Inventory & Analysis of Minor Concrete Infrastructure for the City and County of Denver

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Abstract

The City and County of Denver (CCD) and the University of Colorado Denver (UCD) have been involved in cooperative research since 1997. Although a variety of projects have been completed, the main deliverable has been a comprehensive Geographic Information System (GIS) database containing both major and minor infrastructure. Major infrastructure included assets such as bridges and streets, while minor infrastructure includes assets of alleys and street subsystems, which include curbs, gutters, inlets, sidewalks, driveways, crosspans, and curb ramps. This paper presents the equipment and methodology used for the inventory and analysis summary of CCD's concrete curbs, gutter pans, and alleys.

1. Introduction

The deterioration of the transportation system infrastructure in the United States is an ongoing problem to local, state, and federal agencies. Highways, streets, and local arterials in the United States are deteriorating at unsatisfactory rates because of regular aging in addition to increased traffic loads (El-Korchi and Wittels 1990). Billions of dollars are invested in roadway infrastructure annually to ensure the mobility of people and goods (Collura et al. 1994). In order to optimize available funds in preserving the national transportation infrastructure, the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) mandated that state and local agencies develop and implement various infrastructure management systems, primarily for major infrastructure (Amekudzi and Attoh-Okine 1996). The ISTEA effort has been recently complimented by the Government Accounting Standards Board (GASB), which has helped focus inventory and assessment attention on minor infrastructure.

A pavement management system (PMS) has been defined as "a set of tools or methods that assist decision-makers in finding optimum strategies for providing and maintaining pavements in a serviceable condition over a given period of time" (Haas and Hudson 1978). In this joint UCD CCD research, the word pavement can be replaced with infrastructure covering both major and minor defined types. The database is the core of any PMS or other infrastructure management system. The purpose of this research is to summarize over 7 years of database work developed by the joint CCD UCD research team. The infrastructure assets in the database include alleys, curb and gutter pans, sidewalks, ramps, inlets, and bridges. The scope of this paper is to summarize only the alley and street subsystem inventory and analysis

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systems. The CCD alleys were inventoried and analyzed in 2000 and 2001. Street subsystems were completed during 2001 to 2004. The Reader is encouraged to review (Rens et al. 1998) for the history of the development of the system.

2. Global Positioning System and Geographic Information System

The CCD infrastructure management system relies heavily on Global Positioning System (GPS) technology. The inventory and assessment data is managed with Geographic Information Systems (GIS) software. The accuracy of the GPS was within 1-meter using differential correction. Differential correction requires a second GPS receiver, a base station, collecting data at a stationary position at a precisely known point. The research team utilized the service of Trimble for differential correction. The GIS software manages the data through layers. For example one can add multiple layers such as: sidewalk, inlets, or ramps to analyze certain condition assessment scenarios. The layers can be turned on and off as needed. This feature is only one of the basic operations of ArcMap, the GIS software used in this research.

3. Alley Pavements: Inventory and Assessment System

Alley pavements in the CCD area consist of both rigid and flexible pavements. The Portland Cement Concrete (PCC) pavements or rigid pavements are called concrete alleys. For flexible pavement, the CCD has two types, namely overlaid and Recycled Asphalt Pavement (RAP) alleys. Each of these types is described below.

- Concrete Alleys: The majority of concrete alleys in the CCD were built in the 1970's. The alley serviceable age is around 50 years. The standard width is between 16-21 feet. The CCD has approximately 2,450 concrete alleys, which amounts to almost 50% of the total alley inventory.
- Overlaid Alleys: After around 50 years of service, old concrete alleys become an overlay. In the CCD area, there were 1,389 overlaid alleys inventoried in 2001. The CCD constructed overlaid alleys by covering the old concrete surfaces with 1-2 inches of well-compacted Asphaltic Concrete. When the underlying concrete surface reaches unacceptable condition, the overlaid alleys are replaced with new concrete alleys.
- RAP Alley: In the 1970's, the existing CCD dirt alleys were converted to RAP alleys. The RAP alleys were built from the compacted dirt alley overlaid by 2-3 inches of the recycled asphalt to prevent dust and provide smoothness. The RAP alleys were built during various periods. In 2001, the CCD had 1,089 RAP alleys.

3.1 Alley Inventory Methodology

Beginning in May 2000 and ending in the summer of 2001 all alleys within the CCD were inspected. Currently, a second inspection pass is being completed but this data is not discussed in this paper. The inspectors physically walked through each alley in order to visually inspect and inventory the alley infrastructure based upon a simple condition rating system. Digital photography images were taken to inventory and rate each alley as well. The resulting data, which is managed by Microsoft Access, is the fundamental database of the Alley Management System (AMS) for the CCD. The database has the appropriate information making it compatible to the citywide GIS network.

3.2 Type of Distresses for the Concrete Alley Pavement

The research team after considering all available sources of information (the CCD expertise, literature, etc.) decided to focus on nine distresses for concrete alleys, six distresses for overlaid alleys, and four distresses for RAP alleys. Table 1 shows the nine distresses for concrete alley pavements. For a more comprehensive summary of the alley management system, the reader is referred to (Sathantip 2002).

