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Building a Highway Linear Referencing System from Preexisting Reference Marker Measurements for Transportation Data Management

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Abstract: *To manage events associated with highways, data systems have been developed to store relevant event information. To reap the full benefits of geographic information system technologies, the relative locations can be integrated into a linear referencing system. The objective of this paper is to present a methodology for building a highway linear referencing system by applying preexisting marker measurements to a digital street network. The system was developed for locating motor vehicle collisions in California and resulted in improved accuracy compared to a previously developed system. Nearly 50 percent of the relative collision locations based on the two different systems were within one meter of each other, but 4.1 percent were greater than 1,000 meters. Differences in collision locations were likely because of improved accuracy for (1) an increased number of reference markers were used, (2) all route realignments were accounted for, and (3) all previously identified errors were corrected.*

INTRODUCTION

In the United States, each state has a department of transportation that is tasked with managing, maintaining, and developing state highways. To manage events associated with the highways, transportation data systems have been developed to store relevant event information such as pavement types, construction zones, and motor vehicle collisions. The events are stored in a database with location values that are based on distances from measured points along the highway. However, before the advent of geographic information systems (GIS), the benefit of storing the event locations was limited to tabular analyses and paper maps. GIS now can take full advantage of the spatial location information, but significant work is required to match historical measurement systems on the highways to currently available digital street networks. Making this task even more difficult is the fact that many highways have undergone significant realignments over time and known reference markers for the same location on a highway now may have different measurement values. To account for these changes, a linear referencing system (LRS) can be developed from a digital street network.

Linear referencing is the process of storing geographic locations along a linear feature based on their positions relative to measured reference locations. On a highway, intersections and ramps can serve as reference locations to calculate distances to other geographic locations along the length of the highway. Typically, as changes occur to the roadway, new measurements are developed to account for the differences in the length of the route. For example, a bypass could be constructed, increasing the length of a highway that originally traversed through a city. New measure markers are placed along the bypass, but the entire length of the highway is not recalculated to maintain the consistency of previous event locations. In this situation, the beginning and end measurements of the highway remain the same, but the true distance of the route no longer would be equal to the original distance after the realignment. The ability to incorporate and represent these multiple measurements for the same route is fundamental to the concept of linear referencing and for effective transportation data management.

At the national level, the U.S. Federal Highway Administration (2011) maintains a highway inventory system known as the Highway Performance Monitoring System (HPMS) (http://www.fhwa.dot.gov/policyinformation/hpms.cfm). HPMS contains information on the condition, extent, performance, use, and operating characteristics of the nation's roadways to accommodate a data-driven process for analysis, planning, and funding allocation purposes. States are required to submit roadway geometry information for all public roads with an associated LRS, but are at different stages of the submission process. The final long-term goal is to have a complete, standardized LRS accessible to the public for all roadways in the country. However, this is an ongoing task and many local agencies or private consulting firms have immediate needs for an LRS to locate different types of events on highways. There also may be a need to build an LRS on a newer or more accurate street network for various projects. Therefore, regardless of a national system, local systems frequently are necessary.

Numerous studies have been devoted to conceptual data modeling of linear referencing systems (Vonderohe and Hepworth 1998, Fletcher et al. 1998, Easa and Chan 1999, Adams et al. 2000, Adams et al. 2001, Scarponcini 2002, Curtin et al. 2007). Of these, most of the transportation-focused LRS literature outlines data models or best practices for developing new systems (Fletcher et al. 1998, Kiel et al. 1999, Scarponcini 2002, Steiner et al. 2002, Curtin et al. 2007, Zhang et al. 2010). They provide a comprehensive process for building an LRS from scratch and present guidelines for defining the base measuring system that can be used in new data models. However, this literature is of limited usefulness to researchers or practitioners who must work with a predefined measuring system. Bigham et al. (2009) and Park et al. (2011) developed an LRS by associating preexisting reference markers with a current digital street network. This is a very different procedure, where the goal is to incorporate the past historical modifications into a measuring system to locate recent events in a GIS rather than generating a brand new measuring system. Transportation agencies may not have the luxury to design new measurement protocols when all their legacy data applications and systems rely on the historical system. Therefore, to utilize the benefits of GIS, the labor-intensive process of incorporating the preexisting markers is the only feasible solution.

