W*: I9 = H9/G9				*CR* = (*CI*/*RI*) = I14/0.89 (*RI* for *m* = 4 is 0.89)				

Figure 5. *CR* calculation for a four TLIs' comparison matrix of Expert 1.

Step 5: Global weight calculation

The global priority weight of an attribute (i.e., indicator, sub-indicator, and requirement) at the lower level was calculated by multiplying its local weight with the local weight of the related attribute in previous levels in the hierarchical structure. It should be noted that local weights were identified directly by using the AHP. For indicators, their global weights are equal to those local weights as they are top-level in the hierarchical level. The below example shows the calculation of the global weights for requirements under indicator TL1 as follows:

$$W_{Glob} = \begin{pmatrix} w_{TL1.1.1} = w_{TL1.1.1Loc} \times w_{TL1.1Loc} \times w_{TL1Glob} \\ w_{TL1.1.2} = w_{TL1.1.2Loc} \times w_{TL1.1Loc} \times w_{TL1Glob} \\ w_{TL1.1.3} = w_{TL1.1.3Loc} \times w_{TL1.1Loc} \times w_{TL1Glob} \\ w_{TL1.2.1} = w_{TL1.2.1Loc} \times w_{TL1.2Loc} \times w_{TL1Glob} \\ w_{TL1.2.2} = w_{TL1.2.2Loc} \times w_{TL1.2Loc} \times w_{TL1Glob} \end{pmatrix} \quad (6)$$

where $w_{TL1Glob}$ indicates the global weight of *TL1*, $w_{TL1.iLoc}$ refers to the local weight of sub-indicator *TL1.i*, $w_{TL1.i.jLoc}$ denotes the local weight of requirement *j* under sub-indicator *TL1.i*.

4.2. WSM-Based Calculation

The collected data from the expert perceptions on barrier criticality were analyzed by the WSM method to identify the critical barriers, as presented below:

Step 1: The average criticality score (ACS) of the barrier (i.e., "i") with respect to indicator "j" was calculated by Equation (7).

$$ACS_{ij} = \frac{(n_5)_{ij} \times 5 + (n_4)_{ij} \times 4 + (n_3)_{ij} \times 3 + (n_2)_{ij} \times 2 + (n_1)_{ij} \times 1}{\left((n_5)_{ij} + (n_4)_{ij} + (n_3)_{ij} + (n_2)_{ij} + (n_1)_{ij}\right) \times 5} \quad (7)$$

where $(n_5)_{ij}$, $(n_4)_{ij}$, $(n_3)_{ij}$, $(n_2)_{ij}$, and $(n_1)_{ij}$ stands for the number of experts rating the critical level of 5 (very critical), 4 (critical), 3 (neutral), 2 (less critical), 1 (not critical); i = 1, 2, . . . , 9; j = 1, . . . , 4.

Step 2: Establish the criticality score matrix X:

$$X = \begin{pmatrix} x_{11}, & x_{12}, & \ldots, & x_{14} \\ x_{21}, & x_{22}, & \ldots & , x_{24} \\ \vdots & \vdots & & \vdots \\ x_{91}, & x_{92}, & \ldots, & x_{94} \end{pmatrix}; \; x_{ij} = ACS_{ij} \quad (8)$$

Step 3: Construct the normalized criticality score matrix R:

$$R = \begin{pmatrix} r_{11}, & r_{12}, & \ldots, & r_{14} \\ r_{21}, & r_{22}, & \ldots, & r_{24} \\ \vdots & \vdots & & \vdots \\ r_{91}, & r_{92}, & \ldots, & r_{94} \end{pmatrix} \quad (9)$$

For each column j (j = 1, 2, . . . , 4):

$$r_{ij} = \frac{x_{ij}}{x_{ij}^{\max}}; i = 1, 2, \ldots, 9 \quad (10)$$

Step 4: Construct the final criticality score matrix S:

$$S = \begin{pmatrix} r_{11} \times w_1, & r_{12} \times w_2, & \ldots, & r_{14} \times w_4 \\ r_{21} \times w_1, & r_{22} \times w_2, & \ldots, & r_{24} \times w_4 \\ \vdots & \vdots & & \vdots \\ r_{91} \times w_1, & r_{92} \times w_2, & \ldots, & r_{94} \times w_4 \end{pmatrix} \quad (11)$$

where w_j (j = 1, 2, . . . , 4) is the weight of TLIs retrieved from the AHP method.