Table1. Distress Definitions for Concrete Alley Inventory

No.	Distress Types	Description
1	Surface Wear	Exposed aggregate in the surface caused by repeated traffic.
2	Longitudinal Cracking	Cracks which are parallel to the pavement centerline.
3	Transverse Cracking	Cracks which are orthogonal or perpendicular to the pavement centerline.
4	Concrete Patches	Repair of the pavement with new concrete.
5	Asphalt Patches	Repair of the pavement with asphalt concrete.
6	Broken Panels	Cracks which divide the slab into more than four pieces.
7	Deterioration Panels	Loosed aggregate in the surface.
8	Settled Panels	Panels which are settled or differentially shifted more than one inch.
9	Cave-Ins	Panels which are obviously settled or failed due to undermining.

3.3 Utilization of Condition Rating for the Alley Inventory

The condition rating schemes and final data were subjective in all aspects (excellent, good, fair, poor) and it was necessary to eventually assign a rating. A scale of 1 to 10 with 10 being best condition and 1 representing the failed condition was applied to the alley distress data. Each of the individual distresses were based on subtracting deduct values from the "perfect" value of 10. If a specific alley distress was in excellent condition, a deduct value of zero was utilized. Equation (1) gives the general relationship whereby subjective condition ratings could be converted to numerical results and maintenance priorities could be assigned.

$$R = C - \sum D \qquad (1)$$

Where

R = Condition Rating Index
C = 10
D= Deduct Values

For concrete alley pavement, the following condition rating indices were used to indicate pavement condition:

Concrete alleys:
10 to 9.125 = Excellent condition
9 to 8 = Good condition
6.875 to 6.5 = Fair condition
6.375 to 0 = Poor condition

For concrete alleys, the descriptions of distress conditions adopted by the CCD and UCD research team are shown in Table 2. Inspectors indicated the pavement surface condition utilizing these descriptions. The level of distress condition is classified into four levels, which are excellent, good, fair, and poor. In order to calculate the condition rating index, the deduct values (D) in Table 3 are applied to the individual distresses in Table 2 by using Equation (1).

Table2. Concrete Alley Condition Rating

Distress	Condition	Description
Surface Wear	No	Minimal exposed aggregate
	Yes	Extensive exposed aggregate
Longitudinal Cracking	Excellent	No longitudinal cracking
	Good	Less than 5 panels cracked
	Fair	5 to 10 panels cracked
	Poor	More than 10 panels cracked
Transverse Cracking	Excellent	No transverse cracking
	Good	Less than 5 panels cracked
	Fair	5 to 10 panels cracked
	Poor	More than 10 panels cracked
Concrete Patches	Excellent	No concrete patches
	Good	Less than 2 concrete patches total
	Fair	2 to 5 concrete patches total
	Poor	More than 5 concrete patches
Asphalt Patches	Excellent	No asphalt patches
	Good	Less than 2 asphalt patches total
	Fair	2 to 5 asphalt patches total
	Poor	More than 5 asphalt patches
Broken Panels	Excellent	No broken panels (blocks less than 1/4 panel)
	Good	Less than 5 panels broken (blocks less than 1/4 panel)
	Fair	5 to 10 panels broken (blocks less than 1/4 panel)
	Poor	More than 10 panels broken (blocks less than 1/4 panel)
Settled Panels	Excellent	No settled or differentially shifted panels
	Good	Less than 5 ½"settled or differentially shifted panels
	Fair	5 to 10 ½"settled or differentially shifted panels
	Poor	More than 10 ½" settled or differentially shifted panels
Deterioration	Excellent	No deterioration of surface
	Good	Less than 5 deteriorated panels
	Fair	5 to 10 deteriorated panels
	Poor	More than 10 deteriorated panels
Cave-Ins	No	No apparent cave-ins
	Yes	Obvious settled or failed area due to undermining (area > 15 sq. ft)

Table3. Deduct values for calculating condition rating index of concrete alleys

Surface Wear	Condition	No	Yes		
	Deduct	0	0.25		
Longitudinal Cracking	Condition	Excellent	Good	Fair	Poor
	Deduct	0	0.125	0.25	0.5
Transverse Cracking	Condition	Excellent	Good	Fair	Poor
	Deduct	0	0.25	0.5	0.75
Concrete Patches	Condition	Excellent	Good	Fair	Poor
	Deduct	0	0.25	0.5	0.75
Asphalt Patches	Condition	Excellent	Good	Fair	Poor
	Deduct	0	0.25	0.5	0.75
Broken Panels	Condition	Excellent	Good	Fair	Poor
	Deduct	0	0.5	1	1.5
Settled Panels	Condition	Excellent	Good	Fair	Poor
	Deduct	0	0.5	1	1.5
Deterioration	Condition	Excellent	Good	Fair	Poor
	Deduct	0	0.5	1.5	2.5
Cave-Ins	Condition	No	Yes		
	Deduct	0	2		

3.4 Summary of Alley Pavement Inventory in 2000-2001

One basic unknown prior to this project was an accurate breakdown of the three alley pavement surface types. Inspectors began the inventory just prior to the summer of 2000 and finished around 15 months later. The final count revealed that the city has just over 5,150 alleys that it owns and maintains. The breakdown of these alleys by surface type is illustrated in Figure 1. In general, half of the total inventory consists of concrete alleys and the other half is split between overlay and RAP types. The knowledge of alley pavement surface types and condition will play a crucial role in determination of repair or rehabilitation strategies. Figure 2 shows condition rating index ranges for concrete.

