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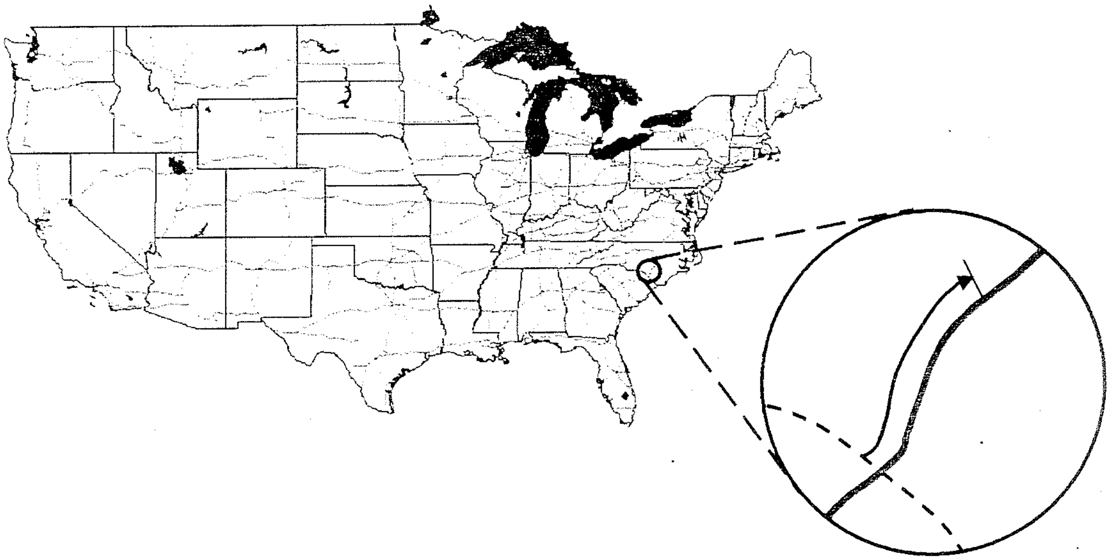
Federal Highway Administration

LINEAR REFERENCING PRACTITIONERS GUIDEBOOK



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by

GIS Trans, Ltd.

Federal Highway Administration

LINEAR REFERENCING PRACTITIONERS GUIDEBOOK

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Acknowledgements

A document of this scope comes only from the collaborative efforts of many individuals. Foremost, the project was funded by the Federal Highway Administration (FHWA), with direction from Vincent Nowakowski (Project's Former COTR) and Roger Petzold.

The Guidebook was conceived largely to support FHWA Workshop on Integrating Transportation Information Systems (ITIS), which presents the broad, enterprise-wide role of information technology in transportation agencies. With recognition of linear referencing as a cornerstone of Integrating Transportation Information Systems, it was felt that ITIS needed to summarize more detailed information and experience in this area. More information on the ITIS workshop is provided in Appendices D and E.

The four case studies provide the glue that holds together the background material, and the participation of the four Departments of Transportation was clearly essential. In particular, appreciation goes to: Randolph C. Rowell, Idaho Transportation Department; Lee Ann Kell, Karen Lister, and Charles Coldwell (consultant), Missouri Department of Transportation; Frank M. DeSendi, Pennsylvania Department of Transportation; Ron Cihon, Washington State Department of Transportation. In addition, many other individuals generously provided their expertise and experience through interviews and phone conversations.

From GIS/Trans, Ltd., the project consultants, principal contributions came from Steven Bower (principle author), John Sutton, Max Wyman and Simon Lewis (project lead for ITIS).

Finally, the contributions of those working in the field of linear referencing must be acknowledged – we hope this Guidebook may contribute to your work. While there are no plans at this time to update the Guidebook, it is our hope that you, the reader, will provide comments and that we may produce a revised edition in the future. Comments can be submitted to the contacts listed in section 1.6.

Abbreviations

AADT	Average Annual Daily Traffic
ATIS	Automated Traveler Information System
ATMS	Automated Transportation Management System
DGPS	Differential Global Positioning System
DOT	Department of Transportation
FGDC	Federal Geographic Data Committee
GDF	Graphic Data Format (of the International Standards Organization)
GIS-T	GIS for Transportation
GPS	Global Positioning System
HOV	High Occupancy Vehicle, as in HOV lane
ID	Identifier
ITD	Idaho Transportation Department
ITIS	Integrating Transportation Information System
ITS	Intelligent Transportation System
IVHS	Intelligent Vehicle Highway System
LRM	Location Referencing Method (see glossary)
LRS	Location Referencing System (see glossary)
MoDOT	Missouri Department of Transportation
NCHRP	National Cooperative Highway Research Program
NSDI	National Spatial Data Infrastructure
PennDOT	Pennsylvania Department of Transportation
RDBMS	Relational Database Management System
SDTS	Spatial Data Transfer Standard
USGS	United States Geological Survey
WADGPS	Wide Area Digital Global Positioning System
WSDOT	Washington State Department of Transportation

Executive Summary

Purpose

This Guidebook provides linear referencing practitioners with the guidance they need to accomplish their work in a rapidly changing technical environment. Direction is provided through the experience of other transportation agencies as collected from four national case studies, coupled with supporting theory and analysis derived from research. The emphasis is on highway systems, although the concepts may be applied to other linear features and networks such as railways, transit lines or pipelines. The implementation of linear referencing with GIS is addressed in detail, although no specific GIS software is discussed other than that reported in the case studies.