Step 5: Determine the final criticality score of each barrier S_i^{WSM} by summing up all entries in each row in the matrix S.

$$S_i^{WSM} = \sum_{j=1}^{4} r_{ij} w_j \quad (12)$$

Step 6: Ranking nine barriers based on S_i^{WSM} values.

5. Results

5.1. Weight Allocation to TLIs

All TLI weights are presented in Table 5. According to the perception of selective experts, building urban road infrastructure for developing multimodal transportation (TL3) was the top importance of sustainable urban road projects with the weighting coefficient of 0.46. Pedestrian facilities (TL1) and utility facilities (TL4) were considered at the second and third place, respectively, for the priorities contributing to sustainability achievement of urban streets. Experts believed that universal design (TL2) for urban streets accounts for the least important compared with other indicators by the weight of 0.10.

Figure 6 shows the weights for different 21 requirements under four TLIs. The requirement TL3.1.1 (i.e., changing the existing structure for bus-dedicated lanes) obtained the highest importance level to transportation livability of urban streets in Taiwan. It is an interesting result in light of the dispute on how to develop dedicated bus lanes and reflects the recent controversial issue in urban road design [43]. In contrast, the requirements of TL1.1.3 (i.e., install street furniture/amenities for pedestrians) and TL4.1.1 (i.e., investigate all existing utility facilities) were viewed as the lowest weight for importance when applying to green street projects.

Table 5. Weighting coefficient for indicators in the livability transportation category.

Indicator		Local Weight	Subindicator	Local Weight	Requirement	Local Weight	Global Weight
TL1	Pedestrian facilities	0.23	TL 1.1. Sidewalk facilities	0.49	TL 1.1.1	0.34	0.037
					TL 1.1.2	0.42	0.046
					TL 1.1.3	0.24	0.026
			TL 1.2. Intersection facilities	0.51	TL 1.2.1	0.49	0.056
					TL 1.2.2	0.51	0.060
TL2	Universal Design	0.10	TL 2.1. Park and Ride	0.59	TL 2.1.1	0.47	0.028
					TL 2.1.2	0.53	0.032
			TL 2.2. Accessibility for disability	0.41	TL 2.2.1	1.00	0.043
TL3	Multimodal trans-portation	0.46	TL 3.1. Dedicated bus lanes	0.45	TL 3.1.1	0.43	0.089
					TL 3.1.2	0.33	0.067
					TL 3.1.3	0.24	0.049
			TL 3.2. Public transit stops	0.20	TL 3.2.1	0.49	0.046
					TL 3.2.2	0.51	0.048
			TL 3.3. Bicycle facilities	0.35	TL 3.3.1	0.41	0.067
					TL 3.3.2	0.41	0.066
					TL 3.3.3	0.18	0.028
TL4	Utility facilities	0.21	TL 4.1. Utility conflict	0.27	TL 4.1.1	0.46	0.026
					TL 4.1.2	0.54	0.031
			TL 4.2. Multiutility tunnels	0.40	TL 4.2.1	0.39	0.032
					TL 4.2.2	0.61	0.051
			TL 4.3. Utility management	0.33	TL 4.3.1	1.00	0.071