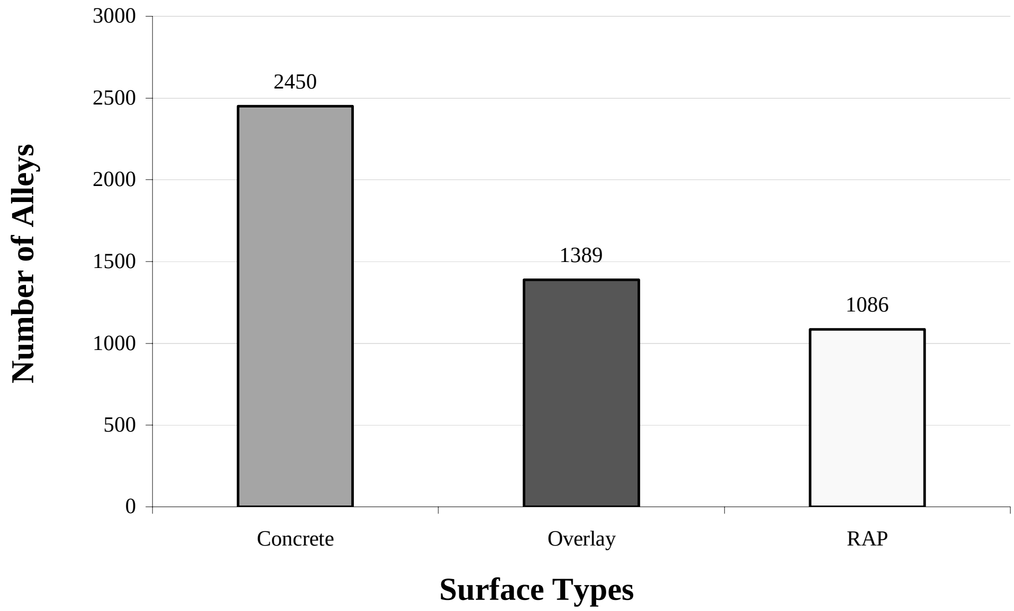

Figure 1. Alley inventory sorted by surface type.

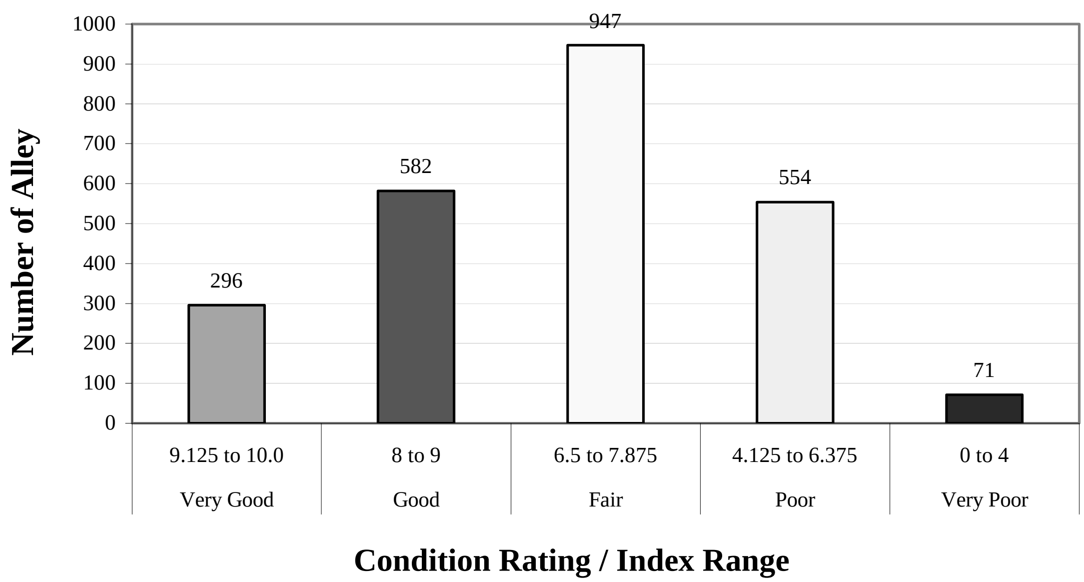

Figure 2. Condition rating of concrete alleys.

3.5 Deterioration Model for Alley Pavement

The process of pavement deterioration is extremely complex since most pavement materials have elastic, plastic, and strength parameters, which change with temperature, moisture, or age. Any attempt to create a deterioration model for pavements must fundamentally include a simplification of all these aspects. Therefore, any available historical data have to be involved in the process of creating and verifying the deterioration model (Ullidtz 1999).

