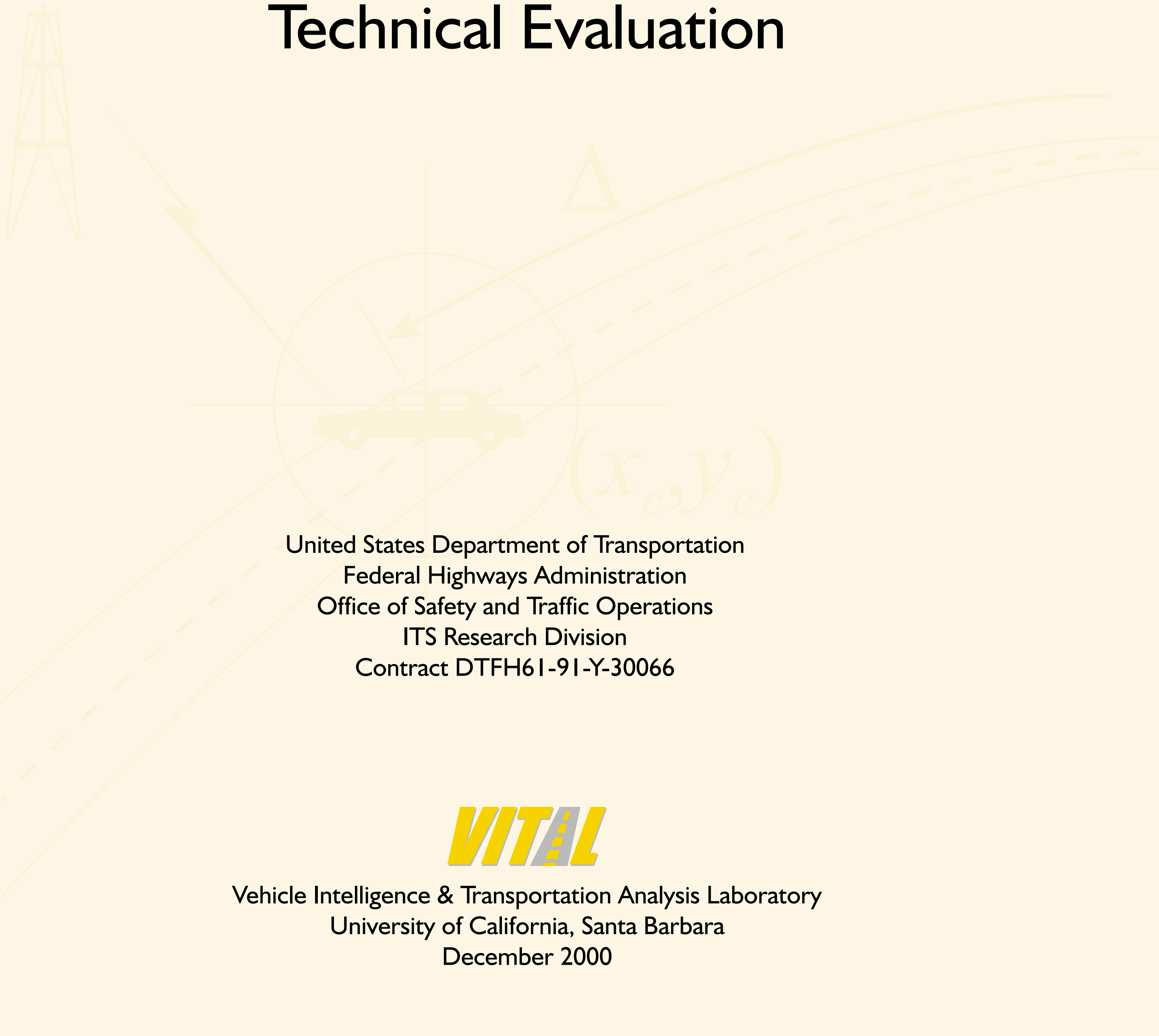
The LRMS Linear Referencing Profile

Technical Evaluation



United States Department of Transportation
Federal Highways Administration
Office of Safety and Traffic Operations
ITS Research Division
Contract DTFH61-91-Y-30066

VITAL

Vehicle Intelligence & Transportation Analysis Laboratory
University of California, Santa Barbara
December 2000

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FINAL REPORT

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The Linear Referencing Profile (LRP) is part of the Location Referencing Message Specification (LRMS), a partial solution to interoperability problems in location expression and exchange (LX) in Intelligent Transportation Systems (ITS). This report is an evaluation of the LRP, carried out by the Vehicle Intelligence and Transportation Analysis Laboratory (VITAL) at the University of California, Santa Barbara. This document assumes that the reader is familiar with the background to interoperability problems in ITS, and the LRMS effort.

The following points clarify the scope of this research:

- Linear Referencing is most popular in GIS-T (Geographic Information Systems for Transportation), however, we treat the LRP as a generic ITS location messaging profile, not constraining our test approach to GIS-T scenarios.
- We do not assume that the original expression of position is accurate; we examine the error in the process by which a linear reference is derived from 2-dimensional coordinates, and the error in measuring a linear offset using a Distance Measuring Instrument (DMI).
- The LRP relies on indices for road sections and intersection nodes, that are common between users. If users communicate with respect to the same database, there is no interoperability problem; if the databases are different, then the task of assigning common identifiers is expensive, and some errors are inevitably introduced in this step. However our testing assumes away this problem, and we do not attempt to model or to estimate such error. We expend considerable manual effort to develop an accurate table of correspondences for a small sample of data, and we caution that in practical implementation, creating this table with requisite accuracy, and overcoming the inherent semantic conflicts (single vs dual line freeways, traffic circles, etc) will be a potential problem.

Testing is built around three sets of experiments. The first involves field surveys using differential Global Positional Systems (GPS) and a Distance Measuring Instrument (DMI). In the preliminaries, we observe various characteristics of DMI readings under normal traffic conditions, and in remote test areas, to estimate the accuracy of the instrument and to quantify its limitations. Then a small sample of roads is selected; we drive those roads, and compare our readings to length calculations and coordinates from digital maps. One of those maps is an engineering scale product; measurements off the map are almost identical to our observations, both in terms of road lengths (±12m) and coordinates (±2m). Other maps disagree by 60–130m in length, and some coordinates are substantially in error (±200m). These numbers are important in understanding both (a) the remarkable degree of agreement between DMI observations and lengths measured from coordinates, despite imperfect driving, lane changes, undulations and elevation changes in the road surface; and (b) the limitations of that agreement, and causes of discrepancies. An important example of (b) is the generous liberties taken by some database vendors in the cartographic representation of ramps in freeway intersections, causing experimental results to be consistently *worse* for freeways than for average, moderately sinuous roads.

To derive a linear reference from a 2-dimensional location expression, coordinates are “snapped” to the nearest line segment, the road is identified and the linear offset is calculated from the designated start of the road. The second set of tests examines the accuracy with which this process takes place, given the inaccuracy of the average digital reference map. Vehicle locations are simulated along the centerlines of the engineering database (because it faithfully represents reality as surveyed by our own GPS), with simulated GPS error of 30m and 100m, and these points are interpreted with respect to the other five test databases. Results are extremely varied. With the best databases and error-free GPS, the correct road is identified 100% of the time, but with 100m error and the worst database, results are in the 20% range. With a good database and 30m error, 96–98% success is achieved. Offset measurement may be in error by nearly 800m in the worst case, while the best results are in the sub-metre range, with an average of about 50m. Again, freeways score poorly, because of the problems outlined above.

The third test set addresses the transfer of a linearly referenced location, generated with respect to one database and interpreted with respect to another. Offset errors are 50m for transfers by absolute offset, and 25m using normalized offsets. Worst case errors are 500m to 1 km. On freeways the averages are much worse: 135m by absolute offset, and 100m for normalized transfers.

The implications of these results are application-dependent, and the costs and liabilities associated with error have to be balanced against the costs of infrastructure and methodology that would lead to better success rates. This research was not mandated to address cost and benefit issues.

Our research leaves open the question of road identity, which is one of two principal information items in the LRP. The considerable problems inherent in matching road identities by road name have already been studied in our tests of the LRMS Cross Streets Profile (VITAL 1998). Clearly the only way to achieve unambiguous and error-free road identification for interoperability is by a coordinated interagency index. Two relevant national efforts are currently underway, (a) a National Spatial Data Infrastructure (NSDI)-sponsored road identification standard, and (b) a national ITS Datum (Siegel et al 1996). While (a) addresses the specific issue of road identification, which is critical to the success of the LRP and other data sharing needs, (b) takes a broader approach to facilitate location exchange in general.

The findings of this research will undoubtedly be useful to anyone planning to use the LRP for location expression — results have been stratified wherever possible to make them relevant to reader needs. But perhaps most interesting is that the research rebuts the assertion that linear referencing, with measurement by DMIs, is the only LX methodology that can reliably be used in transportation. The strong agreement between DGPS, DMI and the engineering database indicate that over the next decade, DGPS can and should replace linear measurement for all but the most demanding road-related LX needs.

DGPS	Differential **GPS.** A means of correcting S/A and other GPS errors by monitoring GPS signals received at known locations.
DMI	Distance Measuring Instrument. A high precision odometer (±1m).
GPS	Global Positioning System.
LR	Linear Reference. A method of expressing location of a point, in terms of distance along a given road.
LRMS	Location Referencing Message Specification (Goodwin et al 1996)
LRP	Linear Referencing Profile, part of the **LRMS**
LX	Location Expression. A means of expressing location, e.g. coordinates, street names.
ORNL	Oak Ridge National Laboratory, Oak Ridge, Tennessee
S/A	Selective Availability. Error of about ±100m deliberately introduced into **GPS** coordinates by the U.S. Department of Defense, for the sake of national security. Expected to be phased out in 1999–2000.
VITAL	Vehicle Intelligence & Transportation Analysis Laboratory, University of California, Santa Barbara
XSP	Cross Streets Profile, part of the **LRMS**

Foreword

In April 1998 the Vehicle Intelligence Testing & Analysis Laboratory (VITAL) was contracted by Viggen Corporation, Tennessee, on behalf of the United States Department of Transportation, Federal Highways Administration, to test the Linear Referencing Profile (LRP), among other tasks. The LRP is part of the Location Reference Messaging Specification (LRMS; Goodwin et al 1996) proposed by Viggen and Oak Ridge National Laboratories (ORNL) for ITS messaging. This document, prepared under a subsequent contract to ORNL, presents our analysis and findings.