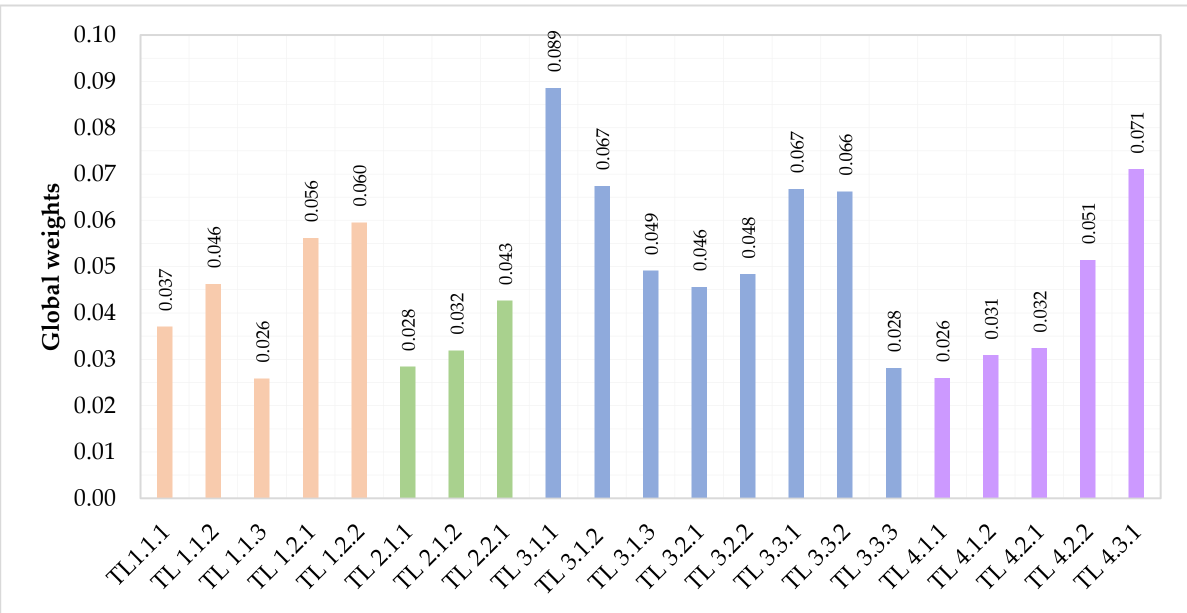

Figure 6. Weights of requirements under four TLIs.

5.2. Assigned Requirement and Indicator Score

Sustainability rating systems recognize the achievement level of sustainable projects based on the obtained points or their percentage complying with the total system score. Hence, scores of indicators and corresponding requirements must be designated, reflective of importance level, as specified by the indicator weights. Beiler [44] provides scores to indicators by rounding weights to one significant feature and multiplying by 10. However, several small weights under 0.05, such as TL1.1.3 (0.026), and TL2.1.1 (0.028), cannot be applied in this way. To this end, this study utilized the relative weights among requirements to assign a score, as follows. The requirement with the smallest weight was seen as the benchmarked score (i.e., 1), and then the relative weights of other requirements were determined based on the ratio between the global weights of such requirements and the smallest one. As shown in Table 5, the requirements of TL 4.1.1 and TL 1.1.3 have the lowest weight (i.e., 0.026) among the 21 requirements. Hence, the relative weights of other requirements were calculated and then rounded to integers to become the scores of each requirement, as shown in Table 6. Then, the overall point of each indicator was summed up by Equation (13).

$$IS_i = \sum_{j=1}^{n} RS_{ij} \tag{13}$$

where IS_i expresses the available score of an indicator "i" while RS_{ij} indicates the score of requirement "j" under indicator "i".

Table 6 presents the requirement and indicator scores in the transportation livability category. When assigning an overall score to each TLI, if there are optional requirements, only the requirement with the highest point was selected to contribute to an indicator score, such as TL 1.1.1 and TL 1.1.2 requirements in the TL1 indicator. When measuring the project performance for each requirement, the scoring approach accords with the principle of full points or no point. It means that users will obtain the full point if fulfilling that requirement and vice versa. After this scoring process, the indicator scores were 7 (TL1), 4 (TL2), 11 (TL3), and 7 (TL4). Accordingly, the weights based on new scores were estimated as 0.24 (TL1), 0.14 (TL2), 0.38 (TL3), and 0.24 (TL4). Compared with the weights assigned directly by expert judgments, the new weights approximately reflect the indicator priority derived from the AHP method. Therefore, it may conclude that the scoring allocation approach used in this work can be accepted.

5.3. Critical Barriers

Table 7 shows the final scores and ranking of nine barriers based on the WSM method. The experts believed that the four most significant barriers that hamper the adoption of TLIs into TGURs include (1) Unfavorable in-situ condition, (2) Lack of interface coordination among different stakeholders, (3) Unsupported owner requirement, government policy and regulation, and (4) Limited budget and schedule. Experts also believe that three barriers accounting for the lowest criticality are (1) Lack of professional knowledge and expertise, (2) Insufficient data, (3) Unavailable resources and techniques. In order to stimulate TLIs, appropriate strategies should be executed to overcome potential barriers. However, focusing on wide barriers can make policies/strategies less effective for public and private owners with limited resources and techniques, notably in developing countries. Hence, this research proposed policies that focus on eliminating the most significant barriers.