The Markovian chain model is well known, has been published extensively, and is accepted by most pavement management agencies. However, for the inventory in 2000-2001, at best only two data points exist. The first data point would be the perfect condition, which would assume to occur at the point of initial construction. The second data point would be the condition ratings acquired during this current inspection period. For one to apply Markovian theories, a larger array of periodic history is needed. Basically, only two options exist for developing any model based on two data points. The first model would be to assume a condition of 10 at the construction year and then by using the 2000-2001 data point, fit curves to predict the relationship by fitting a relationship between these two points. A slightly different technique is to simply conduct curves fitting the relationship between condition rating indexes versus ages for each of the three pavement types. This technique is called the survivor curves or performance curve, which represents the rate of deterioration, life cycles, and remaining life of specific pavement section types. For inventory in 2000-2001, the survivor curve approach was chosen.

3.6 Alley Deterioration Curves

In order to determine the deterioration curves, the discrete least squared approximation method is applied to approximately 1/3 of the sample population for each pavement type where construction history was know. The general form of the polynomial, which is assumed to fit in the selected data points, is given by Equation (2)

$$P_n(x) = a_n x^n + a_{n-1} x^{n-1} + \ldots + a_1 x + a_0 \,, \tag{2}$$

Where

P = Polynomial that a set of data is to represent

$a_0, a_1, \ldots, a_n$ = Constants that minimize the least square error

n = Degree of polynomial

In general, after all selected data points are plotted; the fit curve will be generated based on the assumed degree of the polynomial. These deterioration curves have been produced for the three types of alley pavement. Figure 3 shows the deterioration curve produced for concrete alley pavement based on a third degree polynomial.

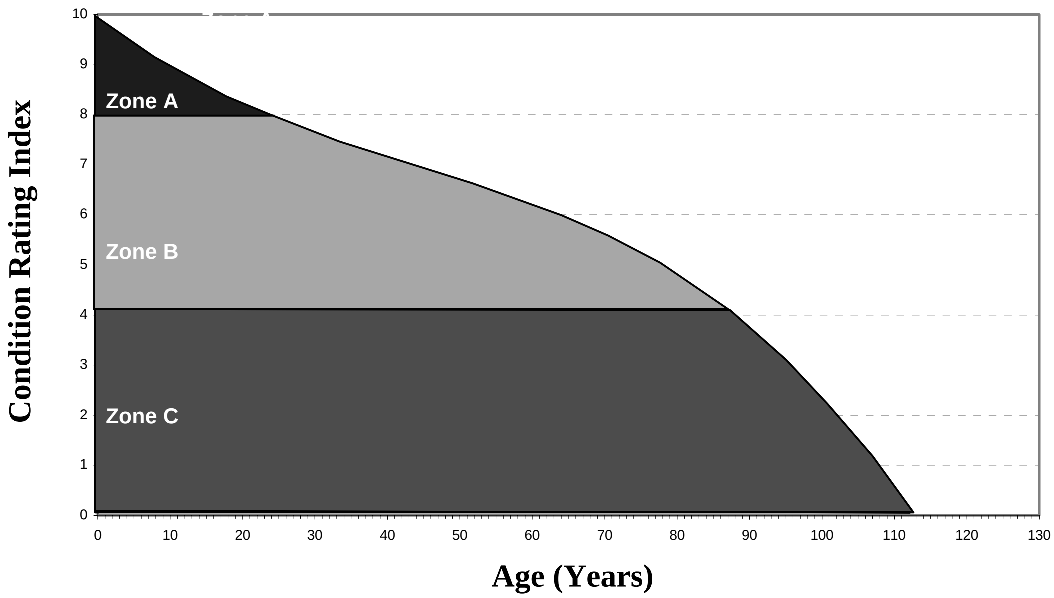

Figure 3. Deterioration model for concrete alleys based on third degree polynomial.

3.7 Alley Inventory in 2005

In 2000, UCD collected CCD alley inventory data using inspection forms (hard copy). Then this data was later manually input into the database at the office. This method can create a tremendous amount of error caused by ineligible writing and data inputting errors when the data is stored into the database. A computer with GIS software can more efficiently handle the collection and processing of the data. Instead of collecting the data using the inspection forms and manually entering the data into the computer, a computer can bypass the data entry process. This is the method of collection used by UCD inspectors in the current alley inventory. A portable computer, the Compaq iPAQ, is used for the current alley inventory. This computer has enough capability to run GIS software that usually requires relatively high computer system requirements.

4. Street Subsystem: Curb and Gutter Inventory

4.1 Introduction

A curb is defined as an edging built along a street to form a part of a gutter, where a gutter is defined as a low area to carry off surface water (Webster 2003).

