Automated Compliance Analysis of Pedestrian Facilities with Accessibility Requirements

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Compliance Analysis of Pedestrian Facilities with Accessibility Requirements

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ABSTRACT

State and local governments are required by law to provide and maintain accessibility on their pedestrian facilities. They need to conduct, document, and update self-evaluations to identify non-compliant pedestrian facilities. This paper presents the development of a novel model for analysing the compliance of pedestrian facilities with accessibility requirements. The model provides original and unique capabilities that enable decision makers to: (1) quantify the degree of non-compliance of all types of pedestrian facilities including transit stops, on-street parking, and passenger loading zones; (2) estimate cost and labour-hours needed to achieve compliance; (3) prioritize upgrade projects for pedestrian facility types; (4) rank pedestrian facilities upgrade projects in multiple geographical regions based on their collective degree of non-compliance; and (5) classify pedestrian facilities based on the type of required upgrade. A case study that includes 1327 pedestrian facilities is analysed to evaluate the performance of the developed model and illustrate its capabilities.

Keywords: Assessment, ADA Transition Plan, Self-Evaluation, Pedestrian Facilities, Public Right-of-Way, PROWAG, ADA Compliance, Curb Ramp, Sidewalk.

INTRODUCTION

The U.S. Census Bureau reported in 2012 that people with disabilities represent 18.7% of the United States population (US Census Bureau 2012). Providing accessible facilities for this...
significant portion of the population is essential to avoid discrimination against people with
disabilities and ensure their active participation in society. This prompted the United States
Congress to enact several laws to prohibit discrimination against people with disabilities,
including (1) the Architectural Barriers Act (ABA) in 1968 (42 U.S.C. §§4151 et seq., 1968), (2)
the Rehabilitation Act in 1973 (29 U.S.C. § 701 et seq., 1973), and (3) the Americans with
public agencies to provide accessibility to people with disabilities on their sidewalks and
pedestrian facilities (Anderson et al. 1995).

The inability of a number of public agencies to comply with the aforementioned
accessibility laws has resulted in costly settlements in recent years, including $1.4 billion
settlement by the City of Los Angeles in 2015 (“Willits v. City of L.A.” 2016), $1.1 billion
settlement by California Department of Transportation (Caltrans) in 2010 (“CDR v. Caltrans”
2010), and $50 million settlement by the City of Chicago in 2007. The aforementioned
settlements highlight the pressing need for compliance with the latest state and federal
accessibility laws and regulations in order to provide and maintain accessibility for people with
disabilities on sidewalks and pedestrian facilities and avoid costly non-compliance penalties.

To achieve compliance with federal accessibility laws, state and local governments need
to perform a Self-Evaluation process to assess their policies, practices, and structures in order to
identify any barriers that deny or limit the participation of individuals with disabilities in their
programs, services, or activities (U.S. Department of Justice 1994). This self-evaluation process
must identify non-compliant sidewalks and pedestrian facilities (“Barden v. Sacramento” 2002)
and its results must be documented, kept on record, and updated regularly (U.S. Department of
Justice 1994).
To perform the aforementioned self-evaluation process, state and local governments are required to measure and record the conditions, dimensions, and geometry of existing sidewalks and pedestrian facilities and evaluate their compliance with accessibility requirements (U.S. Department of Justice 1994). Current practices for conducting self-evaluations often require manual data processing using paper forms and spread sheets to compare existing conditions of sidewalks and pedestrian facilities to accessibility requirements in order to assess their compliance (Axelson et al. 1999). These manual practices for conducting self-evaluations are labour intensive, time consuming, and error prone, which limits the ability of public agencies to efficiently and comprehensively perform and update these required self-evaluations. To overcome this limitation, there is a pressing need to develop a novel methodology that is capable of evaluating the degree of non-compliance of pedestrian facilities with accessibility requirements.

A number of related research studies were conducted to support state and local governments in (1) identifying the required degree of accessibility for sidewalks and pedestrian facilities, and (2) evaluating the compliance of these facilities with accessibility requirements. The first group of studies that focused on identifying accessibility requirements utilized field experiments and surveys to study the impact of varying dimensions of pedestrian facilities on the mobility, safety, and comfort of people with disabilities. For example, Kockelman et al. (2002) conducted a field study to identify critical sidewalk cross slopes that place pedestrians into unacceptable levels of effort or discomfort and reported that the maximum sidewalk cross slope that provides accessibility can range from 5.5% to 6.0%. In this study, people using cane, crutch, or brace and manual wheelchair users who were up to 80 years old were required to traverse 13.75 meters (45 feet) long sidewalk sections with 5% running slope and varying cross slopes
while monitoring their heart rates and level of discomfort. In another field study that was
corrected to evaluate the degree to which users of wheelchairs perceive differences in the
running and cross slope of ramps, Vredenburgh et al. (2009) reported that a ramp should not
exceed a maximum cross slope of 5% or a maximum running slope of 7%.

The second group of studies developed varying procedures to assess the compliance of
existing conditions of pedestrian facilities with accessibility requirements. These assessment
procedures included: (a) Sidewalk Assessment Process (SWAP) that was developed in a Federal
Highway Administration (FHWA) study that was conducted to evaluate the accessibility of
sidewalks, curb ramps, medians, refuge islands, and driveway crossings (Axelson et al. 1999;
FHWA 2001); (b) GIS-based pedestrian audit tool that was developed by Schlossberg et al.
(2007) that required surveyors to provide their subjective assessment on whether pedestrian
facilities comply with accessibility requirements or not; and (c) Ultra-Light Inertial Profiler ADA
system (ULIP-ADA) that was developed in an FHWA pilot program that utilized laser scanners
to capture, process, and record sidewalk dimensions and geometry in a GIS geodatabase format
and required the subjective judgement of assessors on the compliance of pedestrian facilities
with accessibility requirements (City of Bellevue 2008; Loewenherz 2010).