Problem Statement

Transportation agencies are applying their information resources with increasing sophistication to decide *where* the best investments are to be made in the transportation system. Most transportation investments are made at some *location* along a roadway or other linear feature. The key to integrating and analyzing these data is *where* they are located. *Location* is the key to integrating transportation data, and thus to making decisions about transportation investments.

Linear referencing provides a set of methods and procedures for recording and retrieving locations along linear networks. However, modern transportation infrastructure is complex, three-dimensional, multimodal and often changing due to realignments and other construction. Maintaining a stable linear environment in which to collect, store, and retrieve locations can be problematic, with the cost of errors growing in proportion to inventory complexity. For example, the following cases often present difficulties for managing linear locations:

- Corrections to traversal (or ‘route’) lengths or measures (no physical change to the network)
- Realignments (modified network, often affecting ‘downstream’ traversal measures)
- New and abandoned roadways that may impact portions of traversals and their measures
- The introduction of a new nodes along a route (that could impact an existing traversal)
- The definition of traversals for divided highways, ramps and other special types of linear features.

Other complications exist as well. How can locations obtained by different linear referencing methods be translated and integrated? The Global Positioning System now enables collection of locations with sub-meter accuracy – how can these best be linked with linear measures? How can linear referencing, which changes over time, be best applied to manage historical data? This Guidebook presents the experience of the case studies and provides preliminary guidance on how to address these and related issues.

Scope

The intended audience for this Guidebook is the linear referencing practitioner involved in activities such as evaluating or refining an existing linear (or location) referencing system, developing a new linear referencing system, implementing a linear referencing system in GIS, or integrating data from different linear referencing methods (or other location referencing methods).

In particular, this Guidebook is targeted toward those contemplating the adoption, integration, or major modification of their linear (or location) referencing system. New technologies abound, the cost of data collection has dropped significantly and field-attainable accuracy has greatly increased. The question faced by this audience is how to build a location referencing system that can endure the fast pace of technological change and thus assure large investments will meet future needs.

Terminology

The terminology of linear referencing has been inconsistently applied in the literature. This can be a very confusing aspect of linear referencing, which at times has led to misunderstandings. Terminology used in this Guidebook is described and illustrated in Part 2, and every effort has been made to apply a consistent terminology complying with current practice, but with a minimum of jargon.

The Case Studies

The four case studies were selected as leading indicators of linear referencing practices, and for how each has addressed related issues and problems. While it is not possible to capture the representative experience of all state DOTs, the selected cases provide ample material representative of current practice. The objective of the case studies was to provide an analysis of their experience to benefit other transportation agencies facing similar issues.

The case studies included the Idaho Transportation Department (ITD), the Missouri Department of Transportation (MoDOT), the Pennsylvania Department of Transportation (PennDOT) and the Washington State Department of Transportation (WSDOT). The table below summarizes several aspects of each state's use of linear referencing. Detailed findings from each of the case studies are provided by subject area throughout the Guidebook.

Table ES-1. Summary of Linear Referencing Implementation by Case Study

	ITD	MoDOT	PennDOT	WSDOT
Principal linear referencing method	control section (incorporating historical changes)	base-offset (named route/ milepoint)	control section (roughly equal length)	base-offset (named route/ milepoint)
Years in use	20	1	10	50
Number of linear referencing systems in use	1	2 (includes 1 legacy system)	1	2
GIS software	Intergraph/MGE	Arc/Info	Intergraph/MGE	Arc/Info

Idaho Transportation Department

ITD has used a single, enterprise linear location referencing system (linear LRS), for nearly 20 years: the MACS/ROSE (Milepost and Coded Segment/Road Segment) system. This mainframe application is used to manage LRS control files and key event databases. The LRS is based on the concept of 'Segments', which are underlying control sections to which all linear data are referenced. Although the Segments were originally created corresponding to highways as numbered in the field, they are associated with the physical roadway rather than the highway numbers. The Segments thus remain constant even when highways are renumbered or renamed. Milepoint control files maintain known milepoint values at various features along the Segments.

Segments are uniquely referenced by a combination of the segment identifier (a random code) and its effective and expiration dates. The system manages historical data by use of 'effective' and 'expiration' dates within the control files and event tables. The MACS/ROSE LRS is thus a good example of how historical alignments and data may be stored.

The GIS Section of the Planning Division has responsibility for the LRS and for GIS activities. A rudimentary implementation of the LRS has been made in GIS primarily to demonstrate the potential use of GIS. The base map has not been kept fully up to date, but is used to generate custom maps on a case-by-case basis. Only current Segments are included in the GIS base map; effective and expiration dates have not been incorporated, which poses a problem for historical events.

Missouri Department of Transportation

MoDOT is developing the Transportation Management System (TMS), a collection of applications to integrate multiple management systems. TMS will integrate legacy databases through custom loading routines and directly incorporate those systems over time. The system will provide data access and maintenance tools to other offices, and will enable query and reporting through a common interface. As of this writing, MoDOT was nearing completion of the initial system.

At the heart of the TMS is the Travelways system, which provides a standard system for locating events and features along roadways. The Travelways LRS demonstrates how linearly referenced data may be used to form the heart of an integrated transportation information system. Traversals correspond to numbered or named routes as signed in the field. The Travelways LRS provides a number of state-of-the-practice features, including support for multiple linear referencing methods, use of bi-directional traversals on all roadways, inclusion of all ramps and public roads, extensibility to other transportation modes and full integration with the GIS road network base map.