Curbs and gutters are not necessarily major infrastructure but are an integral part of the transportation system as they are used to channel storm drainage, stabilize the roadways, represent a demarcation point for where the street ends, and give the roadways an aesthetic appearance. At the end of the street subsystem inventory in 2004, approximately 3300 linear miles of curb and gutter had been inventoried in the CCD.

4.2 Curb and Gutter Data Collecting Process

One to three data collector GPS units, as shown in Figure 4, were dispatched regularly to collect CCD street subsystem assets. An inspector physically walks through every curb in the CCD region and is able to collect data only by talking to the computer. The inventory and assessment data is automatically fed into a database that can be downloaded to the GIS system. The equipment consists of a backpack, small computer, GPS receiver, and headset. Using software developed by Datria System Inc. an inspector can call out commands to record the city's asset locations and condition. The voice command software enables the inspector to run the computer without having the need to use a keyboard or mouse. Every time the inspector calls out a command, to verify that the computer acknowledged the right command, the program will speak back what command the computer understood with a computer generated voice.

Figure 4. Vocarta System used by UCD.

4.3 Type of Curbs and Distresses

The street subsystem curb and gutter data that is collected was classified into several different types. These types consist of: six- inch vertical, nine- inch vertical, combo, valley pan, flagstone, mountable, and asphalt curb. The three major curb and gutter types in CCD are six-inch vertical, combo, and nine-inch vertical. A six-inch vertical curb has about 2 feet concrete gutter pan with 6-inch high curb face. A nine-inch vertical curb is similar to a six-inch vertical curb, but it has a higher curb face and the gutter is usually paved over with asphalt. A combo curb is the most common curb in the CCD. Combo curbs can mostly be found in a neighborhood area. This type of curb is usually installed when the layout of the driveways for homes are not known. It also serves as sidewalk with a width ranging from 3 to 5 feet. Flagstone curb is fairly rare and can be found in the Denver downtown neighborhood areas. These curbs were mostly installed in the late 1800's and early 1900's. Valley pan curb can mostly be found in the industrial areas. This type of curb serves the purpose of a gutter and allows industrial trucks the ability to drive over this type of curb thus limiting the damage incurred.

There are several types of distresses in the CCD curb and gutter management system. These distresses are major cracks, spalls, curb gone, heaved, settled, drainage and undermined. The explanations of these distresses are as follows.

- Major cracks are fractures on concrete curbs excluding hairlines.
- Spalls are when a portion of the curb larger then 3 inches diameter has been chipped or fragmented.
- Curb gone is when a curb should be and once was in that location but no longer exists.
- Heaved is when the curb is uplifted more then 2 inches.
- Settled is when the curb sinks more then 2 inches.
- Drainage is when there is standing water found on the gutter.
- Undermined is when the base/sub grade of the curb has been washed away and weakened by water.

There are several factors causing these distresses, which some of them are listed below.

Major Crack
- Heavy tire load on gutter or curb
- Weak concrete strength

Spalls
- Heavy tire load on the tip of the curb
- Impact load due to accident or snow plow

Heaved
- Uplift caused by tree trunk
- Freeze and thaw of snow

Settled

- Weak sub grade
- Utility backfill causes weak sub grade under the curb

Drainage

- Poor grade design
- Often caused by settled distress
- Asphalt overlay erosion

Undermined

- Water stream corroding away sub grade material trough a crack creating air gap under the curb

4.4 Rating System for Curbs & Gutters

Curbs and gutters vary in size and condition. It is difficult to rate these curbs only by looking at them. Especially when there is more than one inspector involved. A rating system helps the inspectors to rate the condition of these curbs and gutters more consistently. By collecting the number of distresses per street length, the rating system can rate these curbs and gutters on a scale of 100. However, proper training and an easily understood written manual are needed to achieve this consistency.

4.5 Preparing the Curb and Gutter Data for rating system

The way the current data was recorded, was not properly designed for a rating system. It was designed only for a map display purpose in ArcMap. Rating this set of data is a rather complicated process and time consuming. It requires a high number of manipulations with the GIS data. The curb and distress data are located in two separate files. To determine which distress belongs to a certain curb the attribute tables of each item must be viewed separately. However, this process is extremely difficult to accomplish with Excel. This task is extremely difficult to complete because:

- More than 1 data collector unit is used, therefore; using TIME and DATE field for correlation can be difficult
- Location of the curb is divided into three columns (FROM, TO, TRAVELLING). These three columns must be matched in order to make a correlation with location
- Occasionally there is more than one curb on a location because sometime there are two types of curb.

Since multiple columns have to be matched and the number of rows in the data is high, such a process is difficult to achieve.

The best way to correlate these two columns is by using a GIS program called ArcMap. Using spatial join technique, the curb data can be merged into the distress data based on the locations. Spatial join is a process on ArcMap that can join two different data on a map based on its geographical location as shown in Figure 5. After the spatial join, the joined data table can be exported into a dbf file that can be opened with Microsoft Excel. Using Excel, the number of each distress type on each curb can be calculated.

After the number of each distress type has been calculated on each curb, the process of rating the curb can be started. Two complex tables have been merged into a single simple table, using the spatial join.