Despite the significant contributions of the aforementioned studies, they are incapable of:
(1) quantifying the degree of non-compliance of transit shelters, on-street parking, and passenger
loading zones with accessibility requirements; (2) estimating the cost and labour-hours needed to
upgrade non-compliant pedestrian facilities in order to achieve compliance; (3) generating a non-
compliance index for each type of pedestrian facilities such as sidewalks and curb ramps; and (4)
identifying a non-compliance index for a specific geographical location that represents the
overall compliance of all pedestrian facilities in that location. To overcome these limitations, this
paper presents the development of a novel model for assessing the degree of non-compliance of pedestrian facilities with accessibility requirements.

**OBJECTIVE**

The research objective of this study is to develop a novel model for assessing the degree of non-compliance of pedestrian facilities with accessibility requirements to enable public agencies to maximize their compliance with the ADA self-evaluation requirement. The model is designed to support decision makers in state and local governments in identifying non-compliant sidewalks and pedestrian facilities in their public right-of-way and evaluating the degree of non-compliance of each of these facilities with accessibility requirements. The model provides the capabilities of (1) efficiently quantifying the degree of non-compliance of all types of pedestrian facilities in the public right-of-way with accessibility requirements including transit shelters, on-street parking spaces, and passenger loading zones; (2) estimating the cost and labour-hours needed to upgrade non-compliant pedestrian facilities; (3) generating a pedestrian type non-compliance index for each type of pedestrian facility to enable decision makers to rank these facility types based on their degree of non-compliance with accessibility requirements; and (4) identifying a region non-compliance index for a specific geographical region that represents the overall degree of non-compliance of all pedestrian facilities in that region to enable decision makers to prioritize future upgrade projects by comparing the degree of non-compliance of these regions. These original and unique capabilities of the developed model are designed to support decision makers in improving their efficiency and effectiveness in conducting the aforementioned federally-mandated self-evaluations and in prioritizing their planned upgrade projects to maximize compliance with accessibility requirements.
The model is developed in five main phases: (i) accessibility requirements analysis phase that identifies pedestrian facility types and their related accessibility requirements; (ii) non-compliance assessment phase that develops a Non-Compliance Index (NCI) to quantify the degree of non-compliance of each type of pedestrian facility in the public right-of-way with accessibility requirements; (iii) cost and labour-hours estimation phase that calculates the cost and labour-hours needed to upgrade non-compliant pedestrian facilities; (iv) collective non-compliance phase that aggregates the individual non-compliance indices of a group of pedestrian facilities based on their type and/or geographical location to enable their ranking and prioritization for upgrades; and (v) performance evaluation phase that analyses a case study to illustrate the use of the developed model and demonstrate its novel capabilities. The following sections provide a concise description of these five model development phases, as shown in Figure 1.

ACCESSIBILITY REQUIREMENTS ANALYSIS

The purpose of this phase is to analyse all accessibility requirements and identify all relevant metrics that represent the degree of non-compliance of pedestrian facilities with accessibility requirements. The degree of non-compliance of a specific pedestrian facility can be determined by comparing the existing conditions and measurements of that facility with accessibility requirements (El-Rayes et al. 2016). Accessibility requirements include (1) the Proposed Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way (PROWAG), which focuses on all types of pedestrian facilities that are built for the purpose of transportation of pedestrians in the public right-of-way (U.S. Access Board 2011); (2) Shared Use Path Accessibility Guidelines (SUPAG), which focuses on facilities that are built for either transportation or recreation of pedestrians and bicycles (U.S. Access Board 2011); and (3) Guide
for the Development of Bicycle Facilities (GDBF), which focuses on facilities that are mainly
designed to be used by bicycles (AASHTO 1999). These three guidelines have similar
requirements for sidewalks and shared use paths with the exception of few minor differences
such as the path width requirement which is specified to a minimum of 1.2 meters in PROWAG,
1.5 meters in SUPAG, and 2.4 meters in GDBF for shred use paths. While the main focus of this
paper is pedestrian facilities as listed in PROWAG, the developed model enables decision
makers to specify which standards they need to comply with. For example, decision makers can
elect to comply with PROWAG only, SUPAG only, GDBF only, or the strictest of any
combination of the three.

When a pedestrian facility (e.g. a curb ramp or sidewalk) does not meet the minimum
accessibility requirements specified by state and federal laws and regulations, the pedestrian
facility is considered non-compliant with these laws and regulations (U.S. Access Board 2011a).
This binary classification of pedestrian facilities as either compliant or non-compliant was
reported to be ineffective for assessing the degree of non-compliance of sidewalks and pedestrian
facilities (CCRPC 2016; City of Clayton 2014). The cause of non-compliance for these non-
compliant facilities can be due to major or minor deviations from the minimum accessibility
requirements. While major deviations from accessibility requirements often render facilities to be
fully inaccessible for people with disabilities, minor deviations often enable facilities to be
partially accessible. For example, a 0.6 meter wide and a 1.05 meter wide sidewalks are both
classified as non-compliant because their width is less than the required 1.2 meter minimum
width. In this example however, the 0.6 meter wide sidewalk is fully inaccessible while the 1.05
meter wide sidewalk can provide partial accessibility for pedestrians travelling in one direction
(PROWAAC 2007).
To overcome the limitation of the aforementioned binary classification of compliant or non-compliant, the present model is designed to distinguish between varying degrees of non-compliance by developing a novel non-compliance index (NCI). NCI represents the degree of non-compliance for pedestrian facilities using a scale that ranges from 0.0% for fully compliant facilities to 100.0% for fully non-compliant. NCI of a given pedestrian facility is calculated in the present model by identifying the degree of deviation between its existing conditions, measurements, and geometry and its specified accessibility requirements. The model is designed to calculate NCI for all pedestrian facility types including (1) sidewalks, (2) curb ramps, (3) crosswalks, (4) pedestrian signals, (5) refuge islands, (6) transit stops, (7) on-street parking spaces, and (8) passenger loading zones (U.S. Access Board 2011a). Each of these pedestrian facility types has accessibility requirements that must be satisfied in order to achieve compliance with accessibility laws and regulations, as shown in Figure 2.