The objective of this paper is to expand on the work originally developed by Bigham et al. (2009) and Park et al. (2011) and present a methodology for building a highway LRS by associating preexisting reference markers to a modern digital street network. A key component of the new work is the inclusion of all known highway realignments over the entire history of the system rather than only addressing a subset of the largest realignments. The locations of geocoded collisions between the original and new LRS are compared to verify the improved accuracy.

DATA SOURCES

California State Highway Routes

California highway data was obtained from StreetMap Pro 2003 and StreetMap North America 2005. StreetMap is a TeleAtlas-based street network that is freely available to ArcGIS software license holders. The California Department of Transportation (Caltrans) originally developed a highway postmile measuring system for routes that were in existence on January 1, 1964 (California Highways, http://cahighways.org). The postmile system is used to maintain all aspects of current roadways and to plan for adjustments or new construction. The California postmile system differs from most other states for it uses a county specific postmile system as opposed to a state-level system. The postmile value of a California highway is not a continuous measure across the whole state; it resets to zero when the highway enters a new county.

Table 1. Postmiles and prefix letters for realignments. Source: California Highways Numbering Conventions: Postmiles, http://www.cahighways.org/num-postmiles.html, District 5 postmile book

Prefix	Description
L	Overlapping postmiles
R	Realignment
M	Realignment of R mileage
N	Realignment of M mileage
S	Spur mileage of original of realign mileage
T	Temporary connection of original or realign mileage
C	Commercial lanes paralleling main highway
D	Duplication (because of meandering county line)
G	Reposting duplicate postmile at the end of route
H	Realignment of duplication

Table 2. Data sources of reference markers

Source	Location Type	Number of Markers
TASAS	Intersection/ramp	7,312/10,623
ESRI Data and Maps, 2010	County boundary	1,150
Traffic and Vehicle Data Systems Unit	Intersection, ramp, major landmarks	2,458
Total		21,543

When the highway is realigned, those sections are given updated measurements to distinguish from the original measurements. Depending on the type of realignment or previous changes on the roadway, a number of postmile prefix versions as shown in Table 1 are utilized. Transportation data that are associated with the highways follow this established postmile system.

POSTMILE REFERENCE MARKERS

Postmile reference markers of major intersections, entrance ramps, and exit ramps for all state highways were obtained from the Caltrans Traffic Accident Surveillance and Analysis System (TASAS) and the Traffic and Vehicle Data Systems Unit (available on http://traffic-counts.dot.ca.gov). These reference markers are used to calibrate the LRS. The 21,543 reference markers by location type and data source are summarized in Table 2. County boundary points were generated by creating a spatial overlay of county polygon features on highway line features. Ramps and intersections were manually identified by matching text descriptions to line feature end points on the map.

COLLISIONS

Almost 507,350 fatal or injury collisions occurring on state highways in California from 2001 to 2008 were obtained from the Statewide Integrated Traffic Records System (SWITRS, http://www.chp.ca.gov). SWITRS is maintained by the California Highway Patrol and contains all reported collisions in the state. Several elements are included in each report to record the location of the collision. Collisions occurring on state highways have several additional fields: route number, route direction, postmile, and postmile prefix. An example set of records is shown in Table 3.

Table 3. SWITRS state highway collisions location information example

Route Number	Direction	Prefix	County	Postmile
49	S	-	EL DORADO	22.998
118	W	R	VENTURA	30.430
36	E	L	TEHAMA	40.320
152	W	T	SANTA CRUZ	3.119
78	E	N	SAN DIEGO	17.680