Table 6. The assigned points to requirements and indicators.

Indicators	Subindicators	Requirements	Global Weight	Relative Weight	RS	IS
TL 1. Pedestrian facilities	TL 1.1 Sidewalk facilities	TL 1.1.1 *	0.037	1.43	1	7
		TL 1.1.2 *	0.046	1.79	2	
		TL 1.1.3	0.026	1.00	1	
	TL 1.2. Intersection facilities	TL 1.2.1	0.056	2.17	2	
		TL 1.2.2	0.060	2.30	2	
TL 2. Universal Design	TL 2.1. Park and Ride	TL 2.1.1	0.028	1.10	1	4
		TL 2.1.2	0.032	1.23	1	
	TL 2.2. Accessibility for disability	TL 2.2.1	0.043	1.65	2	
TL 3. Multimodal transportation	TL 3.1 Dedicated bus lanes	TL 3.1.1 *	0.089	3.42	3	11
		TL 3.1.2 *	0.067	2.60	3	
		TL 3.1.3 *	0.049	1.90	2	
	TL 3.2 Public transit stops	TL 3.2.1	0.046	1.76	2	
		TL 3.2.2	0.048	1.87	2	
	TL 3.3 Bicycle facilities	TL 3.3.1 *	0.067	2.58	3	
		TL 3.3.2 *	0.066	2.56	3	
		TL 3.3.3	0.028	1.09	1	
TL 4. Utility facilities	TL 4.1 Utility conflict	TL 4.1.1	0.026	1.00	1	7
		TL 4.1.2	0.031	1.19	1	
	TL 4.2 Multiutility tunnels	TL 4.2.1 *	0.032	1.25	1	
		TL 4.2.2 *	0.051	1.99	2	
	TL 4.3 Utility management	TL 4.3.1	0.071	2.74	3	

Note: Consecutive requirements with (*) are optional requirements; RS: requirement score; IS: indicator score.

Table 7. Ranking the nine barriers.

	Indicators Weights	TL1 0.230 r_{i1}	TL2 0.100 r_{i2}	TL3 0.460 r_{i3}	TL4 0.210 r_{i4}	S_i^{WSM}	Ranking
B1	Unsupported owner requirement, government policy, and regulation	0.483	0.640	0.567	0.857	0.617	3
B2	Unfavorable in-situ condition	1.000	1.000	1.000	1.000	1.000	1
B3	Limited budget, schedule	0.379	0.440	0.367	1.000	0.511	4
B4	Insufficient databases and information	0.345	0.400	0.333	0.571	0.393	7
B5	Lack of specifications and standards	0.379	0.520	0.333	0.571	0.413	5
B6	Lack of professional knowledge and expertise	0.345	0.400	0.333	0.476	0.373	9
B7	Unavailable resources and techniques	0.345	0.400	0.333	0.524	0.383	8
B8	Absence of constructability, operability, and maintainability	0.345	0.440	0.367	0.524	0.403	6
B9	Lack of interface coordination among stakeholders	0.793	0.800	0.733	0.905	0.790	2

Note: r_{ij} is an entry in the normalized criticality score matrix R (see Equation 10), S_i^{WSM} is the final criticality score of each barrier (see calculation in Equation (12)).

According to expert opinions, the unfavorable in-situ condition was believed as the most critical barrier to TLI implementation. In line with this outcome, Bardal et al. [11] stated that accommodating adequate spaces in urban areas plays a vital role in constructing infrastructures for sustainable transport modes, notably dedicated lanes for buses or bikes for public and active transportation. Notably, existing streets in central areas with inherently limited space for transit modes can impede the adoption of these requirements [45]. Moreover, the construction and assessment conditions of buried utilities in urban areas are challenging since they mainly depend on the existing geological features that determine the capability of different pipeline performances [8]. Accordingly, some suggestions might assist in the removal of this barrier. First and foremost, instead of retrofitting the existing transportation infrastructure after the urban street development is completed, providing related infrastructures and facilities for facilitating transportation livability should be planned, designed, and constructed when development first occurs. Second, it is demanding to apply the latest techniques in constructing, operating, and maintaining underground tunnels. To substitute the traditional techniques wherein inspectors must 'see and touch' the defects in pipelines, the building information modeling (BIM) and the remote (a.k.a., non-manual) techniques, such as Ground Penetrating Radar (GPD), should be used to ensure the inspectors' health and safety and significantly increase the inspection efficiency.