**NON-COMPLIANCE ASSESSMENT**

The purpose of this phase is to develop a novel non-compliance index $NCI^p_i$ that represents the degree of non-compliance of each pedestrian facility type $p$ with accessibility requirements, as shown in equation (1).

$$NCI^p_i = \sum_{r=1}^{R} W^p_r \times S^p_{i,r}$$  \hspace{1cm} (1)

Where, $NCI^p_i$ is non-compliance index for pedestrian facility of type $p$ that is located in geographical location $i$, $p$ is pedestrian facility type (see Figure 2), $i$ is geographical location of pedestrian facility, $r$ is accessibility requirement for each pedestrian facility type $p$ (see Figure 2), $R$ is total number of accessibility requirements for pedestrian facility type $p$ (see Figure 2),
$W_{r}^{p}$ is relative importance weight of accessibility requirement $r$ for pedestrian facility type $p$, and $S_{i,r}^{p}$ is non-compliance score of pedestrian facility type $p$ with accessibility requirement $r$ in geographical location $i$.

The non-compliance index $NCI_{i}^{p}$ for each pedestrian facility type $p$ represents the weighted average of non-compliance scores including all its accessibility requirements. For example, the non-compliance index for a sidewalk in location $i$ ($NCI_{i}^{1}$) is determined by calculating the weighted average of non-compliance scores of all the sidewalk accessibility requirements ($r = 1$ to $7$) including its width, running slope, cross slope, surface discontinuities, change in level, bevel status, and protruding objects (U.S. Access Board 2011a). $NCI_{i}^{1}$ is calculated using equation (1) based on the weight of each accessibility requirement $W_{r}^{1}$ and its non-compliance score $S_{r,i}^{1}$. These weights $W_{r}^{p}$ can be specified by decision makers to reflect the relative importance of each accessibility requirement $r$ (see example in Table 1), and the non-compliance score $S_{r,i}^{1}$ can be determined based on the existing condition of the sidewalk and the specified ranges shown in Table 1. It should be noted that the weights $W_{r}^{p}$ and non-compliance scores $S_{r,i}^{1}$ in Table 1 were identified based on the reported values in a number of existing reports and best practices that are utilized by several state and local governments (CCRPC 2016; City of Clayton 2014; City of Bellevue 2008). Similarly, a list of accessibility requirements and their non-compliance score ranges were identified for each of the remaining pedestrian facility types in Figure 2 ($p = 2$ to $8$).

The non-compliance score $S_{r,i}^{p}$ is calculated in the present model to represent the degree of non-compliance of pedestrian facility $p$ in location $i$ with accessibility requirement $r$. Compliance with the aforementioned accessibility requirements can be verified using a wide
range of techniques that vary in the type and frequency of measurements required for verification. Each accessibility requirement can only be verified using one verification technique that requires a specific set of measurements to be conducted and sometimes repeated with a specific frequency depending on pedestrian facility type and the accessibility requirement under verification. This model utilizes a novel verification methodology that conducted a comprehensive analysis and categorization of all accessibility requirements that need to be complied with for all pedestrian facility types. This resulted in identifying four main verification categories: (1) continuous verification, (2) discrete verification, (3) single verification, and (4) presence verification, as shown in Figure 2. Table 2 presents four examples of these accessibility requirements for three pedestrian facility types along with their verification procedure and technique. In Table 2, the sidewalk width requirement example can only be verified by conducting “continuous measurements” of the sidewalk width along its entire length (U.S. Department of Justice 1994), while the sidewalk surface discontinuities requirement example can only be verified by taking multiple “discrete measurements” wherever these discontinuities are encountered along the length of the sidewalk (U.S. Access Board 2011a). Similarly, the height of pedestrian push-buttons requirement example can only be verified by taking a “single measurement” of the button height at each pedestrian signal, while the detectable warning surfaces (DWS) requirement example can only be verified by confirming the “presence” of DWS at curb ramps or other locations. These four categories of verification techniques are used to (a) classify the aforementioned accessibility requirements of all pedestrian facilities into four categories as shown in Figure 2; and (b) calculate the non-compliance score $S_{r,d}$ for each of these accessibility requirement categories as described in the following sections.
Continuous verification

This compliance verification category requires collecting continuous measurements along the entire length of the pedestrian facility to calculate its non-compliance score $S_{i,r}^p$. As shown in equation (2), $S_{i,r}^p$ is calculated in this category by dividing the pedestrian facility into several segments, determining non-compliance score $S_{i,r,a}^p$ for each segment $a$, and calculating the average of these scores to find $S_{i,r}^p$ for the entire pedestrian facility. For example, the non-compliance score $S_{i,1}^1$ for the sidewalk width located in geographical location $i$ is calculated by (i) dividing the entire length of the sidewalk into several segments $a \in (1, 2, 3, ..., A_i^1)$ based on their width, as shown in Figure 3; (ii) determining the sidewalk width non-compliance score $S_{i,1,a}^1$ of each segment $a$ based on its minimum width ($width_a$) and scoring criteria (see example in Table 1); and (iii) calculating an average $S_{i,1}^1$ for the entire sidewalk. This segmentation of the sidewalk example is often needed when the measurement of the requirement under verification varies along the length of the sidewalk. For example, verifying the compliance of the sidewalk width often requires dividing the entire sidewalk length into segments based on variations in its width. The sidewalk in this example needs to be divided to include an additional segment whenever there is a change in its width, as shown in Figure 3.