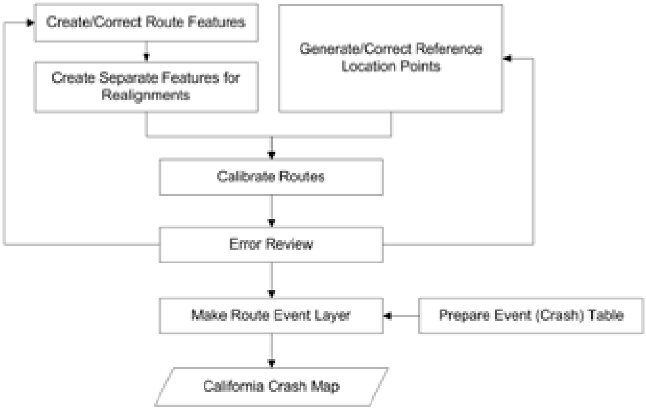


Figure 1. LRS development workflow

Figure 2. 91E-ORANGE realignment

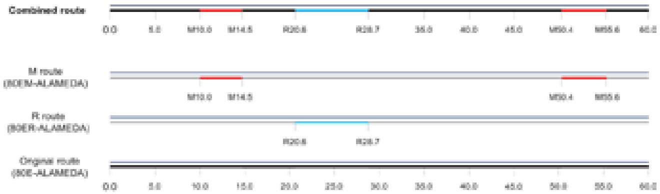


Figure 3. Separate route features for particular prefixes

METHODS

Overview

An overview of the LRS workflow is shown in Figure 1. Each of the steps is explained in detail in the following subsections. The processes all utilized ArcGIS 10 software from Esri. While some of the techniques and instructions will refer to specific functions in the ArcGIS software, the main concepts are relevant to any linear referencing software.

CREATE ROUTES

The first step in building a highway LRS is to create routes using highway street segments extracted from a currently available digital street network. This was a semiautomated process that required selecting connecting segments and merging them into a single route/direction for each county. The process is thoroughly explained in Bigham et al. (2009) and Park et al. (2011).

After route features have been extracted and merged, the ArcGIS Create Routes tool can be used to prepare the routes for calibration. An important feature of the tool is the ability to set a coordinate priority location from which measures are accumulated for each route. The coordinate priority typically would be Lower Left for highways accumulating measures from west to east or south to north. This means that measures will be accumulated from the lower left corner of the bounding rectangle for the entire route. However, some routes in California accumulate in the opposite direction and they require using a Lower Right or an Upper Left coordinate priority. The Lower Right routes were not all known for the initial route creation; many were identified only during the error review process and properly recategorized in future route-creation iterations. Routes must be processed in the Create Routes tool in separate sets for each coordinate priority type before being merged into a single set.

Create Duplicate Routes to Account for Highway Realignments

Different measuring systems are required for realigned routes. Although a current street network cannot reflect all the geometric differences in realigned routes, applying different measuring systems to the same geometry can at least approximate the true locations of events on the route. The original work by Bigham et al. (2009) accounted for the largest realignments, such as the example in Figure 2 when a route starts at zero at the county boundary but resets to zero several miles along the route. However, most routes have multiple realignments that each requires separate linear features for proper measurement along the entire length of the route. An example of this concept is shown in Figure 3, with the original route at the bottom having an initial realignment (R) and then a subsequent realignment of the R (M). The final hypothetical combined route is shown at the top. Events occurring in the realigned sections are likely to have the designated R or M prefix and the postmile value will differ from the original route.

We assigned every route a route identifier, called RouteID in this study, concatenated from multiple fields, including the route number, direction, realignment prefix, and county. The RouteID field is used to match events and their corresponding descriptive fields to a particular route, but each route feature also has a permanent unique numeric identifier in the database. The unique numeric identifier can be used as a reference to accommodate potential route number or geometry changes in the future. As shown in Figure 3, the original route at the bottom was named 80E-ALAMEDA and the realignment (R) and realignment of R (M) were named 80ER-ALAMEDA and 80EM-ALAMEDA, respectively. To accommodate all the potential measuring systems of routes in California, the complete set of routes was copied multiple times to create duplicate sets. Each of the potential

Table 4. Route event (collision) table

RouteID	Route	Direction	Prefix	County	Postmile
49S-EL DORADO	49	S	-	EL DORADO	22.998
118WR-VENTURA	118	W	R	VENTURA	30.430
65S-YUBA	65	S	-	YUBA	1.230
36EL-TEHAMA	36	E	L	TEHAMA	40.320
152WT-SANTA CRUZ	152	W	T	SANTA CRUZ	3.119
78EN-SAN DIEGO	78	E	N	SAN DIEGO	17.680

Figure 4. Original route and new bypass portion

postmile prefixes was associated with every route. If no reference markers on a route existed for a particular prefix version, the route was automatically dropped from the dataset during the route-calibration process.