MoDOTs experience leading to development of the TMS may be familiar to some DOTs. A legacy linear referencing system (the 'old system') maintained three concurrent log systems, and some offices and Districts effectively maintained their own systems (generally with differences in milepoints, not routes). Updates were not synchronized between different offices. Interchanges on divided highways were represented by a single 'point' (all accidents or signs would be coded to the same point). Where routes left and re-entered a county, milepoints would restart where they left off, creating two points on a route with the same milepoint (the same was true for alternate routes on overlapping route sections). Data analysis was typically hampered by the process of determining and rectifying locations.

The new system rectifies these limitations and provides for eventual integration of all management systems. Centralized management of updates will simplify record keeping by individual offices. As well, the Travelways LRS will be completely coded in the GIS base map, and direct query of the database will be provided through a GIS (ArcView) interface. The 'old system' will be supported within the Travelways system to aid in converting and interfacing legacy systems to TMS until the legacy systems are replaced.

Washington State Department of Transportation

The WSDOT State Highway Log, part of a mainframe application, contains roadway data and mileage statistics for all State Highways. The State Highway Log includes the following key elements:

- The 'State Route System' highway network comprises increasing and decreasing routes (traversals) representing each direction of travel
- There are the two main linear referencing methods used by WSDOT:
    - The State Route Milepost (SRMP) method uses reference points along routes, and has jumps and gaps in the route milepoints due to changes to the road geometry over time
    - The Accumulated Route Mileage (ARM) method records the current, actual distance from the beginning of each individual route
- The State Highway Log contains conversion equations to cross-reference SRMP and ARM values
- Field data collection is referenced to the SRMP
- A Realignment File tracks all changes by date and by route.

A GIS application was developed to integrate the State Highway Log with the GIS base map. The application is known as MADOG (Mapping, Analysis and Display Of Geographic data). Its implementation is a specific extension of the capabilities of the State Highway Log in GIS. Developed in the ArcView GIS, MADOG extends the capabilities of the WSDOT LRS in a number of ways:

- Provides a graphical user interface for the query, display and mapping of transportation data
- Adds routes for *ramps* to the two existing referencing methods
- Provides a visual means of viewing the locations of SRMP and ARM values
- Enables graphical input of data by linear referencing (e.g., accident locations)
- Integrates other GIS data sets such as hydrology, administrative boundaries, local roads, etc.

The State Highway Log is managed by the Planning and Programming Service Center (PPSC). GIS activities are distributed throughout the Department. The Geographic Services Office of the PPSC implemented the LRS in GIS and developed the MADOG application. GIS development is coordinated by a GIS Implementation Team made up of staff from various units throughout the Department.

Pennsylvania Department of Transportation

In 1986, more than 12 separate linear referencing methods were placed beneath a single linear LRS titled the Pennsylvania *Roadway Management System* (RMS). The transition was necessary to bring all users beneath a single LRS fully manageable in a computerized environment.

The resulting LRS utilizes control sections uniquely identified by a hierarchical coding scheme (county code, State Route number and segment code). Individual sections are approximately 0.5 miles in length, and are identified in the field by reference posts (or 'field information paddles'). Of particular note is the overall stability of the single LRS – due to the short length of individual sections, locations tend not to change over time. Field calibration points also help to anchor traversal sections and enable display of attributes (events) in their correct locations on the GIS network. Straight-line diagrams are maintained as a principal method for recording and identifying locations.

All state routes have been implemented with control sections coded in the Intergraph/MGE GIS base map (based on USGS 1:24,000 topographic maps). A well-defined business process assures coordination of updates between the GIS section and the mainframe linear LRS control tables. As the GIS office receives reports of updated features, the corresponding updates are made to the GIS data.

PennDOT's Bureau of Maintenance and Operations is responsible for the computer system in which the LRS is stored, while the Bureau of Planning and Research is responsible for GIS.

Linear Referencing Implementation Issues

A main objective of this Guidebook is to help practitioners develop and manage linear reference systems in today's complex infrastructure environment. There are basic issues, such as how to code traversal identifiers or when to use of separate traversals for each travel direction, but these issues become more complicated given:

- Divided highways
- Non-contiguous traversals
- Overlapping traversals
- One-way pairs
- Service roads
- Rotaries
- Ramps and approaches
- Layered or tiered roadways
- Individual lanes (including High Occupancy Vehicle lanes)
- Associated facilities (truck runoff ramps, rest areas, etc.)
- Multimodal integration
- Cul-de-sacs

How should each infrastructure type best be handled? Can current business practice and linear referencing accommodate full and complete descriptions of every possible location? Related issues include determination of traversal/section lengths, calibration or traversal measures, specification of event locations and the synchronization process between LRS control and event databases. Each of these issues is discussed in turn and presented with examples taken directly from each the four case studies.

As information systems become more capable, more options are available for maintaining historical information for trend analysis. Linear referencing as typically implemented has a particular limitation in this regard. Information in separate roadway-related databases (e.g., pavement and traffic data) can be integrated based on where things occur on the ground. However, milepoints (or other measures along traversals) are typically updated over time due to re-measurements, realignments or other construction. Therefore, the milepoint of a particular location may change over time. This complicates the integration of separate transportation databases and, in particular, the management of historical data. Issues and techniques of managing historical data are discussed, along with the experience of the case studies.