Principal investigators on VITAL projects are Michael Goodchild and Richard Church. Other persons responsible for the design and execution of the tests, and generation of this report, are Val Noronha, Somil Kulkarni, Sacid Aydin, Fiona Ross and Nathan Warmerdam. The research was undertaken in cooperation with Viggen, ORNL and the California Department of Transportation (Caltrans). We are grateful for discussions with Mike Figueroa, Ramez Gerges, Cecil Goodwin and Steve Gordon.

Further details on the project are available from VITAL at

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Some of the infrastructure that enabled this work was developed under an earlier contract funded by the Caltrans Testbed Center for Interoperability (TCFI).

Linear referencing has a long tradition of use in the Geographic Information Systems for Transportation (GIS-T) profession. It is usually effective for the purpose, because it is used principally by personnel within a single industry, using standardized identifiers and methodologies. Until recently the GIS-T community operated largely in a 1-dimensional world, with little need to exchange 2-dimensional positional references with other maps. As GIS-T broadens its scope of reference to peripheral information (e.g. land cover, avalanche or landslide activity that impacts road maintenance), there is now greater recognition of the need to address interoperability issues with 2-D location expressions.

As part of LRMS, the Linear Referencing Profile (LRP) is tailored to the needs of GIS-T, but it is not restricted to this user community. This evaluation is based on a general class of applications that require interoperability between location referencing methods and map databases, inside and outside the GIS-T profession. LRMS employs linear offsets in the Cross Streets Profile (XSP) as well as LRP; this report covers linear referencing issues in the context of both these profiles.

The LRP (Table 1) expresses location by means of an offset measured along a road, from a given reference point. The interoperability challenge is for a linear reference determine with respect to a *source* database to be transferable to a *target* database. The LRP may be employed in different ways to express point and segment locations:

- It may reference a point along the road (single offset), or a section of road (start and end offsets).
- Offsets may be expressed as absolute distance (integer decimetres) or relative distance — a percentage of link length, correct to 0.01%. These expressions of precision are equivalent for an offset of 1 km.
- The road section is identified either by a road reference/index (road name or numeric index) or by a logical link reference (start and end node indices).

The LRP also provides for side of road (left/right). This is implied by direction of travel, which must obviously be specified or otherwise be obvious from the road identifiers.

The LRP is premised on a crucial limiting assumption, under which the interoperability problem is greatly diminished. The street segment is identified by (a) start and end node indices, or (b) an index, or (c) a name. Both (a) or (b) require that node and/or link indices be standardized between sender and receiver. Moreover, absolute and normalized offsets are meaningless unless the start and end points of the street are commonly identified, therefore even if (c) is used, the LRP assumes that common start and end points, and direction of offset measurement, are pre-established. This assumes that a set of referencing standards is in place (e.g. a referencing datum), or that the sender and receiver operate with respect to the same database — in which case interoperability is not a problem. In the absence of this, t*he LRP cannot be considered a generic messaging profile for use with reference to current commercial databases.*

Table 1. The Linear Referencing Profile

Bit	Content	Values/Range
0-3	Start Code	0100
4	Pad	
5-7	Record Type:	000 = Road/Index 001 = Logical Link 010-111 = Expansion
Case-Type = Road Reference/Index (12 - variable byte		
8-23	Normalized Offset1	+/- 10,000 0.01 percent of link
24-39	Normalized Offset2	+/- 10,000 0.01 percent of link
40	Side	Binary 0 = right-hand; 1 = left-
41-63	Distance Offset1	+/- 4,194,303 decimeters
64-86	Distance Offset2	+/- 4,194,303 decimeters
87	Street Name/Index Flag	0: Use Street Name 1: Use Street Index
88-95	Street Name/Index Byte	Integer number of bytes of Name data Street Index (0-255)
96-variable	Street Name	(Street Name/Index Byte Count) ASCII of name
96-variable	Street Index	(Street Name/Index Byte Count)
Case-Type = Logical Link Reference (13 byte		
8-39	Start node ID	1-4,294,967,296
40-71	End node ID	1-4,294,967,296
48	Side	Binary 0 = right-hand; 1 = left-
49-63	Normalized Offset1	+/- 10,000 0.01 percent of link
64-79	Normalized Offset2	+/- 10,000 0.01 percent of link
80	Pad	
81-103	Distance Offset1	+/- 4,194,303 decimeters
104	Pad	
105-127	Distance Offset2	+/- 4,194,303 decimeters

Profile Problems

There are a few definitional problems with the LRP:

- "Mileposts" may be appropriate starting positions for offset measurement. They are mentioned in the Profile illustration but they play no role in the Profile itself. This study assumes offsets to be measured with respect to the start of the identified section of road, but findings can be generalized to a milepost reference point.
- Case Type Logical Reference: Start and end node IDs must represent (a) a single link, or (b) a set of adjacent links such that there is one and only one path between them. Moreover, for interoperability to be achievable, files may have to be pre-processed so that non-planar intersections (e.g. overpasses) are uniformly considered as nodes, or disallowed as nodes, across all databases.
- Side and offset require that street direction and start point are agreed upon between sending and receiving databases. For Case Type Road Reference, this assumes that the files have been pre-processed to achieve this agreement.
- Pad bits in Case Type Logical Reference serve no apparent purpose because they are not at byte boundaries.
- There is no reason to pad Case Type Logical Link Reference to 128-bit when Case Type Road Reference/Index is of variable length. If Case Type Road Reference/Index were to be organized as multiple messages, where the initial message was restricted to 128 bits and subsequent messages contained additional information as required, then the padding of Case Type Logical Reference would be justifiable.
- Under Case Type Logical Link Reference, bit values are out of order, and Normalized Offset 1 does not have the required number of bits.
- There are enough bits allocated to accommodate absolute offsets up to 420 km at 0.1m precision. However, insufficient precision is allowed for normalized offsets: 0.01% of anything greater than 1 km is more than 0.1m.

Application Scenarios

A positional reference contained in a LRP message may be derived from:

- Analog map: an object (e.g. hotel) is visually identified on a map, and its offset estimated, or measured by a linear measurement device such as a map measuring wheel. There are obvious sources of error due to (a) generalization of the map, depending on its scale; and (b) error in estimation or measurement.
- Digital map: distance is measured by accumulating distance along the polylinear or curvilinear representation of the centerline. Inaccurate geometric alignment and generalization are the principal

sources of error. Clearly, digital measurements off large scale construction plans or engineering drawings are least susceptible to offset error. However the offset must be interpreted with equivalent facilities at the receiving end.
- GPS: a 2-dimensional GPS coordinate is snapped to the nearest centerline segment, and the offset digitally derived.
- Field measurement of offset: e.g. by Distance Measuring Instrument (DMI) or odometer.

These methods are so different from each other, that the offset values they produce for a given location are likely to be substantially different. An offset is meaningful only if the equipment used to interpret it at the receiving end is comparable to that used for data-gathering.

Sources of Error

The general relationships between polyline geometry and length have been studied by Douglas and Poiker (1973), Buttenfield (1985) and Mandelbrot (1967), among others. In general it is well known that the greater the number of non-redundant points in a polyline[1], the greater its length. Natural lines such as coasts can have an infinite length when measured with sufficiently small calipers. Roads have a specific geometry, at least in design. But realities of construction, and cartographic representations at different scales and levels of accuracy, generalize and distort the idealized geometric sections.

During road construction, objects such as kerb cuts and speed limit signs are positioned with respect to a construction reference line, using precise (0.01m) survey instrumentation. Post-construction maintenance rarely demands great precision. Linear references are measured by Distance Measuring Instruments (DMIs), which are capable of ~1m accuracy. By contrast, linear measurement in ITS relies on the standard vehicle odometer, with an effective precision of 30–50m; in the future, if inertial AVL technology becomes commonplace, motorists may have access to better linear measurement precision.

The LRP has entirely different meanings in these two user communities. In GIS-T[2], a location can be captured, expressed, exchanged and interpreted, all in terms of linear references. In other applications, location would be most likely captured by GPS in two dimensions, translated to a linear measurement at the transmitting end, and interpreted at the receiving end as either a linear reference or a coordinate. Table 2 summarizes the classes of errors at various stages of position capture and transfer.

Table 2. Principal classes of error in location exchange using LRP

	Determine position	Express as LRP relative to database A	Transfer to database B	Interpret position as required
GIS-T	DMI (m) Class I error	—	Class IV error	—
ITS	GPS (lat,long) Class II error	Class III error	Class IV error	Class V error

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[1] As an example of redundancy, if three consecutive points lie in a straight line, the center point is redundant because it contributes nothing to shape or geometry.

[2] The term “GIS-T” is used as shorthand for the world of linear location referencing (e.g. using DMIs). This is not to imply that GIS-T is limited to linear methods; but linear measurement *is* currently dominant in GIS-T.