In some cases, special adjustments can be made to the base routes to account for major realignments that have occurred in recent years. An example is when a new freeway is constructed to bypass the downtown area of a city as shown in Figure 4. The route geometry would be modified for the new freeway and postconstruction route events would use the new realigned measures. Older route events, however, would be located on the original route geometry.

CALIBRATE ROUTES

Once the separate routes have been created for each prefix version, the routes must be calibrated using the associated postmile reference markers. Depending on the route attributes, the ArcGIS Calibrate Routes tool gives several options for designating route, point, and measurement values. The calibration process assigns the known postmile measurements to the continuous route by matching the unique route identifiers. The lengths of route portions between reference markers are interpolated from the known postmile values of the nearest reference markers. Because the actual distance along a route may differ from the measured distance, the reference markers are essential for developing an accurate LRS.

MAKE ROUTE EVENT LAYER

After calibrating the routes, route events with postmile measures can be located by assigning a route identifier (RouteID) field to match to an appropriate route. For our work, the California SWITRS collision dataset, as shown in Table 4, was used as part of a statewide geocoding project outlined in Bigham et al. (2009). A geoprocessing model was developed using the ArcGIS data model builder to import a SWITRS database file and create a new route identifier field. Using the route identifier field and the postmile, the collision events can be georeferenced on the LRS.

The first iteration of making the route event layer, however, should only be used to help verify the quality of the LRS. There are likely to be errors that will require further inspection in order to address the underlying problem. Errors can be reviewed by examining the error fields in the route event layer, visual inspection of route measure anomalies, or accessing measurement attributes through custom programming. Each of these review methods are described in the following sections, followed by a summary table outlining the sources of error and potential resolutions.

View Error Field in Route Event Layer

When creating a route event layer in ArcGIS, there is an option to add an error field to each record that could not be located. This field shows two types of errors: Route Not Found and Route Measure Not Found. The Route Not Found error generally means there is an egregious error in the route-naming system for a record and no route matches can be found. However, it is important to review this error to ensure a necessary route is not actually missing. The Route Measure Not Found error means the route is matched properly, but the measurement is outside the calculated bounds of the route. This could be an error with the event layer measure value or also could identify a problem with the linear referencing calibration, otherwise known as a route measure anomaly. Any potential anomaly can be explored through custom code or visual inspection described in the next two sections.

Table 5. Route measure details

LR_RouteID	MMin	MMax	Monotonicity
101N-MONTEREY	0.00	101.32	Strictly Increasing
37E-MARIN	11.95	14.62	Strictly Increasing
133N-ORANGE	0.00	22563.53	Increasing with Levels
137W-TULARE	-0.08	27.40	Increasing with Levels
152W-SANTA CRUZ	-2.07	8.30	Increasing with Levels
238S-ALAMEDA	0.00	16.70	Increasing, Decreasing