Bound within these implementation issues are the relevant mandates and business processes of transportation organizations. Methods for managing information about each infrastructure element, including its location, must be well defined in order to meet program objectives. Many transportation organizations face problems related to new infrastructure types that cannot be defined within existing LRS business practice. This is often a driving force behind the re-engineering of many LRSs. By focusing on LRS best practices, the main body of this Guidebook presents both mainstream issues and idiosyncrasies other DOTs have or will encounter during their LRS development.

Relevant Technologies and Applications

The number of tools available to assist linear referencing practitioners is large and growing. Some are indeed revolutionary. The mainstay technology for many LRSs remains the video log van fitted with a distance measuring instrument for inventory assessment and archiving. Straight Line Diagrams (SLDs) work well with video logs; however, improving computer capabilities are rapidly displacing the SLD for dynamic map displays. Many states are mounting differential GPS units on their video vans, and building entirely new high-accuracy base maps at very low cost relative to other information operations.

GPS locates points with absolute coordinates of latitude and longitude, while linearly referenced measures are relative to points of known measure along predefined traversals. GIS has enabled the integration of geographic coordinates with linear measures. Linking and calibrating different linear referencing methods through geographic coordinates is a powerful tool, and is a current area of research within the Intelligent Transportation Systems (ITS) community. Development of standards for spatial data transfer is also addressing translations between referencing systems.

Current Research in Linear Referencing

Transportation agencies that share an interest in the common transportation network often use different linear referencing systems and are thus not able to share data. Much of the current research in linear referencing involves the search for a generic data model for linear referencing that would meet the information needs of diverse organizations while enabling them to more readily exchange information. At the heart of this research, it is recognized that the exchange and integration of diverse roadway-related information requires use of a common means of specifying locations.

The ITS datum initiative is an excellent example of the problem at hand. As vehicles receive local ITS information, neither the information provider nor the various receiving vehicles know what LRS the other is using. How can linearly referenced data be exchanged between otherwise disparate users? The ITS datum is visualized as a set of nodes and links which all ITS users would have available as a standard network for referencing purposes. This would create a national network of ground control points that would anchor spatial references between different databases. Translation between different location referencing methods would be accomplished through the common ITS datum. The search for a generic linear referencing data model is an extended application of this concept, and includes NCHRP Project 20-27(2), the GIS-T Pooled Fund Study Linear Reference Engine, and the Dueker-Butler model (see section 7.2 for references).

Conclusions

Linear referencing is well established as the principle means by which transportation agencies manage network-related data. However, emerging technologies, new methods of data collection and the expanding responsibilities of transportation agencies have changed the way the linear referencing is viewed and implemented. Linear referencing is now viewed as just one type of location referencing within a larger location referencing system. The implementation of linear referencing in GIS has become the normal pathway to an integrated location referencing system. Full integration between linear referencing control databases and GIS has become desirable as full-featured display and analysis of current and historical information moves from wishful thinking to a practical reality.

The integration of spatial data within and between transportation agencies is increasingly important for gaining the greatest value from an agency's information resources. The successful implementation of an enterprise LRS may largely be attributed to institutional organization and support. Designation of responsibility for managing and maintaining LRS and GIS operations to specific offices was a common theme between the case studies. Effective management of an enterprise LRS requires clear assignment of responsibility for coordinating and maintaining the system.

The design and refinement of linear referencing systems will continue with greater sophistication to meet new objectives. Greater data integration will enable more thorough analyses to improve the decision-making process of where investments are best made in the transportation network to meet various (often conflicting) needs. Linear referencing methods, as one component of robust location referencing systems, will provide an essential framework for development of integrating transportation information systems (ITIS), intelligent transportation systems (ITS), and related endeavors.

1. Introduction

1.1 Problem Statement

The role of the transportation agency has changed significantly in recent decades. Gone are the days of highway construction on a grand scale and continual expansion of the transportation system. Social and environmental concerns have become an integral part of transportation planning, resulting in the current trend of making the best use of the existing system rather than simply building more roads. At the same time, the technological revolution has provided a profusion of tools for collecting, managing and analyzing information of all kinds. Consequently, transportation agencies are applying themselves to make the best possible use of information, to decide *where* the best investments are to be made in the transportation system.

The operative word here is *where*. Most transportation investments are made at some *location* along a roadway, railway or other linear feature. Decisions about *where* to make investments are based on data about the transportation network. The key to integrating these transportation data is *where* they are located, *where* traffic is congested, *where* accident rates are high, *where* growth is expected to occur. It cannot be overstated that *location* is the key to integrating and analyzing transportation data, and thus to making decisions about transportation investments.

Linear referencing, the means of specifying locations along linear features, remains the mainstay of most transportation data management practice. Although the basic concepts of linear referencing remain unchanged since the last federal guide to linear referencing was published (Baker and Blessing, 1974), recent technology has pushed horizons to a point that a second look is beneficial. In particular, new methods for data collection, such as GPS, videologging and remote imagery, call for more comprehensive methods for managing and integrating location-specific data.