Using the rating system, these clustered distresses that are very hard to interpret can be transformed into a map as shown in Figure 6. With this map, the CCD would be able to determine which areas need more attention without having to zoom into each curb. This rating system breaks down the curbs into 3 colors, red for poor condition, yellow for medium condition, and green for good condition. Using the ArcMap program, the curbs can be broken down into even more than 3 color rating categories.

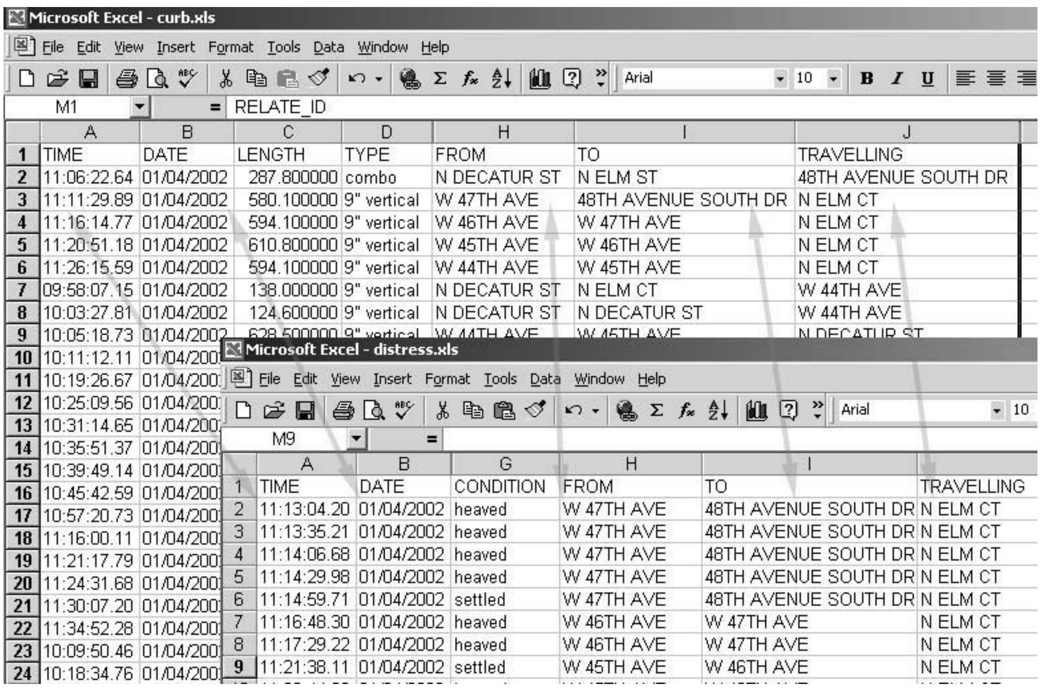

Figure 5. GIS is used to correlate distress with location.

Figure 6. Distresses on curb with a rating system.

4.6 Curb and Gutter Condition Index

Condition index (CI) is a rating system used to evaluate the condition of a structure based on a scale of 0-100. CI was developed by the U.S. Army Corps of Engineers in the 1990's to have uniform condition assessment procedures for its civil works structures.

The main equation of the Condition Index is:

$$CI = 100\,(0.4)^{X/X_{max}} \qquad (3)$$

Where X_{max} is a limiting number of X. In this case, X is the number of distress, where X_{max} is the maximum number of distress when curb is considered in poor condition and immediate action is required. Therefore, if a curb does not have any distress at all, CI will be equal to 100. On the other hand, when X is equal to X_{max}, the CI will be equal to 40. Figure 7 illustrates the equation and Table 4 explains each condition index zone.