$$S_{i,r}^p = \frac{\sum_{a=1}^{A_i^p} \left( \frac{L_a}{BL_i^p} \times S_{i,r,a}^p \right)}{A_i^p}$$  \hspace{1cm} (2)

Where, $S_{i,r}^p$ is non-compliance score for the requirement $r$ of pedestrian facility located in geographical location $i$, $a$ is segment of pedestrian facility, $A_i^p$ is total number of segments in pedestrian facility of type $p$ located in geographical location $i$, $L_a$ is length of segment $a$ of the
pedestrian facility, \( BL_i^P \) is total length of pedestrian facility, and \( S_{i,r,a}^P \) is non-compliance score of segment \( a \) of the pedestrian facility.

**Discrete verification**

This compliance verification category requires conducting discrete measurements along the entire length of a pedestrian facility to calculate its non-compliance score \( S_{i,r}^P \). As shown in equation (3), \( S_{i,r}^P \) is calculated in this category by identifying points \( b \in (1, 2, 3, \ldots, B_i^P) \) where a change in specific pedestrian facility dimensions occur, assigning a non-compliance score to each of these points based on its dimensions, and calculating the average of these scores to find \( S_{i,r}^P \) for the entire pedestrian facility. For example, sidewalk surface discontinuity non-compliance score \( S_{i,4}^1 \) for a sidewalk in location \( i \) is calculated by (i) identifying surface discontinuities \( b \in (1, 2, 3, \ldots, B_i^1) \) in sidewalk, as shown in Figure 4; (ii) determining a non-compliance score \( S_{i,4,b}^1 \) for each surface discontinuity based on its vertical change in level \( SD_b \) and scoring criteria (see example in Table 1); and (iii) calculating an average sidewalk surface discontinuity non-compliance score \( S_{i,4}^1 \) for the entire sidewalk.

\[
S_{i,r}^P = \frac{\sum_{b=1}^{B_i^P} (S_{i,r,b}^P)}{B_i^P} \times \frac{N_{i,r}^P}{N_{r,\text{max}}} 
\]  

Where, \( S_{i,r}^P \) is non-compliance index for requirement \( r \) of pedestrian facility located in geographical location \( i \), \( b \) is a point where a change in the pedestrian facility dimension is recorded, \( B_i^P \) is total number of points \( b \) where a change in the pedestrian facility dimension is recorded, \( S_{i,r,b}^P \) is non-accessibility score of requirement \( r \) of point \( b \) in pedestrian facility, \( N_{i,r}^P \) is...
number of points $b$ per meter in pedestrian facility, and $N^p_{r,\text{max}}$ is the maximum number of points $b$ per meter for all pedestrian facilities of type $p$ in the city.

**Single verification**

This compliance verification category requires conducting single measurements at each pedestrian facility to identify its non-compliance score $S^p_{i,r}$ by evaluating the compliance of its existing conditions with accessibility requirement $r$. For example, verifying the compliance of a pedestrian push-buttons with the accessibility requirement for its height requires conducting a single measurement of that height. This means that there is one value for existing conditions that needs to be verified to ensure compliance with accessibility requirements, as shown in Table 3. Other examples of accessibility requirements in this category include curb ramp width, curb ramp running slope, clear space length, and clear space width, as shown in Figure 2.

**Presence verification**

This compliance verification category requires verifying if the required feature is present, non-standard, or missing to identify its non-compliance score $S^p_{i,r}$ by evaluating the compliance of its existing condition with accessibility requirement $r$, as shown in the curb ramp detectable warning surface example in Table 4.

**UPGRADE COST AND LABOR-HOURS ESTIMATION**

The purpose of this phase is to estimate cost and labour-hours needed to ensure the compliance of non-compliant pedestrian facilities with accessibility requirements. The upgrade work includes installing, changing, or completely rebuilding elements of pedestrian facilities. The scope of the upgrade can be determined based on the accessibility requirements that are not met in the existing conditions of pedestrian facilities. For example, a curb ramp that is missing
DWS can become compliant if a DWS panel is installed without the need to change or rebuild the entire curb ramp. On the other hand, a curb ramp with a non-compliant width, length, or slope will have to be completely demolished and rebuilt in order to achieve compliance. Accordingly, the upgrade of pedestrian facilities in the present model is classified as (a) complete upgrade that requires the complete demolition and reconstruction of pedestrian facilities, or (b) partial upgrade that requires partial installation, alteration, or removal of specific non-compliant elements of pedestrian facilities, as shown in Figure 2. These two categories were used to calculate the estimated upgrade cost $UC^p_i$ and labour-hours $ULH^p_i$ required to achieve compliance with accessibility requirements, as described in the following sections.

**Complete upgrade**

This upgrade category requires the complete demolition and reconstruction of pedestrian facilities in order to achieve compliance with a specific set of accessibility requirements (see Figure 2). Upgrade cost and labour-hours for pedestrian facilities that do not meet accessibility requirements in this category can be calculated using equations (4) and (5).

$$UC^p_i = V^p_i \times TUC^p_i$$

(4)

Where, $UC^p_i$ is total upgrade cost for pedestrian facility of type $p$ that is located in geographical location $i$ (see Figure 2), $V^p_i$ is a binary variable that equals “0” if the pedestrian facility is compliant with all accessibility requirements $r$ in this category ($S^p_{i,r} = 0$) and equals “1” otherwise, and $TUC^p_{i,r}$ is user-specified total upgrade cost of pedestrian facility type $p$ in geographical location $i$. 