Class I—DMI Errors: DMIs employ various technologies, ranging from mechanical or optical revolution counters to electronic pulse sensors, depending on the types of vehicles in which they are used. Current DMIs are theoretically capable of 0.1m resolution, however effective accuracy varies depending on calibration and operation. There are two principal types of error in DMI readings: multiplicative linear error (expressed as a proportion, e.g. "1 metre in 1 km"), and absolute terminal error at start and end points, which arises due to mechanical limitations, or uncertainty in defining the extremities of the path. Multiplicative linear error can be minimized by calibration, typically to about 0.5%. Terminal error is difficult to model, but could easily be as much as 3–5m due to uncertainty in defining the start and end points, and an additional component up to 10m due to operator reflex in measurements taken at highway speeds. Clearly the practical impact of terminal error is greatest in measurement of short distances.

Class II—GPS Errors: GPS inaccuracies arise due to technical limitations (e.g. atmospheric effects, multipaths) and deliberate corruption ("selective availability" or S/A) by the Department of Defense. The situation is expected to improve significantly by the year 2000, as S/A is expected to be phased out, and a national network of differential GPS beacons becomes available. But at the same time, inexpensive mass market GPS receivers are now being built with inferior processors, degrading output quality. This means that at least some GPS readings will continue to be in the ±100m or so error range in the foreseeable future. Moreover, GPS coordinates must always be transformed into linear references for LRP transfer, and are therefore also subject to linear transformation error (below).

Class III—Linear Transformation Error: This occurs when a 2-D point is transformed into a linear reference. Assume that the coordinate is within acceptable bounds of accuracy relative to ground truth. First the point is snapped to the nearest centerline segment: this essentially constrains the 2-D point to the 1-D alignment of the polyline, resulting in loss of information (e.g. lane information is lost) and inaccuracy. Next a linear offset is computed along the centerline. Error in typical commercial centerline databases — usually (a) alignment error and (b) insufficient polyline resolution — results in problems at each of these steps: (a) inaccuracy in representing the true location of the point, and (b) an artificially short linear reference. Worse, it is possible that the point snaps to the wrong link, the wrong segment of the right link, or to the wrong section of the right segment (Figure 1), completely destroying downstream transfer accuracy. In additional, linear errors could occur due to inaccurate positioning of reference points (e.g. an intersection placed a considerable distance from its true location).

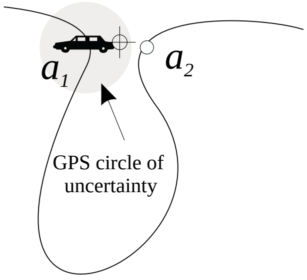

Figure 1. A GPS point intended to snap to a_1 may snap to a_2 instead

Class IV—LRP Transfer Error: This is database interoperability error in the strictest sense, generated when a LRP message is passed from one database to another. There are two potential sources of error: first in identifying the intended street in the target database, and secondly in the value of the linear offset.

The LRP provides for the target segment to be identified in either of two ways: road name or standardized index. The problems with road names have been fully discussed and tested in the Cross Streets Profile report (VITAL, 1998). Standardized indices should fare better, at least in theory, but they too rely on error-free indexing of street records — both manual and automated indexing are susceptible to error.

The value of a linear offset depends so much upon the geometry of the centerline, that two versions of the centerline place the point in different positions. A high offset (close to the end-node in database A) may transfer beyond the end-node in the target database, resulting in a topological error. Such gross errors can be avoided by expressing the offset in relative terms, as a percentage of link length; however, this requires that the length of the entire link be measured, by the same technology that determined the offset. An offset expressed in absolute terms obviously does not change during the transfer process, but its relative position on the target polyline is different; conversely if the transfer is executed as a normalized offset, the absolute offset may consequently change. The severity of these problems generally depends on the ratio of digitized line lengths in the source and target databases, and the distribution of this ratio over the course of the line (lengths may correspond well in one section but not another).

Class V—Reverse Transformation: The linear reference may have to be transformed back into coordinates to be interpreted in 2-dimensional applications such as mapping. If coordinates are subsequently interpreted with reference to the target database, no additional error is introduced by this process.

Error classes I and II (Table 2) are governed by manufacturers, equipment configuration and user skill. This research does not address the origins of those errors, but the first series of tests examines their impacts on measurements of road geometry and length. Two other test sets study interoperability errors: Class III (linear transformation errors) and Class IV (LRP transfer errors). There are no test sets I and II.

Analysis of Road Geometry and Length

The basis of interoperability error in LR is the difference in representation of a centerline in the source and target databases, and in the geometry of start and end points, which can be limited to intersections without loss of generality. The initial analysis explores differences in road length and 2-dimensional geometry of intersections (a) between test databases, and (b) between the databases and our surveys.

Six test databases are used. They were acquired in 1997 from leading commercial vendors and public sector sources. Our purpose is to examine interoperability issues, not to rate the databases for the sake of public evaluation; hence vendor identities are not disclosed, and the databases are coded A through F. Database C is an engineering database, that normally costs about 30 times as much as any of the others.

All analyses in this report are based on a sample of 15 stretches of road in the Santa Barbara area (Figure 2). To be selected, a road must:

(a) be identifiable in all 6 databases,
(b) have at least five intersections along the selected stretch that are common to all 6 databases (this criterion is required for Test Set IV below), and
(c) be easily accessible from Santa Barbara for field measurements.

The sample represents several predominantly straight roads (2 freeway sections, 3 major arteries, 1 downtown street), some minor suburban roads and a few winding mountain roads (Table 3). A simple and useful measure of sinuosity is the ratio of polyline length to Euclidean distance between endpoints.

The most sinuous roads are slightly over-represented in the sample, but this is unavoidable because it is necessary to have a sufficiently large number of samples in each category. Many results are broken down by sinuosity, so that readers interested in any particular category of road can focus on those figures.

Table 3. Sample roads

Road	Length (m)	Sinuosity
1	811.3	1.1660
2	6376.1	1.0076
3	2824.7	1.0023
4	2654.3	1.0007
5	2029.3	1.7422
6	1822.0	1.6334
7	2194.8	1.2235
8	1870.9	1.5722
9	1522.0	1.0043
10	2244.3	3.6386
11	887.2	2.4726
12	7477.0	2.0548
13	2136.0	1.0721
14	3792.1	1.5958
15	2541.3	1.0035

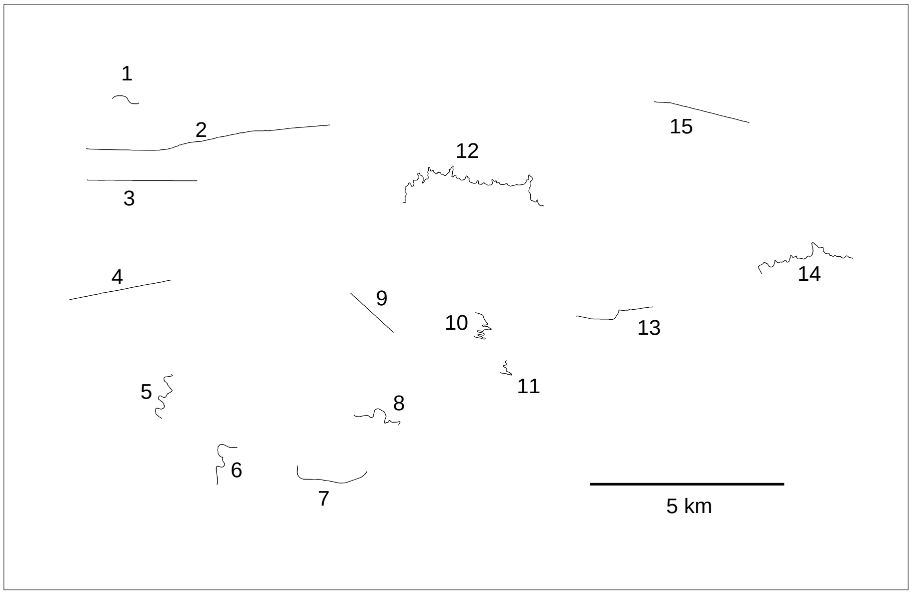

Figure 2. Sample of 15 roads (they are distributed over a wide geographic area in reality; positions are distorted for this illustration).

Test Set III — Linear Transformation Errors

Test Set III examines Class III errors. It is designed to find the likelihood that a given point, sampled in two dimensions while driving along a street network, and matched against a typical commercial reference database, produces an accurate linear reference.

There are four possible outcomes:

a) The street is not present in the reference database. Assuming a maximum snap tolerance is in effect, the coordinate fails to snap to any street (this scenario is not tested due to the nature of our sampling design, which requires the same selection of streets across databases).
b) The sampled point may snap to the wrong street in the reference database. This most often occurs near intersections, but the point may also snap to a parallel street, or other streets, depending on GPS error and the accuracy of street alignment.
c) It could snap to a grossly incorrect position on the correct street (as in Figure 1).
d) It could lie within an "acceptable" distance of its intended position. Clearly the offset varies depending on the reference database in use.

Metrics

This test set examines errors (b), (c) and (d) above. A set of sample points is generated along the street network, and offsets measured from the nearest intersection. Test points are generated in the lab, using the engineering scale database to simulate differentially corrected readings exactly along the centerline, and applying a normally distributed random error in two dimensions to simulate selective availability (S/A) of GPS accuracy. Simulations are preferred to field sampling because

- It is less expensive to generate a large number of sample points
- Due to spatial/temporal autocorrelation in S/A error (i.e. the direction and magnitude of the error does not change dramatically with each observation, but drifts slowly over time), merely turning off differential correction during field GPS collection does not produce a representative sample of S/A error.