Many linear referencing systems developed over recent decades are not sufficiently robust to handle the information needs of today's transportation agencies. Specifically, linear referencing provides a foundation for geographic information systems for transportation (GIS-T), integrating transportation information systems (ITIS), and intelligent transportation systems (ITS). How these concepts are brought into use rests squarely on the shoulders of established linear referencing schemes and their robustness to accommodate fundamental changes in daily business practice.

Over the past decade, and the last several years in particular, there has been considerable research into the theory of linear referencing as a means for integrating transportation-related data, as well as its applicability to complex initiatives like ITS. In response, many transportation agencies are revising their linear and location referencing systems to support these emerging business needs, and there are lessons to be learned on how they have responded to the challenge. However, the current state of linear referencing and experience gained to date has not been compiled in a format easily digested by the practitioners of linear referencing, and this is the overall purpose of this Guidebook.

1.2 Objectives of the Guidebook

This Guidebook aims to provide practitioners of linear referencing with the relevant guidance they need to accomplish their work in a rapidly changing technological environment. Guidance is provided through the experience of others as recorded in four case studies, coupled with supporting analysis. The emphasis is on highway systems, although the concepts may be applied to other linear features and networks, such as railways, waterways, or pipelines. Current issues and research relating linear referencing for highways with other modes of transportation will also be described. This Guidebook will address the implementation of linear referencing with GIS, but will be independent of any specific GIS software (other than that reported in the case studies).

In addition, it is hoped that the Guidebook will provide a broader view of issues related to management of information across the transportation organization. Indeed, one reason for its development was to support a course on Integrating Transportation Information Systems (part of FHWA ITIS Workshop), described further in Appendices D and E.

1.3 Intended Audience

Practitioners of linear referencing include system designers, technicians and managers involved in activities such as:

- Evaluating existing linear (and location) referencing systems
- Extending a linear referencing system to incorporate new features (local roads, ramps, etc.)
- Developing new linear referencing systems
- Implementing an existing linear referencing system using GIS
- Designing database structures for linearly referenced data
- Integrating data using different linear referencing systems
- Integrating linearly referenced data with other location referencing methods (e.g., GPS).

In particular, this Guidebook is targeted toward practitioners that are contemplating the adoption, integration, or major modification of their linear (or location) referencing systems. New technologies abound, the cost of data collection has dropped significantly and field attainable accuracy exceeds that of existing base maps by orders of magnitude. The question faced by this audience is, how to build a location referencing system that can endure the fast pace of technological change and thus assure that large investments in data will meet future needs. Many national research projects are underway, and the central thread through every initiative and case study is well-informed planning and full utilization of the hard-earned experience of other transportation agencies.

Although it is assumed the reader is familiar with the basic concepts of linear referencing, Section 2.1 provides an overview of linear referencing terminology. Particular attention should be given to this section to alleviate potential confusion regarding the terms used herein.

1.4 Use of the Case Studies

Four case studies served as the basis for the information in this Guidebook:

- Idaho Transportation Department (ITD)
- Missouri Department of Transportation (MoDOT)
- Pennsylvania Department of Transportation (PennDOT)
- Washington State Department of Transportation (WSDOT).

Each case study involved initial phone interviews and collection of documentation followed by two days of intensive on-site interviews. A representative from each agency helped to arrange interviews with key personnel as well as providing documentation and editing assistance with the final document. These efforts were central to the success of this Guidebook and reflect the wishes of the participating transportation agencies to promote the further development of best business practices in location referencing.

To help guide the on-site visits, a comprehensive questionnaire was drafted (a copy is provided in Appendix C). The completed questionnaires were compared for both commonalties and differences. It is interesting to note how the four studies may be ordered with respect to location referencing program maturity. WSDOT's system has been in place 50 years, Idaho's for 20 years, PennDOT's for 10 years, while Missouri's system is just now coming on line. The contrast between these systems provides an excellent context for assessing some of the advantages and shortcomings of the various techniques used for linear referencing.

1.5 Guidebook Organization

This Guidebook presents both the theory behind linear referencing, and the practical experience reported for the four case studies. Part 2 provides an overview of linear referencing that should be of interest to both novices and experienced readers. Part 3 describes the case studies and summarizes the findings from each. Part 4 is dedicated to the relationship between linear referencing and GIS, two data management technologies that have converged to provide the most powerful information analysis capabilities. Part 5 presents specific implementation issues relevant to linear referencing, bundling the theory behind each topic area with details from the four prominent case studies agencies. Part 6 discusses technologies and applications relevant to linear referencing, and part 7 provides an overview of current research in the field. In closure, Part 8 summarizes the findings of the Guidebook.

1.6 Further Work and Submission of Comments

This introductory work attempts to provide a comprehensive overview of linear referencing with strong reliance on the case studies. While a broad range of experience in the field has gone into the Guidebook, it is well noted that this topic has attracted a diversity of views. The last several years have seen a continuing series of workshops and meetings on this topic. While some consensus on this topic has been gained (for example, the NCHRP 20-27 report described in section 7.2.1), it is unlikely that debate over the most suitable linear referencing system will subside.

It is the hope of the authors that this work will be widely circulated and critically reviewed. While not formally planned at this time, it is also hoped that the document will be further refined in light of comments received. Comments can be submitted to any of the contacts below:

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2. Overview of Linear Referencing

For both new and experienced practitioners of linear referencing, this section provides an overview of the core concepts of linear referencing and establishes the terminology and framework by which linear referencing is presented in this Guidebook. In addition, several examples of the application of linear referencing are presented from the case studies.