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\[ LH_i^P = V_i^P \times TLH_i^P \]  

(5)

Where, \( LH_i^P \) is total labor-hours for upgrading pedestrian facility of type \( p \) that is located in geographical location \( i \), \( V_i^P \) is a binary variable that equals “0” if the pedestrian facility is compliant with all accessibility requirements \( r \) in this category \( (S_{l,r}^P = 0) \) and equals “1” otherwise, and \( TLH_{l,r}^P \) is user-specified total labour-hours for upgrading pedestrian facility type \( p \) in geographical location \( i \).

In the present model, if the aforementioned complete upgrade is required there will be no need to estimate or execute partial upgrades. Otherwise, the model will estimate the partial upgrade cost and labour hours for non-compliant facilities, as described in the following section.

**Partial upgrade**

This upgrade category requires partial installation, alteration, or removal of non-compliant elements of pedestrian facilities in order to achieve compliance with a set of accessibility requirements without rebuilding the entire pedestrian facility. Upgrade cost and labour-hours for pedestrian facilities that do not meet accessibility requirements in this category can be calculated using equations (6) and (7).

\[ UC_i^P = \sum_{r=1}^{R} V_{l,r}^P \times PUC_{l,r}^P \]  

(6)

Where, \( UC_i^P \) is total upgrade cost for pedestrian facility of type \( p \) that is located in geographical location \( i \), \( r \) is accessibility requirement for each pedestrian facility type \( p \) (see Figure 2), \( R \) is total number of accessibility requirements in this category for pedestrian facility type \( p \) (see Figure 2), \( V_{l,r}^P \) is a binary variable that equals “0” if the pedestrian facility is
compliant with accessibility requirement \( r (s_{l,r}^p = 0) \) and equals “1” otherwise, and \( PUC_{l,r}^p \) is user-specified partial upgrade cost of pedestrian facility type \( p \) with respect to accessibility requirement \( r \) in geographical location \( i \).

\[
LH_i^p = \sum_{r=1}^{R} V_{i,r}^p \times PLH_{i,r}^p \tag{7}
\]

Where, \( LH_i^p \) is total labour-hours required for upgrading pedestrian facility of type \( p \) that is located in geographical location \( i \), \( r \) is accessibility requirement for each pedestrian facility type \( p \) (see Figure 2), \( R \) is total number of accessibility requirements in this category for pedestrian facility type \( p \) (see Figure 2), \( V_{i,r}^p \) is a binary variable that equals “0” if the pedestrian facility is compliant with accessibility requirement \( r (s_{l,r}^p = 0) \) and equals “1” otherwise, and \( PLH_{i,r}^p \) is user-specified partial labour-hours required for upgrading pedestrian facility type \( p \) with respect to accessibility requirement \( r \) in geographical location \( i \).

**COLLECTIVE NON-COMPLIANCE**

The purpose of this phase is to aggregate the previously calculated individual non-compliance indices \( NCI_i^p \), upgrade costs \( UC_i^p \), and labour-hours \( LH_i^p \) of a group of pedestrian facilities based on their type \( p \) and/or geographical region \( g \) to enable their ranking and prioritization for upgrades. The two collective non-compliance indices calculated in this phase are (a) pedestrian facility type non-compliance index \( NCI^p \), and (b) region non-compliance index \( NCI^g \). First, pedestrian facility type non-compliance index \( NCI^p \) is calculated in the present model by averaging all the previously calculated individual non-compliance indices \( NCI_i^p \) for each pedestrian facility type \( p \). Second, region non-compliance index \( NCI^g \) is
calculated by (1) computing pedestrian facility type non-compliance indices \( NCIP^p,g \) for the subset of all pedestrian facility types \( p \) that are located in the user-specified geographical region \( g \); and (2) computing a weighted average of all \( NCIP^p,g \) calculated in the previous step to identify a collective region non-compliance index \( NCIG \), as shown in equation (8).

\[
NCIG = \sum_{p=1}^{8} NCIP^p,g \times WP^p
\]  

(8)

Where, \( NCIG \) is collective non-compliance index for all pedestrian facilities in region \( g \), \( NCIP^p,g \) is collective non-compliance index for all pedestrian facilities of type \( p \) in the region \( g \), and \( WP^p \) is relative importance weight of pedestrian facility type \( p \).

The collective upgrade cost \( UC^g \), and collective labour-hours \( LH^g \) are calculated in the present model by adding all individual upgrade costs and labour-hours needed to upgrade each pedestrian facility in region \( g \), as shown in equations (9) and (10).

\[
UC^g = \sum_{j=1}^{J} UC_j
\]  

(9)

Where, \( UC^g \) is collective upgrade cost for all pedestrian facilities in region \( g \), \( UC_j \) total upgrade cost for pedestrian facility \( j \) in region \( g \), and \( J \) is number of pedestrian facilities in region \( g \).

\[
LH^g = \sum_{j=1}^{J} LH_j
\]  

(10)
Where, $L_{H^g}$ is collective upgrade cost for all pedestrian facilities in region $g$, $L_{H_j}$ total upgrade labour-hours for pedestrian facility $j$ in region $g$, and $J$ is number of pedestrian facilities in region $g$.

**PERFORMANCE EVALUATION PHASE**

The purpose of this phase is to analyse a case study to illustrate the use of the model and demonstrate its novel and unique capabilities. The case study requires assessing the degree of non-compliance of 1327 pedestrian facilities in a small town that includes all pedestrian facility types, as shown in Table 5. Decision makers need to assess the degree of non-compliance of these pedestrian facilities in order to comply with the federal mandate to conduct self-evaluations and prioritize these facilities for future upgrade projects.