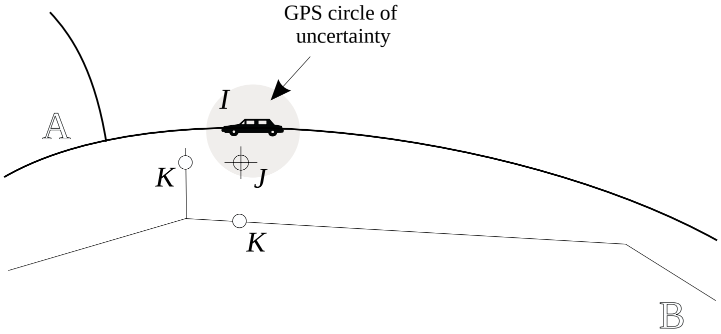

Figure 3. Linear Transformation. Point I is surveyed by GPS, resulting in J, which snaps to K in the reference database B. Two cases of K are shown; one is clearly not on the intended road.

For each test database, the vehicle position along the true course of the road A is known (*I*); the "GPS" sample point generated from this (*J*) is snapped to the nearest segment in reference database B (to the point *K*; two possibilities are shown), and examined visually to determine whether or not the correct segment was identified, and whether a serious error (as in Figure 1) occurred in snapping. The absolute offset δ_K and normalized offset t_K ($0.0 \leq t \leq 1.0$) of the snapped point relative to road B are recorded, and compared with the true offsets δ_I and t_I relative to A.

Differences between δ_I and δ_K are to be expected, because of inevitably different sampling density and alignment of B. In general these differences should be proportional to the difference in total street length, whereas normalized offsets t_I and t_K should be approximately equal. If there is a large difference between t_I and t_K we infer that a serious error could have occurred in relating point *J* to database B.

Offset differences due to variations in road elevation cannot be studied because elevation data are not contained in any of the test databases.

Sampling

Points are sampled at regular intervals along the 15 sample roads, in which straight, moderately sinuous and very sinuous roads are represented.

Test Set IV — LRP Transfer Errors

Test Set IV addresses Class IV errors. It is assumed that the street is correctly identified in the target database. This test set focuses on offset, positional and topological error. It examines the difference in offset of a point transferred using absolute or normalized coordinates.

In general there are three types error that may result from poor LRP transfer:

- Error in absolute offset along the centerline, due to differences in *length* of digitized lines in the source and target databases — this is dependent on the sampling density and accuracy of shape points on the centerline. Intuitively, offset error is most likely to occur on sinuous mountain roads.
- Error in *2-dimensional position* of the point due to positional differences between databases (e.g. translation shift). This type of error matters to users who rely on 2-d positioning (e.g. GPS) to locate the event, whereas it is relatively unimportant if navigation to the event is with reference to the street network. Due to the piecemeal evolution of many maps, 2-d error tends to be spatially autocorrelated, i.e. neighborhoods tend to share similar displacement patterns, and the direction of shift changes abruptly over the boundary to adjacent areas.
- Topological error: the transferred point lies on the wrong side of an intersection, as a consequence of offset error above. Topological error is most likely to occur when a sample point is close to an intersection, hence it depends on density of intersections. Generally speaking, areas of high network density *and* sinuous roads are most susceptible to topological error. Downtown areas, although dense, typically have straight streets.

Given a transfer point expressed as an absolute/normalized offset in database A, this test set is designed to find:

- the difference in offset between the transferred offset and the intended point?
- the 2-dimensional error in this transfer?
- the likelihood that the transfer results in a topological error, i.e. that it could place the object on the wrong side of an intersecting street?

A related question is whether the combination of absolute and normalized expressions can flag or reduce the above errors.

Metrics

Consider a sample point P in database A, with absolute offset δ_P and normalized offset t_P. P' is the equivalent intersection point in database B (determined visually, based on street name, position, shape and topology), with offsets $\delta_{P'}$ and $t_{P'}$ as measured along centerline B. Q is the transfer point using absolute offset, and R is the transfer point using normalized offset (Figure 4). In general, if centerline A is longer than centerline B, Q overshoots P'. A normalized offset compensates for such differences in centerline sampling, but residual inaccuracies remain because differences in sampling density along a given centerline are not constant.

Sample points are chosen at intersections that are visually identifiable in all 6 databases, so that corresponding points in other databases are exactly identifiable, hence P′ is known. Points could be selected at other identifiable points such as sharp elbows, if there is enough consistency between databases.

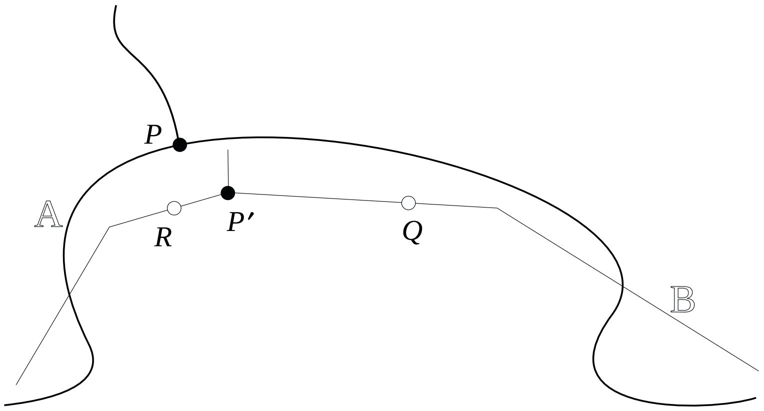

Figure 4. LRP Transfer Errors. Point P should ideally transfer to P′; instead it transfers to Q using absolute offset, and R using normalized offset

Raw measures of error are

1. Absolute transfer error $\mathrm{ATE} = (\delta_Q - \delta_{P'}) = (\delta_P - \delta_{P'})$
2. Normalized transfer error $\mathrm{NTE} = (\delta_R - \delta_{P'})$
3. Absolute transfer: 2-d displacement $\mathrm{A2D} = \sqrt{} \, (x_P - x_Q)^2 + (y_P - y_Q)^2$
4. Normalized transfer: 2-d displacement $\mathrm{N2D} = \sqrt{} \, (x_P - x_R)^2 + (y_P - y_R)^2$

The likelihood of topological error cannot be directly estimated from these tests. The transfer point (Q or R) invariably falls short of or beyond the intended point (P′). It is tempting to take the position that transfer beyond P′ constitutes topological error, whereas transfer short of P′ does not; but this is invalid, and simply results in about 50% error on average. It is more useful to interpret the *magnitude* of the error; one may then speculate that errors of more than say 200m are likely to lead to violate topology.

Sampling

About a hundred sample points are selected along relatively (1) straight, (2) moderately sinuous and (3) very sinuous roads, as in Test Set III above. Because Test Set IV assumes that Q and R lie on the correct street in database B — and earlier LRMS testing (VITAL 1998) has shown that search by name is not always reliable — sampling is manual, and restricted to roads that are common to all databases. As in Test Set III, points are sampled along as few roads as possible. This approach produces both short and long offsets along the same road, allowing for study of offset length as a factor in error.

Analysis of Road Geometry and Length

This initial set of analyses documents variations in length between different versions of road geometry, and independent measurements. Lengths are measured in each database, the roads are field surveyed by GPS, and driven lengths are simultaneously measured with a DMI.

DMI Accuracy

There are several sources of DMI error:

- Terminal uncertainty — Uncertainty in ability to define the start and end points of the course. Four-way intersections range from 10–50m across. Because it is impractical to drive down the centerline of a road, and the intersection of centerlines is not marked on the pavement, some approximation in definition is unavoidable. The problem is worse when roads intersect at angles other than 90°, or where there are jogs in intersections. The effective DMI error can be 3–5m at each end of the course; this estimate is based on poor repeatability of readings taken at some intersections under difficult traffic conditions, compared with good repeatability over similar lengths of road, achieved at isolated locations using well defined road markers. Terminal uncertainty is by far the greatest source of error in *our* DMI observations. Accuracy improvement would necessitate safety compromises or would require frequent disruptions of traffic. Highway maintenance crews have the luxury of uninterrupted measurement and better endpoint definition, and their observations would usually be more accurate.
- Terminal error — Operator reflex error in recording the start and end points. This depends partly on vehicle speed at the time of observation. At freeway speed (100 km/h), a single operator can usually measure a short course (say 500m) with 2m repeatability, corresponding to less than 0.1 second difference in reaction time at start and end points. When working as a team, latencies can be much greater, up to 0.5 second, translating into errors of 10–15m. Again, better readings can be obtained if traffic is controlled and the vehicle is stopped at every observation point.
- Rounding error in DMI output. On our equipment, readings are rounded to 1 metre.
- Proportional error. DMI technology relies on calibration over a course of known length. If the DMI is used over courses longer than the calibration course, errors committed in calibration are multiplied. The calibration course we use is 305m, the recommended length for the equipment.
- Driving lane. On curves, distance depends on the choice of driving lane. On a curve of 200m radius, a vehicle in the outside lane travels 1–2% further than does a vehicle in the adjacent inner lane. It can usually be assumed that errors due to lane choice are self-compensating because roads turn both right and left over the average course.
- Arbitrary deviations from course. Accuracy depends on the driver maintaining a constant lane and steering a straight course relative to lane stripings. However, error due to slight variations in drive line is not significant compared with the above errors. Modeling the drive path as a sine curve, it can easily be shown by trigonometry that even a lane change every 4–6 seconds between two adjacent

3.6m lanes (in practice such conduct would invite a traffic citation) increases distance by less than 1%. A short series of tests on a city street and freeway corroborates this (Table 4); in fact it shows that DMI observation error is far greater than the effect of poor driving.