The lack of interface coordination within and between institutions or stakeholders was considered the second place of most critical barriers. It might cause the immaturity of the livability characteristics of urban roads in Taiwan. For example, different utility owners have distinct responsibilities for delivering the service and maintenance of the pipeline. This barrier is expressed as unclear organizational responsibility, lack of capacity, conflicts within or between organizations, lack of communication between the designers, little coordination of the design inputs, and ambiguous divisions of responsibility. Similar to this finding, the USA House of Representatives [45] found that an uncoordinated effort by different government agencies acted as a significant disincentive to adopt green technologies to transportation infrastructure. In this regard, it is necessary to establish close coordination among stakeholders in the early phases of project planning and development. For example, all utility systems, both utility public and private owners, should coexist in the same facility (i.e., MUT) to minimize possible conflicts. In terms of governance, one single unit belonging to the public agency in charge of the urban roads must be made responsible for the security, operation, and maintenance of all utility systems and other infrastructure systems (e.g., bike/motorcycle share) within the project boundary, both public and private owners.

The third most critical barrier is the lack of owner requirements, government policies, and regulations at different government levels in Taiwan. There is growing evidence supporting that the mandatory requirements/regulations by the government at different levels define the sustainability goals of projects and enforce stakeholders to implement sustainable practices [46]. Indeed, designers and contractors always undertake works complying with regulatory requirements from public agencies. Accordingly, some strategies are demanding to overcome this barrier in Taiwan. Governments at different levels in Taiwan are designated as main stakeholders to enforce stronger legislation and create a policy framework to promote livability standards in urban road projects. Requirements associated with the TLIs should be incorporated to the maximum practical extent into updated specifications and regulations, such as statutory requirements of dedicated bike lanes, sidewalks for pedestrians of urban streets.

Another significant constraint to TLIs adoption is the limited budget and schedule. This barrier is associated with a high initial cost for providing priority facilities for active and public transportation, constructing MUTs. For example, setting utility facilities in MUTs might cause a double initial capital investment [47]. In line with the findings of previous studies, financing these practices for the transportation livability standards of urban streets is more demanding. One of the appealing measures is to adopt a congestion charge for private cars and motorcycles being driven within particular zones, which can be essential funding for sustainable infrastructures investment for bicycling, walking, and public transport. Moreover, financial incentives provide extra funding, for example, to the local agencies if they apply TLIs to urban street projects. Non-financial incentives (e.g., expedited permitting) prioritize the funded sustainable roadway projects. For the sake of time scheduling of utility construction, the utility owners can use a similar period of urban street construction for the strategic planning of utility systems.

6. Discussion

6.1. Transportation Livability Indicators

Among many indicators, incorporating livability characteristics into urban road projects plays a vital role in developing livable and sustainable communities. This is the first study that provides TLIs and their specific requirements for urban road projects in Taiwan. These TLIs can promote the healthy street approach, a human-centered approach for embedding public health in transport, and an emerging term in planning and designing urban roads [48].

The results of surveys revealed that multimodal transportation (TL3) is the most crucial indicator in the transportation livability category. As one of ten healthy street indicators [48], urban roads need to accommodate comfortably and safely on-road public transportation and bike use. The need for enough space for dedicated bus and bike lanes is vital and challenging. This expert judgment is echoed with the perspective of Li et al. [49] who stated that the implementation of exclusive lanes becomes difficult due to physical and cost constraints and institutional issues. However, Arancibia et al. [50] confirmed that this transformation positively impacts the urban economic environment. In addition to conventional bikes, cycle facilities should be suitable for other types, such as tricycles, cargo bikes, electric cycles. This finding will help practitioners or decisionmakers lean towards multimodal transportation during the planning and designing of urban streets.