For this case study, the required input data by the model can be grouped in two main categories: (a) dimensions and slopes of all sidewalks and pedestrian facilities; and (b) the geographical regions that decision makers need to calculate their collective non-compliance index $NCI^g$. The first category of input data is readily available in most municipalities sidewalk network inventory databases (CCRPC 2016; City of Bellevue 2008; City of Clayton 2014). This data can be captured and recorded using several procedures and technologies, including (1) manual measurement tools and techniques such as tape measures, traditional levels, and measuring wheels; (2) computer vision and remote sensing techniques such as photogrammetry; (3) terrestrial laser scanning; (4) LiDAR scanning technologies; and (5) drone based data collection. It should be noted that the developed model is designed to provide decision makers with the flexibility of assessing and analysing any type of existing conditions data regardless of its capture procedures and technologies. The model utilizes this input data to calculate, (1) the
non-compliance index $NCI_i^p$ for each of the 1327 pedestrian facilities in this case study; (2) the collective non-compliance index $NCI^p$ for each pedestrian facility type $p$; (3) the collective non-compliance index $NCI^g$ for each user-specified region $g$ in the case study using the aforementioned calculation procedure.

The generated results for this case study illustrate the novel and unique capabilities of model that can be used by decision makers to (a) efficiently quantify the degree of non-compliance of all types of pedestrian facilities including transit shelters, on-street parking spaces, and passenger loading zones; (b) calculate estimated total cost and labour-hours needed to upgrade each pedestrian facility to achieve compliance; (c) assess the degree of non-compliance of each pedestrian facility type to identify facility types that are in urgent need for upgrades; (d) prioritize pedestrian facilities upgrade projects in multiple regions based on their region non-compliance index; and (e) classify pedestrian facilities based on the type of required upgrade to achieve compliance with accessibility requirements.

The capability of the present model to efficiently quantify the degree of non-compliance of pedestrian facilities can be illustrated by its ability to (a) analyse all types of pedestrian facilities including transit shelters, on-street parking spaces, and passenger loading zones using the aforementioned novel assessment methodology (see Figure 2); and (b) complete the computational assessment of all the aforementioned 1327 pedestrian facilities in 2.053 seconds with an average computational time of 0.0015 seconds per pedestrian facility. This computational efficiency enables the model to perform compliance assessment and estimate upgrade cost and labour-hours for all types of pedestrian facilities for large datasets that are often encountered in larger cities. For example, the accessibility requirements for 48,334 pedestrian
facilities that are included in a dataset for a city with a population of 204,897 residents (CCRPC 2016) can be assessed using the present model in approximately 75 seconds.

The model also provides the capability of assessing the collective degree of non-compliance for each pedestrian facility type to enable decision makers to prioritize the upgrade of these different types of facilities. For example, the case study results illustrate that on-street parking spaces suffer from the highest level of non-compliance and therefore they have the greatest need for upgrades as shown in Figure 5. In addition, the model calculates the ranges of non-compliance for each pedestrian facility type to highlight the deviation of individual facilities from the collective index. For example, the results indicate that pedestrian signals exhibit varying degrees of non-compliance ranging from 0.0% to 82.5%; while sidewalks exhibit a narrower range of 0.0% to 33.8% (see Figure 5).

The model can also be used to prioritize pedestrian facilities upgrade projects in multiple geographical regions based on their non-compliance index. This enables decision makers to rank upgrade projects based on the overall non-compliance in each region. For example, the second region in this case study has the highest collective non-compliance index of 39.1% and therefore it has the greatest need for upgrade, as shown in Figure 6. This region contains 59 pedestrian facilities including 37 sidewalks, 15 curb ramps, 2 crosswalk, 1 pedestrian signal, 1 refuge island, 1 transit stop, 1 on street parking, and 1 passenger loading zone.

Additionally, the model is capable of calculating the estimated upgrade cost and labour-hours needed to bring all pedestrian facilities in a specified geographical region into compliance with accessibility requirements. The model is capable of integrating cost and labour data from several sources including DOT databases, construction companies, or construction manuals. For
example, basic cost data form RSMeans manual was used to estimate upgrade costs and labour-hours for all regions in this case study (RSMeans 2016). The results show that the second region requires an upgrade cost of $148,700 and 1186 labour-hours in order to achieve compliance with accessibility requirements, as shown in Figure 7 and Figure 8.

Furthermore, the model enables decision makers to classify pedestrian facilities as (a) complying, (b) non-compliant requiring partial upgrade, or (c) non-compliant requiring complete upgrade. This capability assists decision makers in state and local governments in evaluating and visualizing general conditions of each pedestrian facility type and determining the urgency of its upgrade. For example, the model can be used to report the number of compliant facilities, non-compliant requiring partial upgrade, and non-compliant requiring complete upgrade for each facility type in the case study, as shown in Figure 9.

SUMMARY AND CONCLUSIONS

This paper presented a novel model for assessing the degree of non-compliance of pedestrian facilities with accessibility requirements. The model was developed in five main phases: (1) accessibility requirements analysis phase that identified pedestrian facility types and their related accessibility requirements, (2) non-compliance assessment phase that quantified the degree of non-compliance of each pedestrian facility with accessibility requirements; (3) cost and labour-hours estimation phase that calculates the estimated upgrade cost and labour-hours needed to upgrade non-compliant pedestrian facilities; (4) collective non-compliance phase that aggregated the individual non-compliance indices, upgrade cost, and labour-hours of a group of pedestrian facilities based on their type and/or geographical region; and (5) performance evaluation phase that analysed a case study to illustrate the use of the developed model and demonstrate its novel capabilities. The analysis of the case study illustrated the novel capabilities
of the model in (a) efficiently quantifying the degree of non-compliance of all types of pedestrian
facilities including transit shelters, on-street parking spaces, and passenger loading zones; (b)
calculating the estimated upgrade cost and labour-hours required to achieve compliance, (c)
assessing the degree of non-compliance of each pedestrian facility type to identify facility types
that are in urgent need for upgrades; (d) prioritizing pedestrian facilities upgrade projects in
multiple regions based on their non-compliance index; and (e) classifying pedestrian facilities
based on the type of required upgrade to achieve compliance with accessibility requirements.
The model was able to assess the degree of non-compliance with accessibility requirements for
1327 pedestrian facilities that cover all pedestrian facility types and calculate pedestrian facility
type $NCI^p$ and region $NCI^g$.