2.1 History of Use

Linear referencing has been in use for over two thousand years, dating back to the use of 'mile' stones in Roman times. Widespread use of highway markers in the United States began with concrete mileposts installed on the roadways of a few states in the early 1920s. The realignment and abandonment of roads, and construction of new roads, made many of the old mileage signs virtually useless and they were gradually replaced by signs displaying point-to-point distances and route numbers based on the uniform highway numbering system.

The use of mileposts took on new significance when the Highway Acts of 1956 and 1966 required their use as a basic element in the planning, construction, and administration of the national highway system, and in the identification of accident locations. This contrasts markedly with their earlier use as a device primarily for the convenience of travelers.

2.2 Essential Terminology

The language of linear referencing is often ambiguous and confusing. Different authors and transportation agencies often use the same term with quite different meanings. At the level of linear referencing data models, in particular, fine distinctions are made as to the meaning of different terms (Vonderohe et al., 1997; Dueker and Butler, 1997; USGS, 1992). To alleviate potential confusion, this section introduces essential terminology for linear referencing as used in this Guidebook. A full glossary is provided in the appendices, including the sources used for the definitions.

First, for convenience, this Guidebook generally refers to linear referencing in the context of **roadways**, which includes all traveled roads. Of course, linear referencing is not confined to roadways, and has been applied equally well to railways, rivers, pipelines, electric lines, fault lines and other linear features. Use of the term 'roadway' or 'highway' in no way diminishes the importance of linear referencing to other transportation networks. In fact, many transportation agencies wish to extend their use of linear referencing on roadways to other modes of transportation. However, linear referencing has most prominently been used for 'roadways', which is much more convenient than specifying 'linear feature'.

One area of general agreement is with the following two terms (originally from Baker and Blessing, 1974):

> **Location referencing system (LRS).** The total set of procedures for determining and retaining a record of specific points along a roadway. The system includes the location referencing method(s) together with the procedures for storing, maintaining, and retrieving location information about points and segments on the roadways.

Location referencing method (LRM). The technique used to identify a specific point or segment of a roadway, either in the field or in the office.

A **linear referencing method** is a location referencing method in which a location is specified as occurring at some distance from a known point along a linear feature (for example, at some number of miles from the beginning of a roadway). A transportation agency usually has one **linear referencing system**, which may include multiple linear referencing methods (different ways of specifying linear measures along roadways).

Linear referencing is but one type of location referencing, and the relationship to other types of location referencing (e.g., geographic coordinates) are essential to achieving full data integration. Therefore '**LRS**' is used here for the more all-encompassing 'location referencing system', while '**linear LRS**' is used for 'linear location referencing system'.

A **node** is the junction between two or more **links**, or an end point of a **link**. The term 'link' may have different definitions depending on context. A distinction is often made between a link in an abstract network model (a line segment with no shape points), and a link between two nodes in a GIS layer (which has the shape of the feature represented). This distinction is important in the context of data modeling. However, for this Guidebook the terms node and link will also refer to their common meaning for GIS data, in which they have two-dimensional (x,y) or three-dimensional (x,y,z) locations.

A **traversal** is made up of a set of links (or parts of links), in a certain order, and with a certain direction (Figure 1). For example, a highway which begins at 'zero' at its southern end, with milepoints that increase throughout its length, is a traversal. A traversal is any uniquely identified path through a network for which a **linear measure** (e.g., a milepoint) can be determined at any point along the path. The more familiar but ambiguous term '**route**' is best avoided, and used herein only where the context is clear (e.g., 'U.S. Route 1'). A traversal may correspond to a named street, a bus route, a train line, or even a single path that includes travel by both car and train. A single link may be a traversal, as in a link-node linear referencing method (described below). A traversal does not have to be contiguous, but may have spatial gaps. Likewise, the measures along a traversal may be discontinuous, as is the case where mileage equations are used (described in section 5.4).

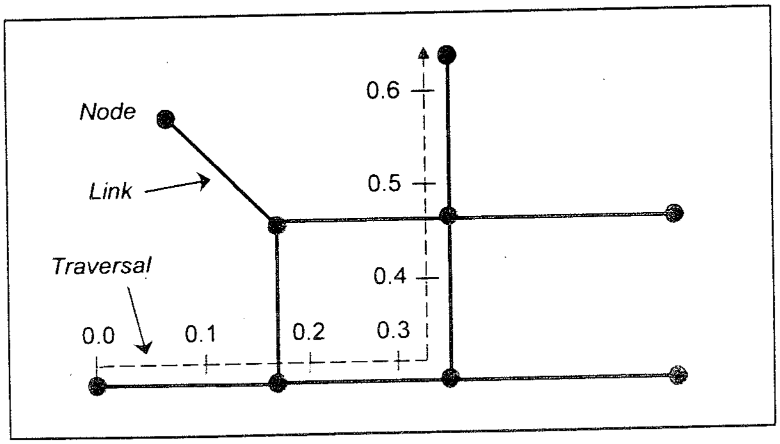


Figure 1. Nodes, Links and Traversals

A **milepoint** is one type of linear measure, which usually measures the distance in miles from the beginning of a traversal (which does not have to start at zero). The term 'milepoint' is often used in this

Guidebook for convenience, where **kilometer point** would serve just as well. The term **log mile** has been used by many transportation agencies to refer to milepoints, due to the practice of recording milepoint locations along roadways in a 'log' book.