Allocating pedestrian facilities makes urban roads more community-oriented and should be considered thoroughly at the early stage as one of the essential elements of the urban transportation system. A pedestrian facility indicator was assigned weights in the second place. Figure 6 shows the significant role in providing the prioritized traffic safety facilities (i.e., TL1.2.1) and building grade-separated crossings for pedestrians at intersections (i.e., TL1.2.2). According to Cui and Lin [51], underground tunnels or bridges are perceived to be much more expensive than other types of measures at the street level. However, in the case of high-speed and high-volume arterials, grade separation for walking is a feasible and appropriate measure.

Utility facilities facilitate the contribution of the basic needs to fulfill the livability standards of urban dwellers. The adoption of this indicator to Taiwan's urban right-of-way ranked at the third importance level among four TLIs. In TL4, the most significant concern is the pipeline network management (TL4.3.1), which refers to maintaining the buried utility facilities in case of avoiding damage to the surface street infrastructure, followed by requirements of the multi-utility tunnel (MUT) construction (i.e., TL4.2.1, TL4.2.2). Although requiring significant initial investment costs and complicated construction methods, adopting MUTs can enable the inspection, maintenance, and replacement activities cost-effectively while avoiding the damage of pavements induced by the trenching technique [52]. Because different public and private companies independently own various pipelines and equipment, conflicts may occur at the interference between utility facilities and surface infrastructures or within different utilities. To this end, urban utility facilities should be considered at the early stages of urban road projects by effective communication and coordination with utility owners or agencies [7].

With respect to the lowest weighting, indicator TL2 encourages the application of the universal design principle to urban streets. It is evident that this concept has been widely used worldwide, and some contents might already be in effect in local official documents. This fact supported the less attention on TL2 in the TGUR rating system. TL2 suggested in this study provides major features to facilitate convenient and comfortable movement for all users, especially people using wheelchairs or other mobility scooters. Moreover, another important consideration is the connection among all travel models through vehicle-sharing stations within the project boundary. Over past decades, bike-sharing, electric bike-sharing, and motorcycle sharing services have been realized as the alternative sustainable way of transportation by shifting personal mobility from ownership to service use [53].

6.2. Comparison with Existing Rating Systems

There is heterogeneity in indicator weights among rating systems that reflect the diverse concerns of developers based on the distinct conditions. This means that the indicator weights may vary from system to system, originating from different countries/regions. Hence, a comparative analysis was conducted to investigate differences and similarities in the allocated points to TLIs among existing systems and proposed TLIs in this research, as demonstrated in Figure 7.

In line with existing rating systems, this result finding shows the most attention on the multimodal transportation aspect for urban road projects by accounting for approximately 50% of total weight. On the other hand, the significant difference among rating systems stems from the indicator of utility facilities. Except for Greenroads, four current systems do not incorporate this issue into the indicator system. This might be due to these four rating systems focusing on highways instead of the local road system. Because utility facilities are prerequisite elements of urban roads, this study allocated utility concern the important roles to ensure the integration between urban roads and other infrastructure projects in cities. In accordance with the extensive application in street design, the universal design concept was defined in the local technical standards or regulations as one of the most important factors, specifically in developed nations. Thus, developers do not spend much proportion in the weighting system on the universal design principle to avoid double-counting. It can be briefly summarized that the findings in this research showed efforts to reflect the distinct characteristics of urban road projects and Taiwan conditions.