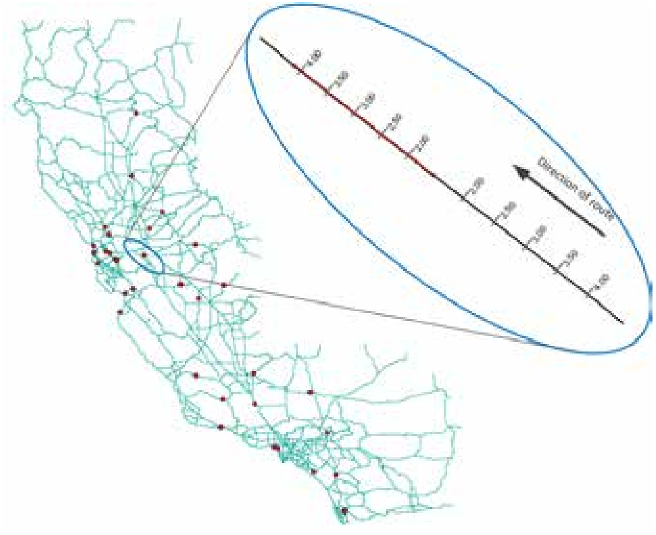


Figure 5. Route measure anomalies

Access Route Measurement Attributes through Custom Programming

A custom ArcGIS plug-in was written in ArcObjects and Microsoft .NET to review potential errors in the route measurements. The tool directly accesses route-measurement attributes to produce a table for each route showing the monotonicity (trends in measure values over the length of the curve), minimum measure value, and maximum measure value as shown in Table 5. The monotonicity shows whether the measurements along the route increase or decrease, remain constant over some intervals, and whether gaps are present in the measurements. In Table 5, the route with a monotonicity value of Increasing, Decreasing shows consistency issues with the route measurements for it always should be Strictly Increasing or Increasing with Levels for the postmile system. The negative minimum measure values for 137W-TULARE and 152W-SANTA CRUZ also are problematic for the routes should begin at zero or higher. Finally, the maximum measure value for 133N-ORANGE is an extremely large value, which is obviously incorrect and needs to be reviewed by visual inspection.

Visual Inspection of Route Measure Anomalies

After discovering anomalies from the data tables, the routes in question should be visually reviewed to verify measure consistency. ArcGIS provides built-in tools to view route measure anomalies. By activating the Routes option in the layer properties, all the point or section anomalies will appear as red dots or lines on the map as shown in Figure 5. If an anomaly is present, the route will be incorrectly calibrated and events within the range of the error will be improperly located. The events may be clustered around an incorrect postmile marker.

The Identify Route Locations tool also can be used to identify postmile values and measure trends of the calibrated route. ArcGIS user manuals provide instructions on how to properly use these software features and other GIS software should have a similar mechanism to display improperly calibrated routes (ESRI 2010). However, what the manuals do not provide are practical examples of the types of route measure anomalies and how to resolve these issues. A comprehensive overview of the most common causes of errors and potential solutions along with before and after diagrams of example routes is shown in Table 6.

RESULTS

The LRS was created for the California state highway system. The 1,017 base routes that cover 50,835 km (31,587 miles, equivalent to 15,794 centerline miles) for both directions (east and west) are summarized for selected counties in Table 7.

All identified errors were corrected in the LRS using the methodology outlined in this paper. The locations of geocoded collision route events were compared to the locations from the original LRS developed by Bigham et al. (2009). A random sample of 580 SWITRS state highway collisions from 2007 to 2008 stratified by county (ten collisions for each of the 58 counties) was selected for the comparison. The relative distance between the collision locations based on the Bigham et al. (2009) LRS and the new LRS measurements is shown in Table 8. Nearly 50 percent of the relative locations were within one meter of each other, while approximately 96 percent were within 1,000 meters. Four percent of locations were greater than 1,000 meters.

The relative distance between collision locations subset by an urban/suburban/rural population classification system is shown