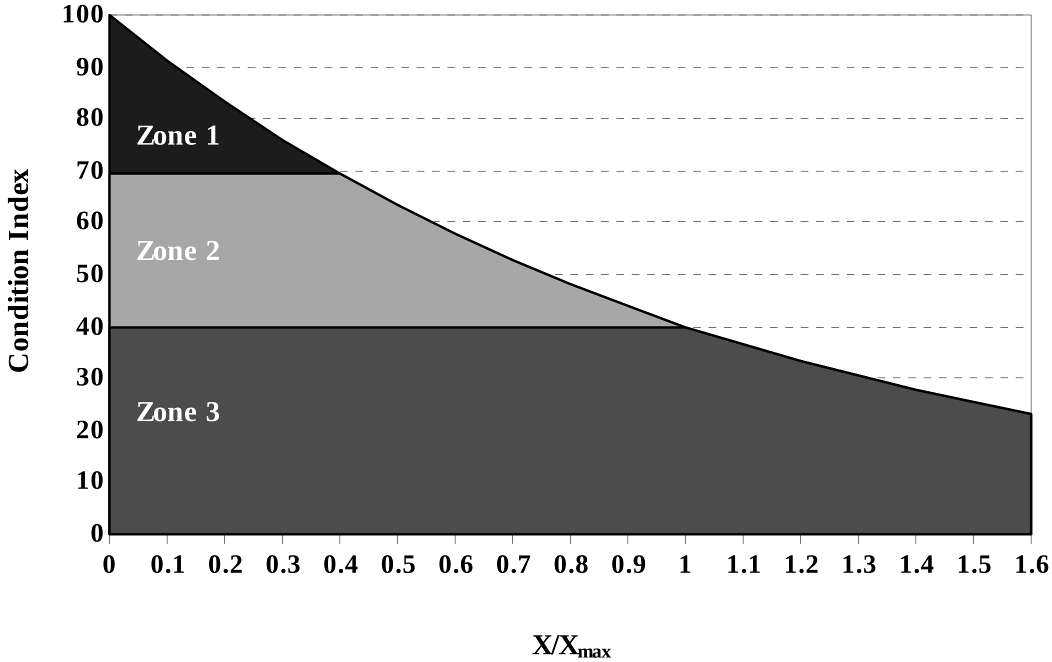

Figure 7. Condition index as related to X (a measurement or distress occurrence) / X_{max} (limiting value of the distress).

Table 4. Condition Index Zones.

Zone	Condition	CI	Recommended Action
Zone 1	Excellent	90-100	Curb is most likely newly constructed and have few or no distresses
	Good	70-89	Normal wear and tear is noticeable. A minor repair is recommended.
Zone 2	Fair	40-69	Curb is deteriorated and looks unattractive. Repair is recommended.
Zone 3	Poor	0-39	Immediate repairs or replacement is needed (whole curb)

Since the lengths of the curbs vary, some adjustments are needed in normalizing the value of CI. X_{max} is decided from average result of X_{max} that was retrieved from the questionnaire sent to the experts based on 400 ft (50 stones) stretches of curb and gutter. Each curb and gutter CI is broken into several CI, one for each distress type. Since heaved and settled distress are somewhat similar, these distresses can be combined into one CI. Overall Condition Index (OCI) is then calculated by summing the CI of each distress multiplied by its weighting factor (WF). The weighting factor is the percentage of how much each distress controls the overall CI. The overall Condition Index (OCI) equation is:

$$OCI = WF_{major\ cracks}\, CI_{major\ cracks} + WF_{spalls}\, CI_{spalls} + \ldots + WF_{undermined}\, CI_{undermined} \quad (4)$$

The weighting factor (WF) of each distress was also determined from the questionnaire sent to the experts. An example of this process is shown in Table 5.

Table 5. Example of Overall Condition Index (OCI).

Distress	CI	WF	CI * WF
Major cracks	75	14.4	1080
Spalls	83	6.5	539.5
Curb Gone	92	20.1	1849.2
Heaved/Settled	79	24.4	1927.6
Drainage	100	20.4	2040
Undermined	100	14.3	1430
∑		100.1	8866.3

$OCI = \sum (CI*WF) / \sum WF =$ 88.

Where ∑ = Summation

4.7 X_{max} and Weighting Factor (Curb and Gutter)

In order to come up with a fair and unbiased rating system, a panel of experts was gathered. Six CCD employees who have experience in infrastructure management particularly curb and gutter was decided upon. This group was asked to determine X_{max} and the weighting factor of each type of distress on different curb types. The X_{max} for this rating system is the maximum number of stones (out of 50 stones) when the curb is considered poor and immediate action is required. This immediate action is a complete repair or replacement of curb and gutter. The weighting factor of each distress means how significant each type of distress impacts the condition index. The weighting factor may vary for the different types of curb. Table 6 shows the average weighting factor and X_{max} for all types of curbs obtained from experts.

Table 6. Weighting Factor and X_{max}.

Distress	WF av.	X_{max}
Curb Gone	20.1	30
Major Cracks	14.4	38
Spalls	6.5	38
Settled/Heaved	24.4	32
Drainage	20.4	32
Undermined	14.3	30

4.8 Simplified Curb and Gutter Condition Index

Unlike the Condition Index, the Simplified Condition Index (SCI) treats every type of distress the same way. The SCI is basically the percentage of stones in good condition. The SCI can be calculated by dividing the number of undamaged stones by the number of total stones. A stone is the length of the sawn concrete curb approximately equal to 2.4 meters (8 ft). The number of total stones can be calculated by dividing the length of the curb by the length of the stone.

SCI = number of undamaged stones / number of total stones

SCI numbers are usually slightly higher than the OCI numbers; however the SCI is easier to calculate. An inspector can easily calculate SCI without the need of a computer. The weighting factors for different type of distresses obtained from the panel of judges are fairly similar as seen in Table 6. Since curb and gutter is not a very complex structure, SCI is sufficient enough to show the performance for the curb and gutter as shown in Figure 8. For a more comprehensive summary of the curb and gutter management system, the reader is referred to (Usagani 2004).