ACKNOWLEDGMENTS

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reflect the views of the Illinois Department of Transportation.

NOTATIONS

The following symbols are used in this paper:

$A_i^p = \text{total number of segments in pedestrian facility of type } p \text{ in geographical location } i$;

$a = \text{segment of pedestrian facility}$;

$b = \text{a point where a change in the pedestrian facility dimension is recorded}$;

$B_i^p = \text{total number of points } b \text{ in pedestrian facility of type } p \text{ in geographical location } i$;
465 \[ BL_i^p = \text{total length of pedestrian facility}; \]
466 \[ I = \text{total number of pedestrian facilities}; \]
467 \[ i = \text{geographical location of pedestrian facility}; \]
468 \[ I^{p-g} = \text{total number of pedestrian facilities of type } p \text{ that are located in the region } g; \]
469 \[ L_a = \text{length of segment } a \text{ of pedestrian facility}; \]
470 \[ LH_i^p = \text{total labor-hours for upgrading pedestrian facility of type } p \text{ that is located in geographical location } i; \]
471 \[ LH^g = \text{collective upgrade cost for all pedestrian facilities in region } g; \]
472 \[ NCI_i^p = \text{non-compliance index for pedestrian facility of type } p \text{ in geographical location } i; \]
473 \[ NCI^p = \text{collective non-compliance index for pedestrian facility type } p; \]
474 \[ NCI^g = \text{collective non-compliance index for all pedestrian facilities in region } g; \]
475 \[ NCI^{p-g} = \text{collective non-compliance index for all pedestrian facilities of type } p \text{ in geographical region } g; \]
476 \[ N_{l,r}^p = \text{number of points } b \text{ per meter in pedestrian facility}; \]
477 \[ N_{r,\text{max}}^p = \text{the maximum number of points } b \text{ per meter for all pedestrian facilities of type } p \text{ in the city}; \]
\( PUC_{i,r}^p \) = partial upgrade cost of pedestrian facility type \( p \) with respect to accessibility requirement \( r \) in geographical location \( i \);

\( PLH_{i,r}^p \) = partial labour-hours required for upgrading pedestrian facility type \( p \) with respect to accessibility requirement \( r \) in geographical location \( i \);

\( p = \) pedestrian facility type;

\( R = \) total number of accessibility requirements for pedestrian facility type \( p \);

\( r = \) accessibility requirement of pedestrian facility type \( p \);

\( S_{i,r}^p \) = non-compliance index for requirement \( r \) of pedestrian facility located in geographical location \( i \);

\( S_{i,r,a}^p \) = non-compliance score of segment \( a \) of pedestrian facility;

\( S_{i,r,b}^p \) = non-accessibility score of requirement \( r \) of point \( b \) in pedestrian facility;

\( TLH_{i,r}^p \) = total labor-hours for upgrading pedestrian facility type \( p \) in geographical location \( i \);

\( TUC_{i,r}^p \) = total upgrade cost of pedestrian facility type \( p \) in geographical location \( i \);

\( UC_i^p \) = total upgrade cost for pedestrian facility of type \( p \) that is located in geographical location \( i \);

\( UC^g \) = collective upgrade cost for all pedestrian facilities in region \( g \);
\( V^P_i = \) a value that equals “0” if \( (S^P_{i,r} = 0) \) for all accessibility requirements \( r \) in the \textit{complete upgrade} category and “1” otherwise;

\( V^P_{i,r} = \) a value that equals “0” if \( (S^P_{i,r} = 0) \) and “1” otherwise;

\( W^P = \) relative importance weight of pedestrian facility type \( p \);

\( W^P_{r,p} = \) relative importance weight of accessibility requirement \( r \) for pedestrian facility type \( p \).

\section*{REFERENCES}


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### Table 1. Example Weights and Non-Compliance Scores for Sidewalk Requirements