Table 4 . Effect of lange changes

	Course Length	# Lane changes	Time/ change	Trigonometric calculation	DMI Reading in Road Test	Percent error (trig)
City street	306m	5	4 secs	308.6m	308m	0.85%
Freeway	654m	4	6 secs	654.8m	658m	0.12%

- Road conditions. Imperfections in the road surface, from localized bumps to gentle undulations, do increase DMI measurements, but not significantly. A uniform rise of 10m over a 500m stretch of road increases driven length by 0.1m or 0.02%; a rise and fall (one complete cycle of a sine curve) of amplitude 1m in a 500m road increases length by 13mm or 0.03%. Conditions that could cause wheels to spin (e.g. heavy rain or ice) could cause unpredictable errors.
- Traffic conditions. Stops and starts over the measured course, as required by traffic signage or congestion, may affect readings, because the DMI may not be accurate at extremely low speeds. This effect depends on the design and circuitry of the instrument. Our equipment loses about 1m for every three dead stops and starts; it is stable at speeds above 3 km/h, and care is taken to avoid slowing below this speed during measurement, by anticipatory braking, etc. Another model of DMI, tested earlier, registered “spikes” of 5–10m on each dead halt. This model was poorly supported by the manufacturer, and was not used for any of the observations in this study.
- Tire pressure and ambient temperature. Tire pressure is normally maintained at 200 kiloPascals (kPa). A 25% drop in pressure, to 175 and 150 kPa, increases DMI readings over the measured course from 305m to 306m. Allowing for rounding error in the DMI display, this is about 0.6%.

Table 5. Summary of DMI errors (worst case)

	Absolute Error (m)	Proportional Error (%)
Terminal uncertainty	5	
Terminal error (team, 100 km/h)	10	
Rounding	1	
Dead stop	0.3	
Lane (non-compensating, 200m)		2
Crooked driving		1
Tire pressure		0.6
Bumps, rises and falls		0.03

GPS Length Estimate

The trace of GPS coordinates is measured for selected roads, to derive an estimate of length. Sources of error in this estimate are

- Definition of terminal points, as above.
- The path of the vehicle may not accurately reflect the course of the road, particularly at T-intersections and turns in general.
- Residual coordinate inaccuracy after differential correction. This is variable and unpredictable. In the worst case, a vehicle proceeding at 50 km/h, and receiving GPS with a constant error magnitude of 3m, and changing error direction by 180° every second (Figure 5), would record a 9% greater road

length. At 75 km/h the error would be 4%, and at 100 km/h, about 2%. Given that S/A and other errors usually vary slowly over time, road length is probably over-recorded by 1–2% at most.

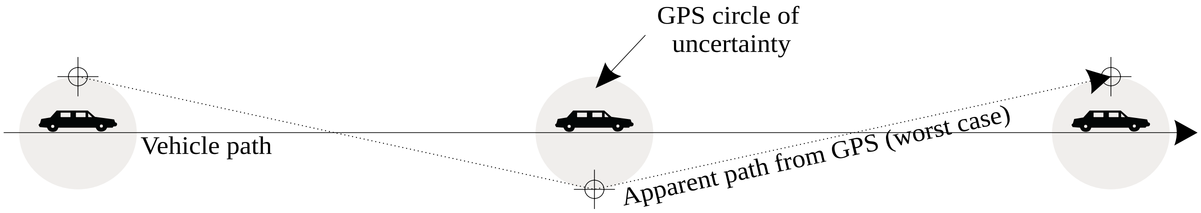

Figure 5. Worst case scenario of GPS error reversing itself at every observation

- Latency between successive GPS outputs (~1 second), causing flattening of curves. The amount of flattening is directly proportional to vehicle speed. A vehicle negotiating a 200m-radius curve at 75 km/h records a flattening error of 0.07%.
- Difference between 2-D and 3-D coordinate traces. In theory a 3-dimensional coordinate trace would more accurately reflect the rises and falls in the road surface. In reality, because the error in elevation from GPS is relatively high (typically twice the horizontal error), and particularly considering that the effect of rises and falls on driven distance is minimal, such calculations would be misleading.

Experimental Observations

The measurements of road lengths in the 6 test databases, and our measurements using DMI and GPS, are shown in Appendix B, and selected results are summarized in Table 6. Error is measured in two ways: (a) the difference between the longest and shortest versions of the same road, expressed as an arithmetic difference or the deviation of the ratio from 100%, and (b) relative deviation among the lengths (standard deviation divided by mean).

GPS-length and DMI measurements differ from each other by 16m or 1% on average (mean calculated over 15 sample roads), with worst case discrepancies of 31m and 3%. By comparison, in terms of longest vs shortest, the 7 versions (A–F and GPS) vary from each other by 214m or 8% on average, with worst case length discrepancies of 671m and 16%. The engineering scale database (C) has the most accurate alignment, and it follows that road lengths derived from it should also be accurate. This is confirmed by the results: the average discrepancy between database C and the DMI is just 12m, or 0.5%, whereas nearly all the other databases vary from the DMI by more than 100m and 4%.

Table 6. DMI vs lengths measured from coordinates

	Average deviation from DMI measurement	
	Absolute (m)	Percent
A	108	4.2%
B	115	4.4%
C	**12**	**0.5%**
D	129	4.0%
E	61	2.2%
F	116	4.4%
GPS	16	0.9%
Mean	79	2.9%

The difference between the longest and shortest length of a given road is 15% in the worst case, and 8% on average. There are strong consistencies in the ranking of the databases in terms of length. Database C, an engineering scale database, has the longest lengths — an indication of digitizing detail — which are almost identical to the DMI measurements. Databases B and F have the shortest lengths, reflecting their highly generalized geometry; and the values are almost identical, reflecting the well known fact that one was derived from the other. A and D are marketed as navigation databases; they fall short of the highly accurate engineering category, but are slightly superior to B and F. Database E is unusual, in that its geometry is grossly inaccurate, but the lines are expressed with a high density of shape points, resulting in superior esthetic appearance, and lengths in the higher ranges (Figure 6).

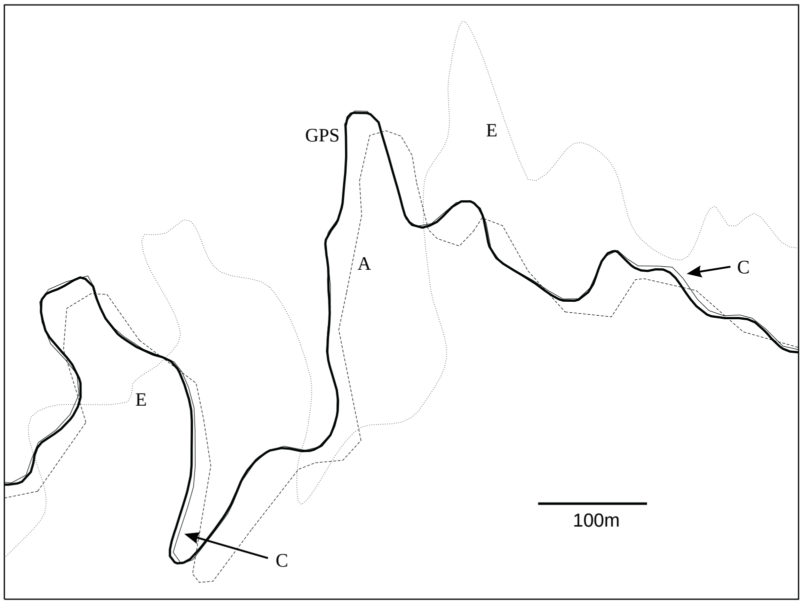

Figure 6. Overlay of maps A, C and E, and GPS data (bold). C is almost completely obscured due to its agreement with GPS. E is grossly inaccurate, but shape points are dense and curves are smooth. A is relatively true but generalized.

Predictably, the amount of absolute error is related to road length — this empirically justifies the use of normalized offsets as an alternative to absolute offsets. Figure 7 relates the difference between the longest and shortest version of a road ("Absolute Error") to the DMI length. The cluster of points near the origin suggests that a base error up to 100m exists regardless of road length, with a second error component that is proportional to length. The relationship between absolute error and road length is strong (R^2=0.81).

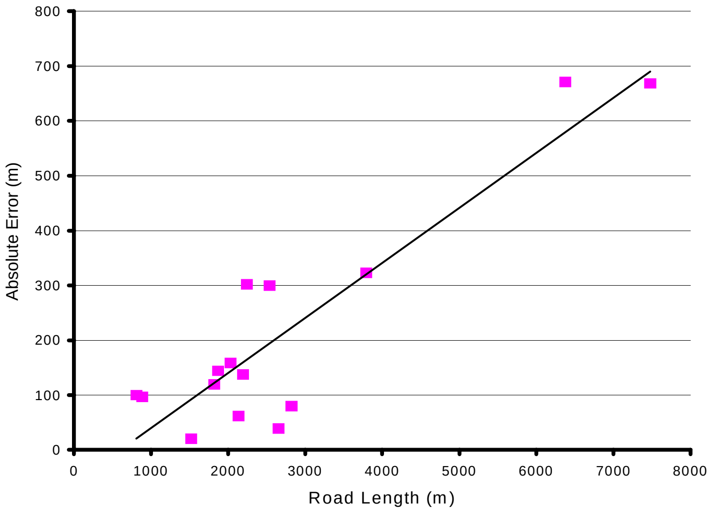

Figure 7. Absolute Error (longest minus shortest) as a function of Road Length

Similarly, as expected, there is a moderately strong relationship between relative deviation and sinuosity (Figure 8), but at least three straight roads in the sample have high relative deviations, for reasons unrelated to sinuosity.