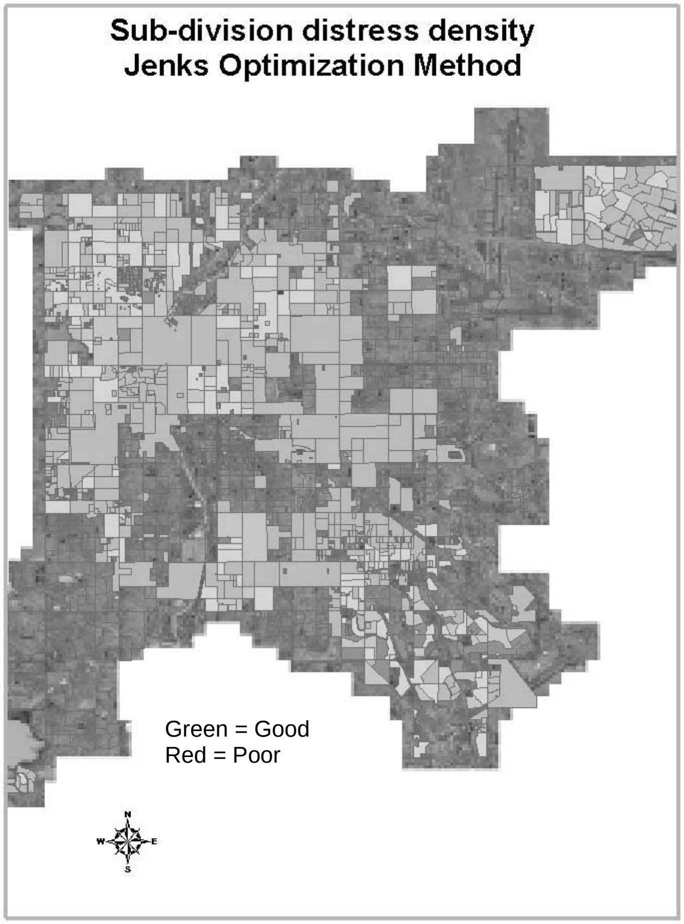

Figure 8. View of SCI in CCD.

4.9 Deterioration Curves for Curb and Gutter

For 6-inch concrete vertical curbs an example of a deterioration curve using historical data, similar to the alley deterioration curve in Section 3.6, is shown in Figure 9. Although somewhat limited this equation can be used to compare with other case studies.

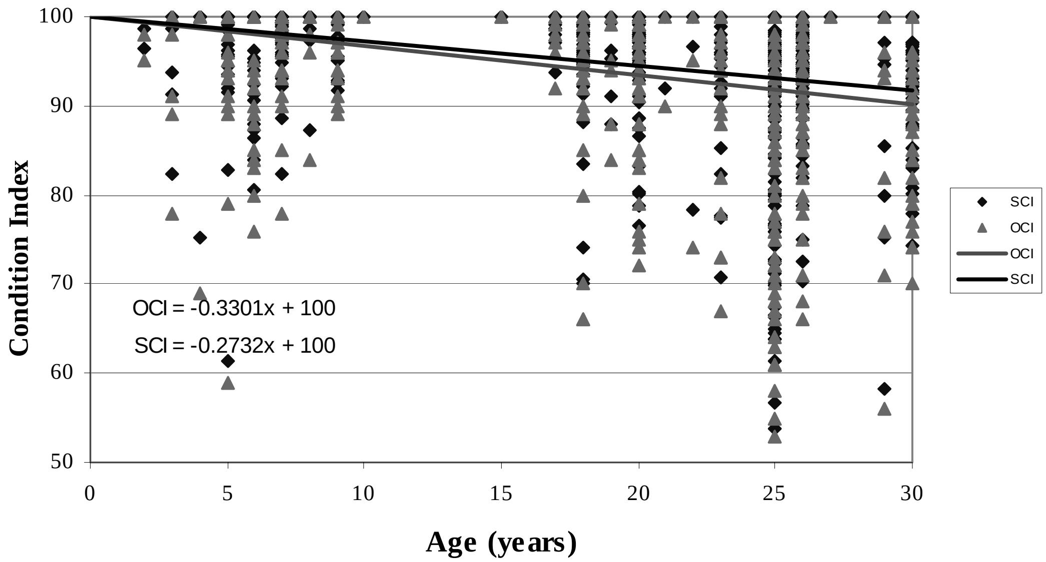

Figure 9. OCI and SCI deterioration curve for 6” vertical curb.

Conclusions

Developing the deterioration models for alley pavements can be complicated. Many factors are involved in the deterioration process and the limitation of available historical data can be a major barrier to establish accurate deterioration models. The deterioration models for alley pavements have been developed based on limited available information. The proposed deterioration models can be the prototype for deterioration process of alley pavements until more information is made available such as the results from the next periodic inventory and assessment. The results of alley inventory are useful for the CCD to understand the characteristics of the entire network of alley pavements.

Like any field data, flaws do exist in the current curb and gutter data collection process. Such flaws prevent an accurate analysis of deterioration and cost. Deterioration models for curb and gutter have been developed based on only what is currently available. This is however the first known research completed on curbs and gutter condition rating. This condition rating will assist in future condition-rating development for curb and gutter or similar structures. Even though the data collection contains errors, this inventory and rating process is starting point for the next cycle of curb and gutter inventory and assessment.

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