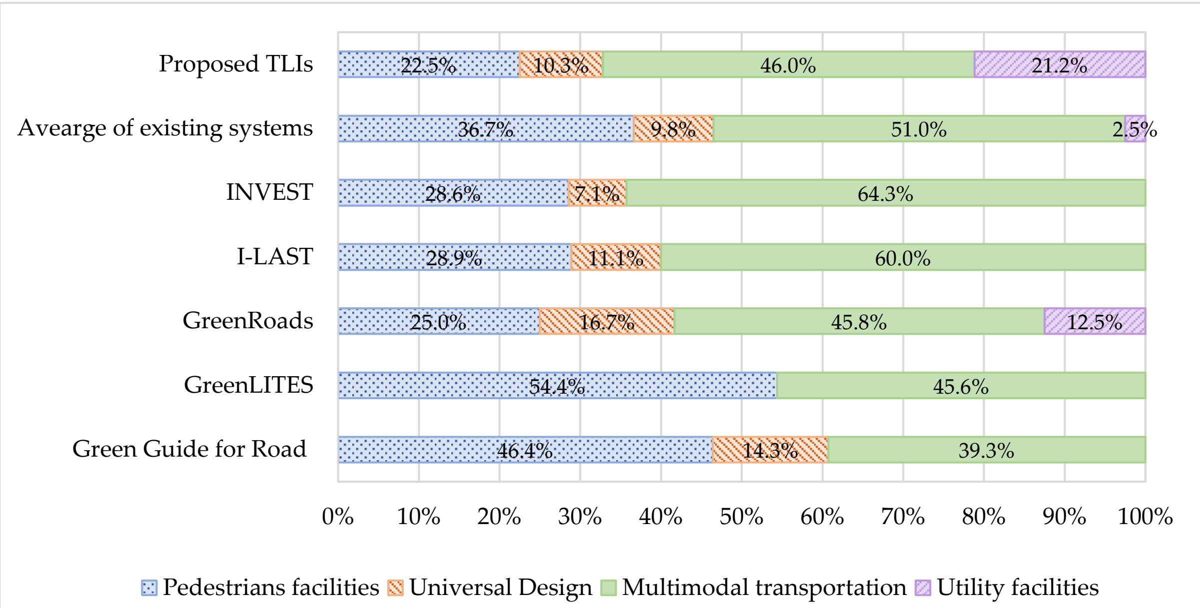

Figure 7. TLI weights in this research and existing rating systems.

6.3. Barrier Sensitive Analysis

One of the main issues when applying the MCDM methods is the changeability in data. Hence, a sensitivity analysis can be supportive of verifying the proposed model [54]. The sensitivity analysis can demonstrate that the slight modification in weights among indicators might provide a significant change in the final ranking of critical barriers. Since the indicator weights were often based on individual subjective judgments, the stability of barrier ranking under varying indicator weights should be tested.

This research conducted the changing indicator weight for WSM in the sensitivity analysis. When an indicator weight is changed, other weights of indicators are decreased and increased by the proportional change of the indicator weight. Table 5 reveals that the TL3 indicator has the highest weight and thereby influences the other indicators. Accordingly, this indicator was selected with its weight varying from 0.1 to 0.9 with a 0.2 increment. Because the original weight of TL3 (i.e., 0.46) is close to 0.5, this value was not considered in the sensitivity analysis. The change in other indicator weights was calculated by the proportional adjustments in Equation (14).

$$wf_{adj.i} = \frac{\left(1 - wf_{ch.j}\right)}{\left(1 - wf_j\right)} \times wf_i \tag{14}$$

where $wf_{adj.i}$ = the adjusted weight factor of indicator "i" except weights of TL3, $wf_{ch.j}$ = changed indicator weight factor of TL3 (i.e., 0.1, 0.3, . . . , 0.9), wf_j = original indicator weight factor of TL3 (i.e., 0.46), wf_i = original weight factor of indicator "i" except the original weight of TL3.

Because of the alteration in the indicator weights, the final criticality score and the ranking might change in the sensitivity analysis. The variation in barrier ranking was illustrated in Figure 8 according to each value of the TL3 weight. Although there is a slight change in the barrier ranking, the order of the four most critical barriers, i.e., B2, B9, B1, and B3, remained constant following the changes in indicator weights in all possible combinations. Thus, it can be concluded that these barriers have more impact on the TLI adoption, and the TL3 indicator needs greater attention to promote the transportation livability characteristics of urban road projects in Taiwan. If these four barriers are eliminated, the remaining barriers are likely to be eliminated.