Table 6. Causes and solutions to calibration errors

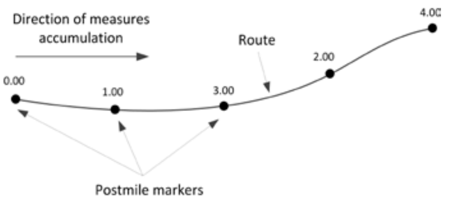
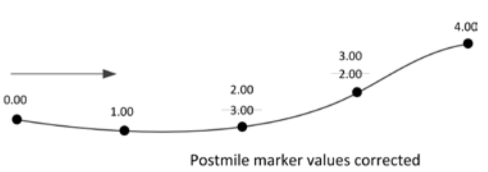
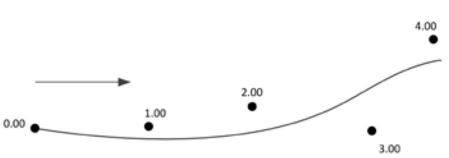
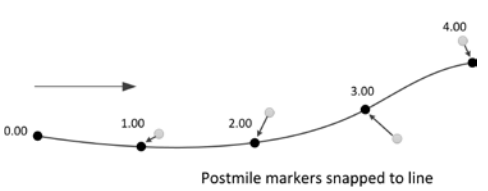
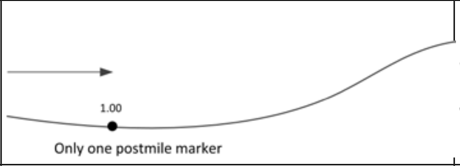
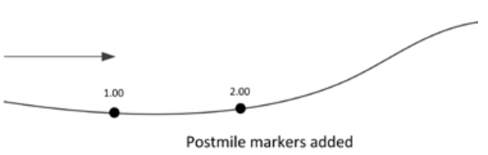
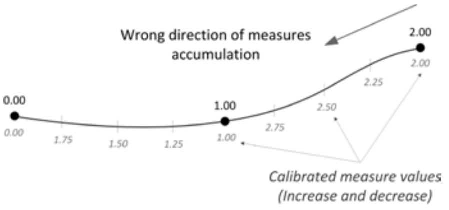
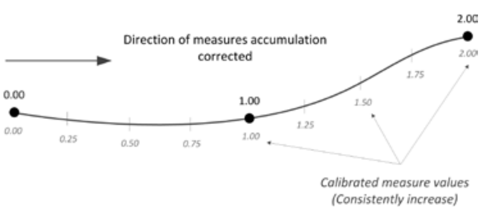
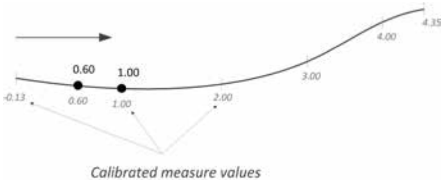
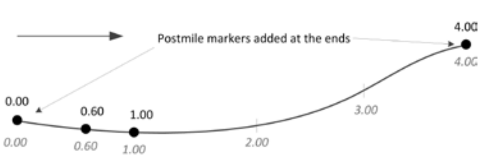
Problem and Solution	Before	After
Incorrect postmile marker placement (nonsequential order) → Fix postmile markers		
Incorrect postmile marker placement (not on route) → Snap postmile markers to route (Note: This can be automatically fixed by implementing a topology rule)		
Only one known postmile marker on route → Add a postmile marker manually measured along the route to allow calibration		
Incorrect measures of accumulation (Increasing, Decreasing) → Modify the coordinate priority position when creating the route to achieve a Strictly Increasing or Increasing with Levels result		
No postmile markers near the end of a route, creating invalid minimum or maximum measure values → Add additional postmile markers at the beginning and end of route		

Table 7. Summary of the constructed linear referencing system for largest and smallest length counties

County	Number of Routes	Sum of Length Km (Mi)	Percent	Number of Postmile Reference Markers
Los Angeles	68	2742.5 (1704.1)	5.40%	2,700
Kern	36	2819.2 (1751.8)	5.55%	807
San Bernardino	50	3919.1 (2435.2)	7.71%	1,171
…	…	…	…	…
San Francisco	10	86.9 (54)	0.17%	135
Yuba	8	208.5 (129.6)	0.41%	98
Alpine	6	262.4 (163)	0.52%	52
State Total	1,017	50,835 (31,587)	100%	21,543

Table 8. Distance differences between original LRS collision locations (Bigham et al. 2009) and new LRS

Distance Difference	Count	Percent	Cumulative Count	Cumulative Percentage
Less than 1 m	289	49.8%	289	49.8%
1–10 m	63	10.9%	352	60.7%
10–100 m	107	18.4%	459	79.1%
100–1,000 m	97	16.7%	556	95.9%
Greater than 1,000 m	24	4.1%	580	100.0%
Total	580	100.0%		

Table 9. Distance differences by population categorization per SWITRS population value for each collision. (Rural: less than 10,000; Suburban: between 10,000 and 100,000; Urban: greater than 250,000)

Area	Less Than 1 M	1–10 M	10–100 M	100–1,000 M	Greater Than 1,000 M	Total
Rural	165 (43.7%)	40 (10.6%)	79 (20.9%)	74 (19.6%)	20 (5.3%)	378 (100%)
Suburban	98 (57.0%)	20 (10.9%)	25 (18.8%)	17 (10.2%)	4 (3.1%)	164 (100%)
Urban	26 (68.9%)	3 (12.2%)	3 (5.4%)	6 (13.5%)	0 (0.0%)	38 (100%)
Total	289 (49.8%)	63(10.9%)	107(18.4%)	97(16.7%)	24(4.1%)	580(100%)

in Table 9. Nearly 70 percent of urban collisions were adjusted by less than one meter, while only 44 percent of rural collisions were geocoded that closely. Rural areas contributed to most of the larger differences, with approximately 25 percent of collision locations adjusted more than 100 meters.