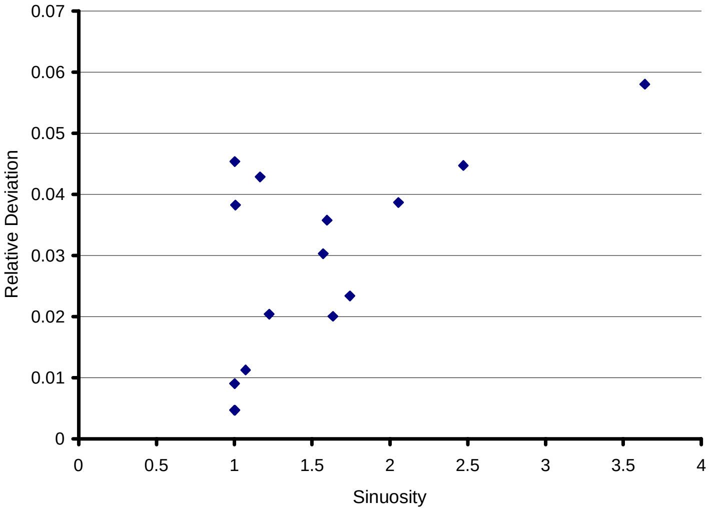

Figure 8. Relative Deviation (std devn/mean) as a function of Sinuosity

Causes of Length Error

Error in road length as computed from a digitized centerline is difficult to predict, because it is a function of a number of factors: density of shape points, alignment accuracy, and the accuracy with which intersections are represented.

Density and Alignment of Shape Points

Shape point density is usually related to the scale of source data: maps constructed from large scale sources show greater detail, requiring more shape points. When a road is represented at a high point density, its length is usually greater. But density alone does not make for accuracy, either of length or position. Figure 6 shows an instance of high point density associated with inaccurate coordinates (database E). Similarly the relationship between length and point density is not particularly strong ($R^2 \approx 0.5$). In Figure 9, database C's version of the mountain road (recall Figure 6) is generalized using a well known algorithm (Douglas & Poiker 1973) to reduce it to 175 points, the same number as in database A. This reduces the length in C by 1%, from 7472m to 7412m, but the length in database A is still substantially lower at 7075m, a 5% difference. This illustrates the effect of alignment, not just the number of shape points, on length.[3]

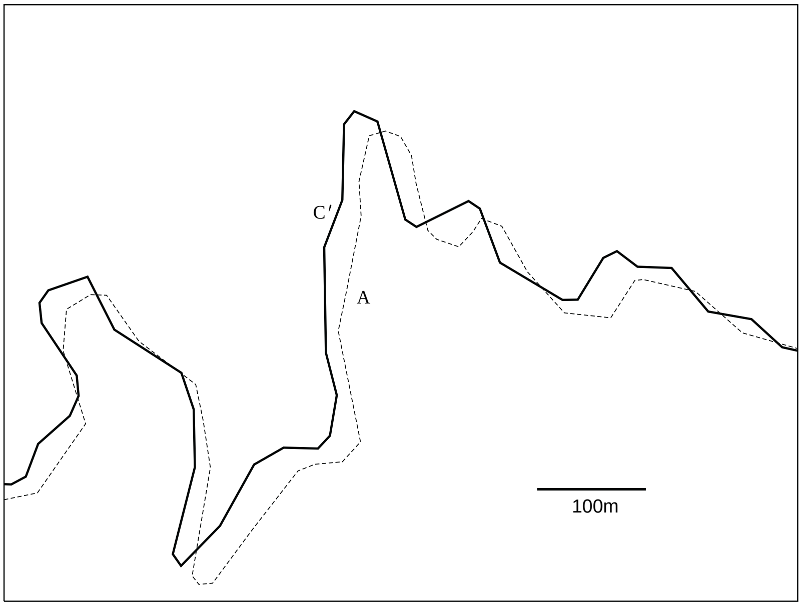

Figure 9. Shape points in database C are weeded out to produce C', which has the same number of shape points as A. The length of C' is 7412m, still higher than A's 7075m.

Positioning of Intersections

Liberties are sometimes taken in the representation of freeway interchanges. One sometimes encounters the view that the complexity of the dual-carriageway structure is readily represented by single-line geometry, and that interchanges can be represented by generic codes: one code for a "cloverleaf" pattern, another for a "diamond," etc. Such abstraction has consequences on the definition of end-points of freeway segments, which ultimately affect linear measures. Figure 10 shows an example where two databases disagree on whether a ramp meets a freeway east or west of an overpass. The impact on segment length in this case is more than 200m.

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[3] The Douglas-Poiker algorithm deletes the most redundant points in a polyline, for a given lateral tolerance. In the context of the earlier discussion on redundancy (page 10), this is the most appropriate generalization algorithm.

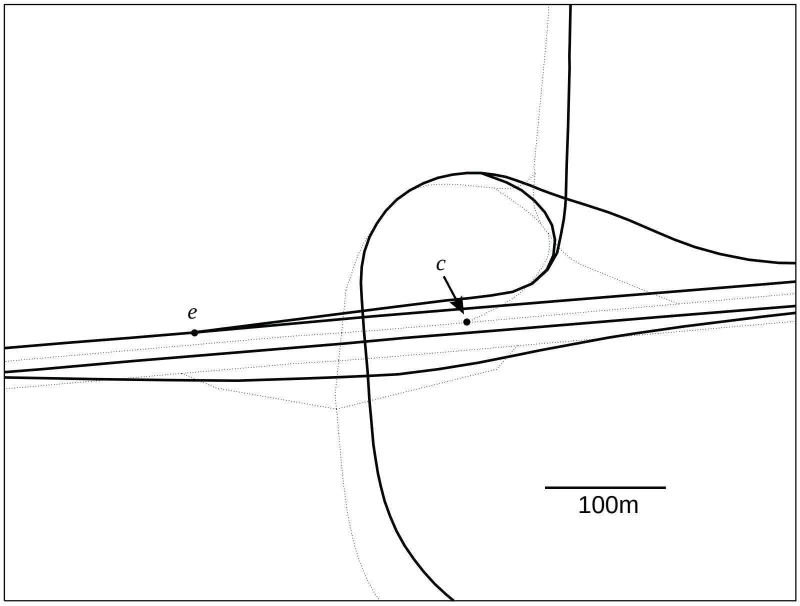

Figure 10. Overlay of maps C (bold) and E, showing different positions (c and e) where ramp meets freeway. The impact on freeway segment length is more than 200m.

Test Set III

To recapitulate, Test Set III documents the problems in converting a 2-dimensional position to a linear measurement, due to inaccuracies in reference maps. The interoperability problem studied here is not between pairs of map databases; it is between ground truth as expressed by GPS, and the centerline databases. For experimental purposes we take the position that database C is accurate, and may be assumed to represent the true course of a road. About 100 vehicle locations are simulated along the 15 sample roads with respect to database C, with varying amounts of error generated to simulate GPS error; these 2-D positions are transferred to each of the five other databases. Mean, minimum and maximum are calculated over these five observations.

Road Identification Error

Probably the most important concern for accuracy in Test Set III is whether or not the coordinate snaps to the correct road, the correct topological section and the correct section (recall Figure 1) of the road. Table 7 shows the results of these tests for three settings of simulated GPS error: 0m, 30m and 100m. The test for correct road is partly automated using street name, and manually checked. Correct topological section could in theory be determined automatically if cross street names were reliable, but previous VITAL research (VITAL 1998) has established that this is not the case. Correct section is to some degree a matter of subjective judgement.

Not surprisingly, the results are best with 0m error, and worst with 100m error. At 100m error, only just over half the coordinates snap to the correct road; some of these find the wrong section of the right road, leaving 48% and 44% on the correct topological section and correct section respectively. These are average rates; worst case rates are in the 20% range. Even at 0m error, average success is only 85–90%, and with the worst database even at 0m error only 30% of test points identify the correct section of road. On the other hand, with a good quality database, even a 30m GPS error produces 96–98% success, and 100% accuracy is achieved with the best GPS (0m).

Table 7. Success rates for coordinate snapping to intended section of intended street. All percentages are calculated with respect to the full set of test points, therefore "Correct Road" has the highest figures.

	Correct Road			Correct Topological Section			Correct Section		
	0m	30m	100m	0m	30m	100m	0m	30m	100m
Mean	90%	80%	58%	86%	75%	48%	83%	75%	44%
Min	72%	54%	26%	72%	51%	21%	29%	51%	18%
Max	100%	98%	84%	100%	96%	78%	100%	96%	67%

Offset Error

The second aspect of Test Set III examines the offset values in the above tests. The principal results are summarized in Table 8, categorized by GPS error[4]. Average offset errors are in the 90m range for 0m GPS error, 98m at 30m error, and about 135m at 100m error (but recall from the previous chapter that high-sinuosity roads are over-represented in these means). In the worst cases (worst database, 100m GPS), errors of nearly 800m could be encountered. At the other end of the spectrum, best case results are in the sub-metre range.

Normalized offsets vary from perfect agreement to substantial disagreement. Offsets differ arithmetically by as much as 30% in the worst case. In terms of offset ratios (where 100% indicates perfect agreement), one stray case produces a 4000% error because of topological disagreement; the next worst error is in the 500% range. For the most part, with accurate GPS, average errors are 1–3% in terms of offset differences, and 5–6% in terms of ratios.

Table 8. Offset discrepancies, Test Set III

GPS Error	Absolute Offset Error (m)			Error in Normalized Offsets (Difference)			Error in Normalized Offsets (Ratio)		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
0m	91.7	0.0	667.5	1%	0%	35%	105%	100%	300%
30m	98.0	1.3	690.1	1%	0%	34%	106%	100%	393%
100m	136.3	0.1	786.6	3%	0%	27%	126%	100%	4026%

In Table 9 the above results are broken down by sinuosity. Some figures are counter-intuitive, e.g. mean errors are greater for low sinuosity roads than for medium sinuosity, at 0m and 30m error — this is largely

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[4] When coordinates snap to incorrect roads, offsets measured along the wrong roads are not included in the calculations in this section

due to discrepancies between representations of freeway/ramp intersections, such as illustrated in Figure 10. The high mean offset ratio of 159% (100m, low sinuosity: shaded cell) is due to the single test point that produces the 4000% maximum ratio; if this point is omitted from the sample, the figure of 159% is reduced to 110%.

Table 9. Offset discrepancies, broken down by GPS error class.