<table>
<thead>
<tr>
<th>Sidewalk Requirement</th>
<th>$r$</th>
<th>Weights ($W_r^1$)</th>
<th>Range of Existing Conditions</th>
<th>Non-Compliance Score ($S_{Ir}^1$)</th>
</tr>
</thead>
</table>
| Width                | 1   | 20               | $\begin{align*} 
    & Width < 0.9 \text{ meters} \\
    & 0.9 \leq Width < 1.0 \text{ meters} \\
    & 1.0 \leq Width < 1.05 \text{ meters} \\
    & 1.05 \leq Width < 1.15 \text{ meters} \\
    & 1.15 \leq Width < 1.2 \text{ meters} \\
    & Width \geq 1.2 \text{ meters} 
\end{align*}$ | $\begin{align*} 
    & 100 \\
    & 80 \\
    & 60 \\
    & 40 \\
    & 20 \\
    & 0 
\end{align*}$ |
| Running Slope        | 2   | 20               | $\begin{align*} 
    & Running \text{ Slope} > 12.5\% \\
    & 12.5\% \geq Running \text{ Slope} > 10\% \\
    & 10\% \geq Running \text{ Slope} > 8.33\% \\
    & 8.33\% \geq Running \text{ Slope} > 5\% \\
    & Running \text{ Slope} \leq 5\% 
\end{align*}$ | $\begin{align*} 
    & 100 \\
    & 50 \\
    & 10 \\
    & 5 \\
    & 0 
\end{align*}$ |
| Cross Slope          | 3   | 20               | $\begin{align*} 
    & Cross \text{ Slope} > 8\% \\
    & 8\% \geq Cross \text{ Slope} > 6\% \\
    & 6\% \geq Cross \text{ Slope} > 4\% \\
    & 4\% \geq Cross \text{ Slope} > 2\% \\
    & Cross \text{ Slope} \leq 2\% 
\end{align*}$ | $\begin{align*} 
    & 100 \\
    & 50 \\
    & 25 \\
    & 5 \\
    & 0 
\end{align*}$ |
| Surface Discontinuities | 4 | 20               | $\begin{align*} 
    & Vertical \text{ Change in Level} > 25.4 \text{ mm} \\
    & 25.4 \geq Vertical \text{ Change in Level} > 20 \text{ mm} \\
    & 20 \geq Vertical \text{ Change in Level} > 13 \text{ mm} \\
    & 13 \geq Vertical \text{ Change in Level} > 6.4 \text{ mm} \\
    & 13 \geq \text{ Change in Level}>6.4 \text{ mm, Beveled} \\
    & \text{ Vertical Change in Level} \leq 6.4 \text{ mm} 
\end{align*}$ | $\begin{align*} 
    & 100 \\
    & 80 \\
    & 25 \\
    & 5 \\
    & 0 \\
    & 0 
\end{align*}$ |
| Protruding Objects    | 5   | 20               | $\begin{align*} 
    & Protrusion \text{ Distance} > 175 \text{ mm} \\
    & 175 \text{ mm} \geq Protrusion \text{ Distance} > 125 \text{ mm} \\
    & 125 \text{ mm} \geq Protrusion \text{ Distance} > 100 \text{ mm} \\
    & Protrusion \text{ Distance} \leq 100 \text{ mm} 
\end{align*}$ | $\begin{align*} 
    & 100 \\
    & 50 \\
    & 5 \\
    & 0 
\end{align*}$ |
<table>
<thead>
<tr>
<th>Pedestrian Facility Type</th>
<th>Accessibility Requirement</th>
<th>Verification Procedure</th>
<th>Verification Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sidewalks</td>
<td>Width</td>
<td>Collecting continuous measurements along the entire length of the pedestrian facility.</td>
<td>Continuous</td>
</tr>
<tr>
<td>Sidewalks</td>
<td>Surface Discontinuities</td>
<td>Conducting discrete measurements at specific points along the length of pedestrian facility.</td>
<td>Discrete</td>
</tr>
<tr>
<td>Pedestrian Signals</td>
<td>Pedestrian Pushbuttons Height</td>
<td>Taking a single measurement of one of the dimensions of pedestrian facility.</td>
<td>Single</td>
</tr>
<tr>
<td>Curb Ramp</td>
<td>Detectable Warning Surfaces</td>
<td>Verifying if the required features such as detectable warning surface is present, non-standard, or missing.</td>
<td>Presence</td>
</tr>
</tbody>
</table>
Table 3. Example Non-Compliance Scores for Pedestrian Pushbutton Height

<table>
<thead>
<tr>
<th>Pedestrian Pushbutton Height</th>
<th>Non-Compliance Score $S_{I3}^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Height &gt; 1.20$ m</td>
<td>100</td>
</tr>
<tr>
<td>$1.20$ m $\geq$ $Height$ &gt; 1.05 m</td>
<td>50</td>
</tr>
<tr>
<td>$1.05$ m $\geq$ $Height$ &gt; 0.75 m</td>
<td>0</td>
</tr>
<tr>
<td>$0.75$ m $\geq$ $Height$ &gt; 0.50 m</td>
<td>50</td>
</tr>
<tr>
<td>$Height$ &lt; 0.50</td>
<td>100</td>
</tr>
</tbody>
</table>
Table 4. Example Non-Compliance Scores for Curb Ramp Detectable Warning Surfaces

<table>
<thead>
<tr>
<th>Curb Ramp DWS</th>
<th>Non-Compliance Score $S_{15}^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Missing</td>
<td>100</td>
</tr>
<tr>
<td>Non-Standard</td>
<td>50</td>
</tr>
<tr>
<td>Present</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 5. Pedestrian Facilities in the Case Study

<table>
<thead>
<tr>
<th></th>
<th>Pedestrian Facility Type</th>
<th>Number of Facilities in the Case Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sidewalks</td>
<td>864</td>
</tr>
<tr>
<td>2</td>
<td>Curb Ramps</td>
<td>384</td>
</tr>
<tr>
<td>3</td>
<td>Crosswalks</td>
<td>32</td>
</tr>
<tr>
<td>4</td>
<td>Pedestrian Signals</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>Refuge Islands</td>
<td>14</td>
</tr>
<tr>
<td>6</td>
<td>Transit Stops</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>On-Street Parking</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>Passenger Loading Zones</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>1327</strong></td>
</tr>
</tbody>
</table>
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Figure 9. Classification of pedestrian facilities in each type
Phase I: Accessibility Requirements Analysis

Facility Types
- Sidewalks
- Curb Ramps
- Crosswalks
- Pedestrian Signals
- Refuge Islands
- Transit Stops
- On-Street Parking
- Passenger Loading Zones

Phase II: Non-Compliance Assessment

Verification Techniques
- Continuous Verification Techniques
- Discrete Verification Techniques
- Single Verification Techniques
- Presence Verification Techniques

Phase III: Upgrade Cost Estimation

- Upgrade Cost Estimation
- Man-Hours Estimation

Phase IV: Collective Non-Compliance

Grouped By
- Pedestrian Facility Type
- Geographic Region

Phase V: Performance Evaluation

Performance Evaluation