DISCUSSION

The LRS is essential for locating the approximately 40 percent of collisions in California that occur on state highways. Standard intersection-based or address-based geocoding procedures are not able to accurately locate events along highways, especially near large freeway interchanges. These interchanges have multiple crossings that also can vary by the direction of travel, making it unfeasible for a geocoding process to match to a basic intersection name. Also, a recorded intersection on a highway collision report may not actually be a true intersection for it could represent an overpass or a dead-end street that stops at the freeway. Without the LRS, a significant portion of highway collisions could not be geocoded.

The LRS developed in this study resulted in improved accuracy for locating events along the routes compared to the original Bigham et al. (2009) LRS. Differences in collision event locations shown in Table 8 were presumed to be due to improved accuracy based on several factors: (1) an increased number of postmile reference markers were used, (2) all route realignments were accounted for, and (3) all identified LRS errors were corrected. The third factor is especially important for the correction of LRS errors alleviated the need for further manual checks to verify the location of each randomly selected collision. Overall, the most significant improvements occurred along rural routes. Any correction or addition of postmile markers in a rural area impacted a larger portion of a route because of the infrequency of the postmile markers. A rural route may have 50 miles between postmile markers, while an urban route could have a marker every single mile. Thus, when comparing to the original Bigham et al. (2009) LRS, 5.3 percent of rural locations had greater than a 1,000-meter difference, while urban locations were always less than 1,000 meters.

The greater volume of route events in urban areas also simplifies visual inspections of the routes. Long portions or rural routes lacking route events would not raise any red flags, but the same situation in urban areas is easily recognizable and requires further investigation. This need for manual visual inspections is an inherent drawback but is necessary to identify errors that do not break the rules of the LRS. For example, an incorrectly located reference marker with a postmile value that falls within the range of the nearest reference markers on either side would not register as an error. However, by incorporating more reference markers and resolving all known errors, the reliance on visual inspections is greatly decreased.

LRS development from preexisting reference markers also is discussed by Park et al. (2011) based on their work for the Korean expressway system. However, there are major differences between the Korean expressway system and the California state highway system. First of all, the sheer size difference between the roadway systems is enormous, with approximately 26,000 kilometers in California compared to only 3,350 kilometers in

South Korea. The size difference is further magnified by the fact that realignments of California highways are required for most routes, essentially doubling or tripling the total length of routes necessary for LRS development. The Korean expressway system currently does not have realignments and construction projects are focused on developing new roadways, while in California, much of the work is focused on maintaining or modifying existing roads. Thus, realignment measures are necessary for the California LRS, while the Korean expressway LRS can avoid this extra layer of complexity. Secondly, the larger size and inclusion of realignments in California decreases the feasibility of relying heavily on manual reviews of the LRS. Our methodology included a more systematic error-checking approach that utilized custom code to extract route measurement attributes. These measurements could be summarized and reviewed in a table format instead of being diagnosed during visual inspections. Finally, we were able to address the calibration issues that Park et al. (2011) referred to as a potential software error. The invalid calibration of some routes that resulted in clustered events was due to incorrect coordinate priorities.

There is always some degree of uncertainty when establishing the true location of a route event on an LRS. The positional accuracy of the street network and the postmile value associated with a record can heavily impact the calculated location. This makes it difficult to systematically quantify the level of accuracy. If the street network slightly deviates from the actual road placement in some locations, those discrepancies will be incorporated into the LRS, but this does not indicate a deficiency in the route calibration. There also can be difficulties when reviewing locations of route events that are assigned postmile values based on descriptive location information. For example, the collision data used in our analysis have a postmile value that the department of transportation manually calculates by translating the descriptive location information in the police report. However, there is a potential for translation error and the postmile value may not correctly match the descriptive location information. Occasionally, the discrepancies are obvious, but other times they cannot be determined without access to the original police report.