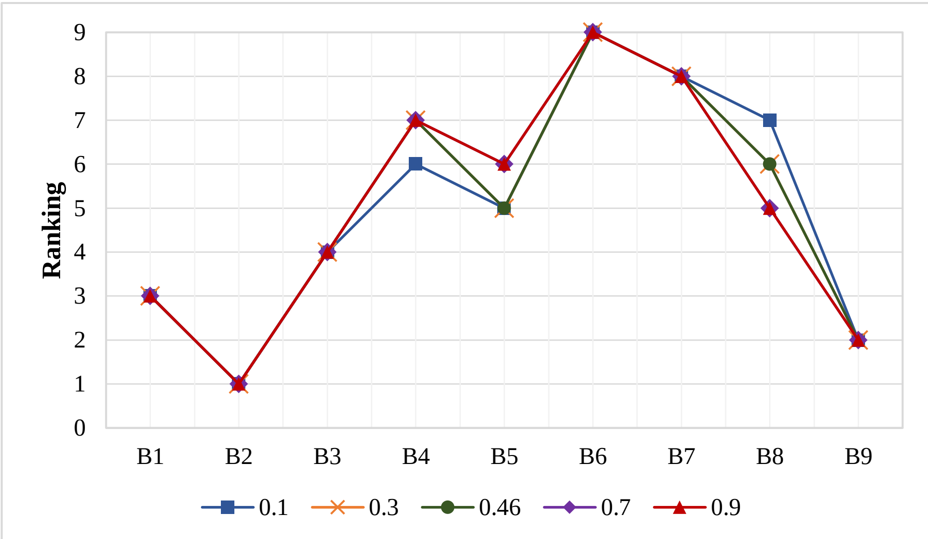

Figure 8. Ranking of barriers when changing TL3 weight. Note: B1: unsupported owner requirement, government policy, and regulation; B2: unfavorable in-situ condition; B3: limited budget, schedule; B4: insufficient databases and information; B5: lack of specifications and standards; B6: lack of professional knowledge and expertise; B7: unavailable resources and techniques; B8: absence of constructability, operability, and maintainability; B9: lack of interface coordination among stakeholders.

7. Conclusions

In order to deliver livability at the street project level, livability-oriented design requires new design approaches instead of conventional design guidelines and regulations. This study proposed the adaptive process, which integrates top-down and bottom-up approaches, to develop TLIs adaptable to the urban road programs in Taiwan. In the top-down method, drawing broadly from the literature review of existing rating systems and scholarly works, legal documents, and an expert discussion, four TLIs and nine barriers to their adoption in urban road projects in Taiwan were selected. Then, based on the AHP analysis derived from an expert panel survey in the bottom-up method, the weights and scores of indicators and corresponding requirements were allocated, as follows: pedestrian facilities (7 points), universal design (4 points), multimodal transportation (11 points), and utility facilities (7 points). In addition, the WSM method was carried out to identify the four most critical barriers, including (1) unfavorable in-situ conditions, (2) lack of stakeholders' coordination, (3) unsupported government policy and regulation, and (4) limited budget and schedule.

The study findings hold several practical implications for practitioners and decision-makers in the transportation industry. First, TLIs may enhance the awareness of planners and designers in terms of transportation livability management at the street project level. Thus, TLIs may be an advisory baseline for adopting those sustainable practices in urban road projects. Second, the decisionmakers also can tailor existing manual designs/specifications to TLI-related best practices. Integrating TLIs into the improved legal documents can compel practitioners to apply those indicators in urban road planning and design to improve the livability performance of urban streets in Taiwan. Hence, in the transportation industry, developing TLIs in a rating system can be an intermediate step to turn state of the art in transportation livability into standard practices in planning, designing, and constructing urban streets. It is worth noting that this integrating process needs to be based on the specific conditions to select the proper practices to improve their feasibility. Indicators with a low difficulty level to their application should be prioritized at the initial stage of the integration process to encourage practitioners to apply those practices to roadway projects. Third, identifying significant barriers enables the government to frame and execute appropriate incentives or regulations to promote the livability characteristic in street projects.

Although this research experimented only on transportation livability characteristics of urban street projects in Taiwan, the systematic approach integrating the top-down and bottom-up methods offers a direction for further topic discussions. Researchers and rating system developers in other regions/countries can extrapolate this transparent and reproducible research framework to develop indicators for a sustainable roadway rating system based on the local context. When applying this framework, future works need to refer to local regulatory documents and select local experts involved in the panel discussion and the questionnaire survey for the AHP and WSM methods in such countries/regions. The selected experts should have expertise and experience related to specific indicator categories of roadway projects, such as materials, environment and ecology, economy, and society. This implication reflects the unique roadway engineering conditions in establishing adaptability indicators/requirements and allocating corresponding weights.

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