	Sinuosity	Absolute Offset Error (m)			Error in Normalized Offsets (Difference)			Error in Normalized Offsets (Ratio)		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
0m	Low	41.8	0.2	276.6	1%	0%	6%	104%	100%	247%
	Medium	32.5	0.0	129.2	1%	0%	5%	104%	100%	136%
	High	151.1	0.2	667.5	1%	0%	35%	106%	100%	300%
30m	Low	40.6	1.8	229.0	1%	0%	5%	106%	100%	393%
	Medium	35.6	1.3	120.6	1%	0%	4%	105%	100%	155%
	High	157.8	1.3	690.1	2%	0%	34%	106%	100%	278%
100m	Low	55.3	0.3	199.8	2%	0%	7%	159%	100%	4026%
	Medium	66.4	0.1	171.8	3%	0%	12%	114%	100%	190%
	High	189.9	2.1	786.6	3%	0%	27%	114%	100%	451%

In general, low sinuosity and accurate GPS produce the lowest error, as expected. Mean error is 1–3% in terms of offset differences, and 4–6% in terms of offset ratios with accurate GPS. With 100m GPS, the average error is 10–14%.

Test Set IV

This series of tests addresses the interoperability problem when a LR based on one map database is interpreted as a LR relative to another map. It is assumed that the original LR is accurately determined, and that a suitable convention exists between communicating parties to express road identity unambiguously. Therefore Test Set IV focuses only on the value of the offset, expressed as an absolute or normalized value.

The requirement of sample points is that they be identifiable in all maps, i.e. intersections. The points are selected visually. They are transferred by absolute and normalized offsets from each of the six databases (A, B, C, D, E, F) to each of the other five databases, for a total of 30 dyads (e.g. A→B is a dyad). Because the transfer points are known in the target database (P′ in Figure 4), the apparent transfer points Q and R can be compared with the intersection in the database. Measures of success are ATE, NTE, A2D and N2D, as detailed in the previous chapter.

All Roads

About 100 points are tested in each dyad. The mean, minimum and maximum for the dyad are found, then summaries are calculated for all dyads. In Table 10, Lowest Mean difference is the average disagreement between the two most compatible databases, and Highest Mean is between the two least compatible.

The mean offset error is about 50m for absolute transfers, and 25m for normalized transfers. Overall means are representative, in that they are not overly biased by one or two extreme values. Worst case errors are extremely high, in the range of 500m to 1 km. Two patterns are evident. First, normalized-offset transfers (NTE) invariably fare about twice as well as absolute offsets (ATE), except that the worst case error for normalized offset difference (955m) is greater than the absolute equivalent. Secondly, 2-D displacement is usually slightly higher than offset difference — this is intuitively correct because Euclidean error depends not only on the accuracy of the linear component of the transfer, but also on the positional correspondence between the two maps. It follows that normalization does not improve Euclidean error (N2D relative to A2D) as much as it does offset error (NTE relative to ATE).

Table 10. Offset and 2-D errors, all roads

	Offset Difference (m)		Euclidean Distance (m)	
	Absolute (ATE)	Normalized (NTE)	Absolute (A2D)	Normalized (N2D)
Overall Mean	50.4	22.8	53.1	34.2
Lowest Mean	6.0	3.2	6.7	4.6
Highest Mean	65.7	37.8	78.6	54.1
Overall Max	821.3	955.5	665.1	437.9

Freeways

Table 11 quotes the corresponding results when the sample is limited to points on the two freeway stretches. The errors are 2–3 times as high as in Table 10, and there is less of a distinction between absolute and normalized offsets. Euclidean distance error is actually less than offset error. These patterns can be explained as follows:

- Offset errors are greater only partly because the freeway stretches are longer, by 50% on average.
- Normalized offsets are higher relative to absolute offsets, because the roads are straight and there is less linear error due to differences in shape and alignment.
- Euclidean distance error is not as high, again because these roads are straight, and perhaps because vendors pay more attention to positional accuracy of freeways than to less trafficked roads. The fact that Euclidean error is *lower* than linear error also highlights the liberties taken in positioning ramp/freeway intersections — a point to which we have alluded earlier.

Table 11. Offset and 2-D errors, freeways only

	Offset Difference (m)		Euclidean Distance (m)	
	Absolute (ATE)	Normalized (NTE)	Absolute (A2D)	Normalized (N2D)
Overall Mean	135.1	100.3	101.9	80.1
Lowest Mean	13.2	11.6	8.8	6.4
Highest Mean	204.0	187.9	168.0	162.4
Overall Max	821.3	955.5	229.3	437.9

Effect of Sinuosity

Table 12 reports variation in error as a function of road sinuosity. Again, the straightest roads show greater errors than medium sinuosity roads — in fact, the highest errors in this test set are recorded by the freeways — while the most sinuous roads predictably perform poorly.

Table 12. Offset and 2-D errors by sinuosity

	Sinuosity	Offset Difference (m)		Euclidean Distance (m)	
		Absolute (ATE)	Normalized (NTE)	Absolute (A2D)	Normalized (N2D)
Overall Mean	Low	40.1	24.2	41.6	31.8
	Medium	36.7	16.4	53.8	36.3
	High	107.4	22.4	103.0	43.5
Overall Max	Low	821.3	955.5	275.0	437.9
	Medium	318.7	103.7	322.3	140.5
	High	664.0	175.7	665.1	222.2

Effect of Offset Size

The final analysis in Test Set IV is similar to one in Set III (Figure 7), examining the relationship between absolute offset error and magnitude of offset. A clear relationship justifies the use of normalized offsets rather than absolute offsets. But Figure 11, based on about 100 transfers from A to B, suggests that length is a weak predictor (R^2=0.28), and that other factors (in particular, terminal error) are involved. Because of the large number of points in the table, the correlation is significant at better than the 0.01 level.

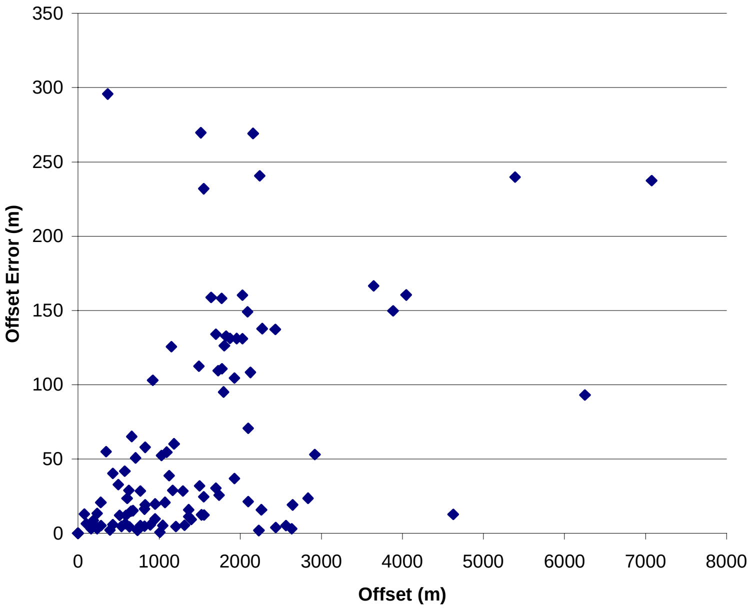

Figure 11. Absolute offset as a function of magnitude of offset

There is sometimes a cost involved in deriving a normalized offset, in that the denominator length must be measured by the same process that derived the absolute offset or numerator. A weak relationship implies that the marginal cost of deriving the normalized offset may not always be justified by improvement in transfer accuracy. The details of the cost-benefit relationship are application-dependent.

Conclusions

This research has examined three independent aspects of linear referencing in the context of location exchange. In this concluding chapter we integrate the findings of the individual test sets, and examine their lessons for practice.

Principal Findings

The first series of tests, based largely in the field, illuminated aspects of road measurement, that placed the study in a practical context. First, and most important, the tests showed (a) that DMI measurements correspond closely to the most accurate digital representations of a centerline (i.e. the engineering scale database *and* our DGPS survey), and (b) that such close correspondence in length has much to do with geometric truth, and cannot be fabricated by spuriously controlling the density of shape points. We found that inability to define the start and end points of a road were the greatest impediments to accurate measurement, more so than tire pressure, style of driving, or minor vertical irregularities in the road surface. In comparisons of road lengths in the six digital maps used in the study, absolute error was predictably found to be related to the length of the measured course, and also partially to sinuosity. An important finding was that freeway ramps were often carelessly represented in these digital maps, causing length measurements on freeways to be particularly error-prone.

The test established a practical guideline for interpreting subsequent test results, suggesting that differences of up to 10m in length measurements are inevitable in the course of field observation, and should not be interpreted too strictly (this error occurs at terminal points and is unrelated to proportional error due to miscalibration of equipment). Clearly there is a cost and benefit issue involved. Accuracy (as indicated by repeatability) of our field observations could have been improved had we been prepared to compromise safety, or to disrupt traffic in the process of positioning the measuring vehicle — work crews often have such freedom to survey roads under measurement-friendly conditions. If accuracy is critical to the outcome of some analysis, then more accurate survey may be worth the added cost.

The second test set (Set III) examined errors in the source data in a LR transfer, i.e. the likelihood that a GPS coordinate could snap to the wrong street, and the magnitude of offset error when it snapped to the correct street. Generally the results were intuitively correct, i.e. accurate GPS (±0m) produced the best results with a 90% success rate in identifying the correct road, with offset error in the 30–40m range; whereas with ±100m GPS, the chance of hitting the correct road dropped to 58%, with about 135m mean offset error. The most sinuous roads predictably fared worst, but the straightest roads placed second after medium-sinuosity roads, again because of definition of freeway endpoints.