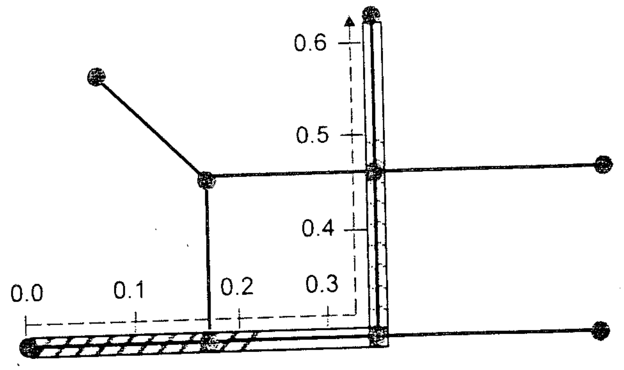
An **offset** is a distance along a traversal from a point with a known linear measure. The offset may be from the beginning of the traversal (e.g., a milepoint) or from a **reference point** (such as an intersection or signpost) at some point along the traversal. A distinction may be made between the reference point representing a physical object, and a **traversal reference point** that exists only as a location on a traversal corresponding to the reference point. The term '**control point**' is often used synonymously with reference point, but sometimes is restricted to mean a point at a node with a known measure along a given traversal, used to calibrate the traversal's measures.

A **reference post** is a physical sign or marker that displays either the linear measure for its location or a code for which the associated linear measure can be looked up. **Mileposts** and **kilometer posts** are reference posts that display their respective units of measure.

The terms **section** and **segment** have often been used rather ambiguously. Unless otherwise specifically defined, they both refer to a continuous length of roadway on one or more links (or portions of links). However, **control section** is often used to describe a section of roadway, with well-defined end points and a known length. Control sections may be established based on consistent linear attributes (pavement type, number of lanes, etc.), but this is not required. In some linear referencing methods, 'control sections' are established with associated linear measures, and are thus used as traversals.

An **event** is any feature, characteristic or occurrence along a traversal, such as a bridge, pavement condition or crash. A **point event** is located at a single linear measure, whereas a **linear event** has length, with location specified by a begin measure and an end measure.

Dynamic segmentation is a method of locating events along the traversals of a linear network with no previous segmentation of the network (Figure 2). The term is generally (but not always) associated with the application of linear referencing in GIS. With dynamic segmentation, linear events can begin and end at any points along a given traversal, and are not restricted to whole links. In contrast, **static segmentation** is a method of assigning attribute values to pre-defined segments along the linear network. With static segmentation in GIS, roadway attributes are therefore confined to complete links. If an attribute value varies along a pre-defined segment, an average value may be assigned.



traversal	begin milepoint	end milepoint	pavement condition
'State Route 302'	0.00	0.22	poor
'State Route 302'	0.22	0.32	good
'State Route 302'	0.32	0.50	fair
'State Route 302'	0.50	0.62	good

Figure 2. Dynamic Segmentation

The terms **anchor point** and **anchor section** were coined in the effort to develop a generic data model for linear referencing (Vonderohe et al., *NCHRP Results Research Results Digest 218*, 1997). An **anchor point** is a location that can be uniquely identified in the real world such that its position can be recovered in the field (e.g., "the intersection of Oak and Maple Streets"). An **anchor section** is a continuous linear feature connecting two anchor points. Anchor sections have a direction specified by a 'from' anchor point and a 'to' anchor point, and have a 'distance' attribute which is the length of the anchor section measured on the ground. More complete definitions are provided in the glossary (Appendix A), and the generic data model is further described in section 7.2.1.

2.3 Linear Referencing Methods

A linear referencing method provides a means for specifying locations along a linear network. Four elements common to all linear reference methods are:

1. Identification of a traversal
2. Identification of a known point on the traversal
3. Specification of a distance from the known point (an offset), and
4. Specification of a direction of measurement.

There are two standard approaches by which these elements are employed. The **base-offset method** (Figure 3) involves measurement along a roadway determined from a single base point at the beginning of the traversal, with an offset that may be an absolute or interpolated distance. Where milepoints are used, the base-offset method is sometimes called a route-milepoint method. **Engineering stationing** is a base-offset method in which, typically, the base point is a surveyed location and offsets are measured along a surveyed base line in feet. This method may be very precise, although the base line usually cannot be determined in the field without a survey.

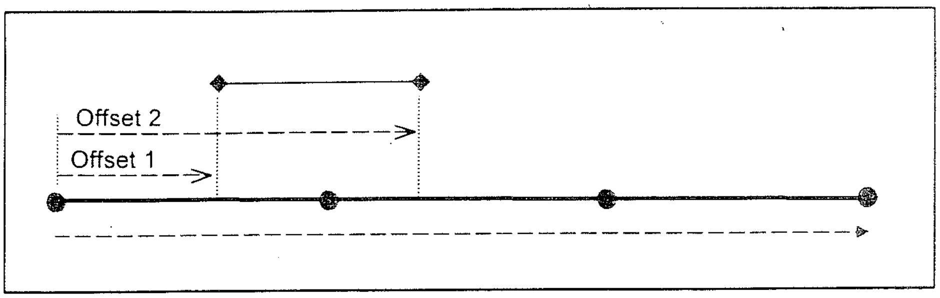


Figure 3. Base-offset Linear Referencing Method

The second approach, the **reference point method**, utilizes a series of reference points along the road (Figure 4). Measurement is made relative to these points, which are typically located at intersections, bridges (center or end points), railroad crossings or other local landmarks. One variation of the reference point method is the **intersection-offset** method, in which an intersection is typically specified by naming the crossroads (this must be unambiguous). The identification of the traversal along which the offset is measured may be by road name and direction (north, east, etc.), or simply by direction, but this again must be unambiguous.