CONCLUSIONS

Many transportation agencies have legacy data systems and need to transition to new GIS-based systems. However, they may not have the luxury to define a new measurement system for road network events. Associating preexisting markers with a current digital street network is the best way to incorporate their legacy data into new applications. The described methodology presents an LRS development approach with an emphasis on components that frequently are overlooked. The methodology clearly outlines how to utilize preexisting reference marker measurements, account for route realignments, and identify and resolve route measure anomalies. The resulting LRS can more effectively locate events occurring on sections of highways that have undergone multiple realignments.

The development of an LRS is essential to managing a highway road network system based on relative measurements. Building a complete, accurate system is a major—but manageable—task that will likely result in future cost savings and allow agencies to take advantage of numerous GIS technologies. An accurate LRS also can lay the foundations for the development of new measurement protocols and ease the transition from an old system. However, specific protocols are needed for updating the LRS because new roadways are continually being built. The fact that multiple departments in an organization may be utilizing the same LRS also emphasizes the need for proper coordination across the entire organization. Newer multilevel LRS management systems now are available to help simplify long-term maintenance and provide access to common applications to maximize the benefit of an LRS.

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References

Adams, T. M., N. Koncz, and A. P. Vonderohe. Functional requirements for a comprehensive transportation location referencing system. North American Travel Monitoring Exhibition and Conference (NATMEC), Middleton, Wisconsin, August 27 to 31, 2000.

Adams, T. M., N. Koncz, and A. P. Vonderohe. 2001. Guidelines for the implementation of multimodal transportation location referencing systems. NCHRP Report 460, Transportation Research Board, National Research Council. Washington, DC: National Academy Press.

Bigham, J. M., T. M. Rice, S. Pande, J. Lee, S. H. Park, N. Gutierrez, and D. R. Ragland. 2009. Geocoding police collision report data from California: A comprehensive approach. International Journal of Health Geographics 8 (72).

Curtin, K. M., G. Nicoara, and R. R. Arifin. 2007. A comprehensive process for linear referencing. Journal of the Urban and Regional Information Systems Association 19 (2): 23-32.

Easa, S., and Y. Chan. 1999. Implementation of linear referencing systems in GIS. Reston, VA: American Society of Civil Engineers, 79-98.

ESRI. 2010. ArcGIS Desktop Help. ESRI. Http://resources.arcgis.com/content/arcgisdesktop/ 10.0/about, December of 2011.

Fletcher, D., J. Espinoza, R. D. Mackoy, S. Gorden, B. Spear, and A. Vonderohe. 1998. The case for a unified linear reference system. Journal of Urban and Regional Information Systems Association 10 (1): 7-11.

Kiel, D., W. Rasdorf, E. Shuller, and R. Poole. 1999. Linear referencing system for North Carolina Department of Transportation. Transportation Research Record: Journal of the Transportation Research Board 1660: 108-13.

Park, S. H., J. M. Bigham, S.-Y. Kho, S. Kang, and D.-K. Kim. 2011. Geocoding vehicle collisions on Korean expressways based on postmile referencing. KSCE Journal of Civil Engineering 15 (8): 1,435-41.

Scarponcini, P. 2002. Generalized model for linear referencing in transportation. GeoInformatica 6 (1): 35-55.

Steiner, R., I. Bejleri, X. Yang, and D.-H. Kim. Improving geocoding of traffic crashes using a custom ArcGIS address matching application. Twenty-second Environmental Systems Research Institute (ESRI) International User Conference, San Diego, California, July 8 to 12, 2002.

U.S. Federal Highway Administration. 2011. Highway performance monitoring system (HPMS). U.S. Department of Transportation. Http://www.fhws.dot.gov/policyinformation/ hpms.cfm.

Vonherhoe, A. P., and T. D. Hepworth. 1998. A methodology for design of measurement systems for linear referencing. Journal of the Urban and Regional Information Systems Association 10 (1): 48-56.

Zhang, J., S. You, L. Chen, and C. Chen. A hybrid approach to segment-type geocoding of New York City traffic data. Proceedings of the First International Conference on Computing for Geospatial Research and Application, Washington, DC, June 21 to 23, 2010.