The third set of tests (Set IV) focused on the transfer of linear references between map databases, and found offset errors of about 50m on average. Not to belabor the point, freeways again performed poorly, and this was borne out in two stratifications of the sample, by road class and sinuosity. Offset magnitude was shown to be a weak predictor of error, because several other factors are involved. This appears to contrast with the analysis in the preliminary test of road length, where a strong relationship was observed.

However, there is a considerable difference in the number of observations on which these are calculated (15 vs 100), and therefore in the degrees of freedom in interpreting the significance of R^2. In both cases R^2 is significant at better than the 0.01 level.

Issues

Road Identifiers

It could be argued that Test Set IV is purely academic. The test makes the assumption that communicating parties share a robust system of road identification — an inter-agency index — or would otherwise be subject to road naming interoperability errors (documented extensively by VITAL 1998). One could then argue that if the agencies share a system of road naming, surely they can share coordinate information too.

It is true that sharing coordinates would eliminate transfer errors, but this is not always feasible because agencies have different mandates, requirements, semantics and practices. An office charged with reporting road incidents from the viewpoint of funding and administration might find it advantageous to view a divided urban road as a single centerline; but the agency providing *service* to those incidents would need to reach the incidents promptly, and would need to know the details of carriageway separation. Even if there are similarities in functional requirements, agencies may have different databases for historical reasons. The Bureau of Transportation Statistics (BTS), part of the U.S. Department of Transportation, is currently proposing a road identification standard for the National Spatial Data Infrastructure (NSDI), which would assign a standard identifier to every stretch of road in the U.S., and the scheme would allow a logical mapping of multiple-carriageway roads to higher level (lower resolution) identifiers. Similarly, the ITS Datum initiative (Siegel et al 1996), currently being promoted by Oak Ridge National Laboratory, and under study at VITAL, seeks to establish not just identifiers for points and segments, but also authoritative coordinates for the points, and a process of real-time geometric correction. In the context of this work it is realistic, albeit futuristic, to think of agencies agreeing on road identifiers but not on coordinate strings.

Absolute vs Normalized Offsets

Both Test Sets III and IV examined absolute and normalized offsets and their relative effectiveness. A question that naturally arises is whether absolute and normalized offsets could be used simultaneously, whether or not this would constitute useful qualitative or quantitative metadata, and whether or not a compromise value could or should be calculated. Undoubtedly, agreement between absolute and normalized offsets is an indicator of reliability, and it is always good practice to compare two different measures. For field-measured offsets (as opposed to offsets computed from the digital centerline), normalized offsets come with a cost, because it is necessary to measure the total length of the road using the same equipment that derived the absolute offset. Test Set IV shows (a) that normalized offsets sometimes produce only marginal improvements in transfer accuracy, and (b) that offset error is not well predicted by section length. A quick algebraic analysis (Appendix A) shows that even an object close to the start of the road (or other reference point) is better described by normalized than by absolute offset.

But when the cost of normalization is considered, it may be that for low offsets, the benefits of normalization may be too slight to justify the additional cost.

Recommended Modifications to Profile

The LRP specification needs a few minor edits:

1. Vehicle-based road measurement technology (i.e. DMI) does not exist to support offsets at 0.1m precision — only construction engineers operate at this precision. Unless there is pressure from LRMS stakeholders to continue to support this, precision could be coarsened to 1m without any sacrifice to utility. The width of all absolute offset fields could then be reduced from 23 bits to 21 bits (±1,048,575m).
2. While the LRP accommodates offsets up to 400 km, there is inconsistency between the precision of an absolute offset (0.1m) and a normalized offset (0.01%, equivalent to 40m at this length). The 16 bits allocated to normalized offset should be increased to 21 bits (±1,048,575, accommodating 1,000,000 units, each 0.0001% of the link) to support a precision of 0.4m. If the specification for absolute offset is modified to support 1000 km as recommended above, a 21-bit normalized offset would have just over 1m precision on a 1000 km road.
3. Typographic errors in bit sequencing are to be corrected, and pad bits should be rearranged to coincide with byte boundaries.

Recommendations for Practice

We have illustrated several issues by quoting from the engineering scale database (C). If such a database were available everywhere, location referencing problems would be eliminated, at least at the level required to support current requirements. This database is 30 times the cost of the others, about $45,000 for the County of Santa Barbara, but we have shown that such quality is easily matched by DGPS, and one could reasonably expect that databases of this caliber will be available nationwide and perhaps worldwide, at a much lower price, within 5–10 years.

Database C was created by private-sector-initiated coordination of data sources, from photogrammetry to private utility databases. To produce a comparable product at the state or national scale, a substantial coordination effort would be required. There are two models of this: one is the top-down approach, where the government identifies (a) geographic information products of strategic importance, and (b) the core inputs that make those products possible; and takes primary responsibility for creating them. This is the model followed with considerable success in the state of Victoria, Australia, where the state took the initiative to create cadastral, resource, street centerline and other geographic databases; current efforts to create a national ITS Datum in the U.S. also advocate the top-down approach but with a smaller scope, addressing the need for street centerline data only.

A second option, involving far less commitment of resources, is for the government to *facilitate* the process of data sharing. The NSDI road data identification standard, cited earlier in this chapter, is a government-sponsored effort to create a framework, not a database *per se*, but a system of open external identification keys, that allows agencies at any level to share data; the intent is that the best quality data will in all cases emerge as the backbone. This approach is yet unproven, and the cost advantage over the former approach is yet to be established. More important, it is not certain that the private sector will find this to be suitable, and subscribe to it with the enthusiasm required to make it succeed.

In many areas of development in ITS, there is a danger that solutions developed to today's problems are inadequate for tomorrow's applications, e.g. the 10m-or-so allowance that was often applied in this study could be found too lax for future needs. This probably is not the case with linear referencing, because it has historically been a method largely limited to the GIS-T road construction/maintenance community, to serve needs at a particular scale of application, with particular tolerances. Needs for more stringent tolerances may well be met in the future by other methods, conceivably including DGPS.

Until such efforts mature and produce databases of the required quality, the best course for interacting agencies is to agree on one database for maximally interoperable results. There are several technical and institutional reasons why this is not easy to achieve, and further it only addresses Type IV (transfer) errors, not the other types of error identified in Table 2. Even the most accurate GPS coordinates will snap to the wrong roads, and DMI readings will not agree with digitally calculated offsets. Whether or not these problems are serious depends on application requirements. This report offers numerical results, hopefully from a sufficiently wide range of viewpoints that the reader can estimate the impact on operations.

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How Normalized Offsets Reduce Error

Let δ = absolute offset
Δ = total road length, measured by the same device
t = normalized offset
t' = normalized offset with embedded uncertainty
a = amount of terminal error at each endpoint (e.g. 10m)
b = coefficient of proportional error (e.g. 1 in 100)
ε_δ = uncertainty in measurement of δ (additive)
ε_Δ = uncertainty in measurement of Δ (additive)
ε_t = uncertainty in offset calculated by t

Then
$t = \delta/\Delta$
$\varepsilon_\delta = 2a + b\delta$
$\varepsilon_\Delta = 2a + b\Delta$
$t' = (\delta \pm \varepsilon_\delta) / (\Delta \pm \varepsilon_\Delta)$
$\varepsilon_t = \Delta\,(t' - t)$

The argument for normalization is often based on the assumption that b is non-zero, and a correction must be applied, but it does not recognize the existence of a. Indeed as $a \rightarrow 0$, the effect of b cancels out:

$$
\begin{aligned}
t' &= (\delta \pm b\delta) / (\Delta \pm b\Delta) \\
&= \{\delta\,(1+b)\} / \{\Delta\,(1+b)\} \\
&= \delta/\Delta
\end{aligned}
$$

which is the desired effect of normalization.

When a is non-zero, t' does not reduce neatly to δ/Δ. It can be shown that ε_t is greatest when δ is lowest (i.e. at the start of the road), but that ε_t is always less than ε_δ.

In other words, normalization is always an improvement over absolute transfer from the standpoint of accuracy. However, since normalization may require additional measurements, the costs may not always justify their use.

Appendix B

Table of lengths (metres) of 15 sample roads in each test database, and independent measures by DMI and GPS.

Rd#	Test databases						Independent Measures	
	A	B	C	D	E	F	DMI	GPS
1	826	884	819	831	809	887	811	787
2	6252	6345	6351	5705	6250	6355	6376	
3	2837	2860	2839	2854	2786	2866	2825	2854
4	2633	2636	2665	2646	2626	2648	2654	2647
5	2125	2016	2058	2083	1966	2016	2029	2044
6	1729	1838	1803	1808	1794	1848	1822	1809
7	2270	2133	2181	2191	2198	2144	2195	
8	1796	1892	1862	1801	1749	1893	1871	
9	1524	1511	1521	1511	1531	1517	1522	
10	2091	1942	2236	2077	2187	1964	2244	2240
11	823	806	881	837	866	805	887	901
12	7075	6837	7472	7081	7330	6808	7477	7446
13	2101	2079	2141	2114	2112	2083	2136	
14	3646	3479	3788	3604	3670	3469	3792	3776
15	2242	2482	2524	2313	2426	2476	2541	2541

Deviation of length in each database from DMI measurement. Column averages are quoted in Table 6.

Rd#	Test databases						Independent
	A	B	C	D	E	F	GPS
1	15	73	7	20	2	75	25
2	124	31	25	671	126	21	
3	12	36	14	30	39	41	29
4	21	18	11	9	29	7	8
5	95	13	29	53	63	14	14
6	93	16	19	14	28	26	13
7	75	62	14	4	3	51	
8	74	21	9	69	122	22	
9	2	11	2	11	9	5	
10	153	302	9	167	57	280	5
11	65	81	6	50	21	82	14
12	402	640	5	396	147	669	31
13	35	57	5	22	24	53	
14	147	313	5	188	122	323	16
15	300	59	18	228	116	65	1