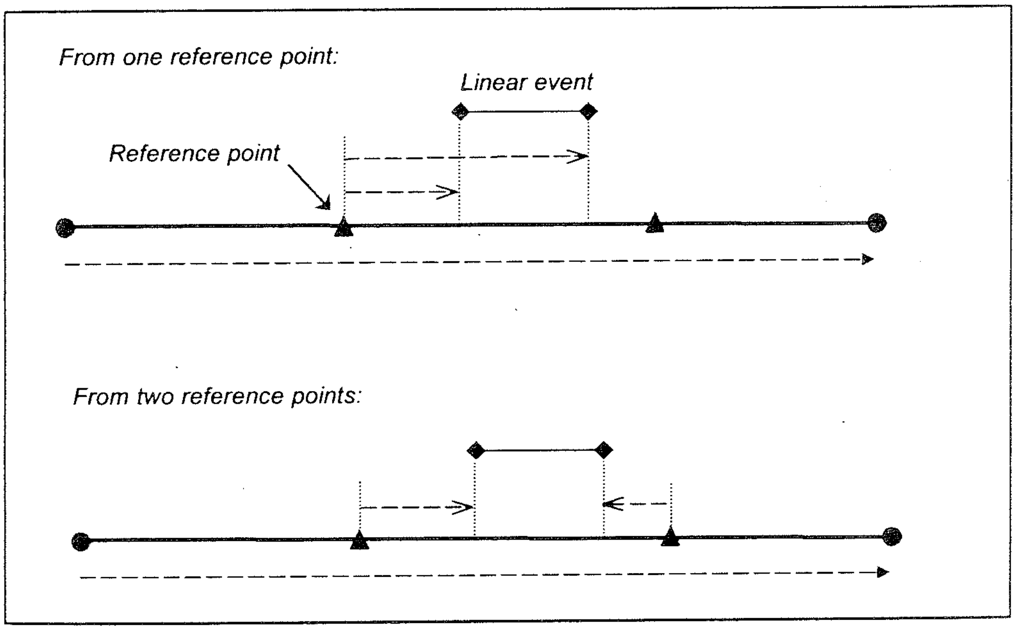


Figure 4. Reference Point Linear Referencing Method

Address geocoding is the process of coding street address ranges along the roadway network and enabling the display of individual addresses as interpolated along the links of the network. Address geocoding is accomplished in GIS in a manner similar to dynamic segmentation, however address ranges are typically coded for each side of each individual link. The GIS uses interpolation along links to determine the locations of addresses. If the intervals between addresses are not proportional to their distances along a link, inaccurate positions may be derived. Although this situation is not necessarily desirable, it is easily implemented and satisfactory for many less demanding applications.

Note that linear referencing methods and systems are completely independent from GIS, and were widely used well before the advent of the transistor. In linear referencing, locations are specified by a one-dimensional measure (an offset) along a linear feature (a traversal). In GIS, location is specified by two (x,y) or three (x,y,z) dimensions. The integration of linear referencing with GIS is currently the principal method for integrating linearly referenced data with data located by other methods (e.g., GPS), however the distinction is important to keep in mind.

Linear referencing methods are put into practice by two general methods:

1. *Sign-oriented methods* involve placement of physical signs along roadways. There are two subcategories:

    (a) The milepost method employs signs that indicate the actual or approximate milepoints of locations from some zero reference point, the beginning of the traversal, usually at the beginning of the roadway, or at a state or county boundary.

    (b) The reference post method, in which the signs themselves do not necessarily indicate known distance from a fixed point. The signs may be placed at a variety of recognizable features (e.g., intersections, jurisdictional boundaries) or at some fixed interval. Central office records are used to equate unique reference post IDs (which do not necessarily follow any logical sequencing) with actual mileages.

2. *Document-oriented methods* avoid the costs of installing and maintaining signs in the field. The first type of document-oriented method uses a log, strip map, or other diagram (straight-line diagrams, or SLDs, is a pertinent example) to associate identifiable roadway features with their milepoint or reference point numbers. Another method employs street maps to locate incidents or attributes on the roadway system.

It should be clear that whatever method is employed, the measurement of distance from a base point or reference point is the basis for all linear referencing.

2.4 Traversal Organization Schemes

It is difficult to describe how traversals may be organized in general terms, because there are so many variations in how this can be done (as evidenced in the case studies). Three traversal organization schemes, or variations thereof, are employed by most transportation agencies (adapted from Nyerges, 1990).

1. A **named route** scheme employs a road naming convention (as a standard procedure for assigning names to highways and streets) and linear offsets (e.g., milepoints) from the beginning of each named route (Figure 5, below). Each named route is a traversal. One common variation of this methodology, used by many state Departments of Transportation, breaks routes having a common posted name into separate traversals for each county or maintenance division.

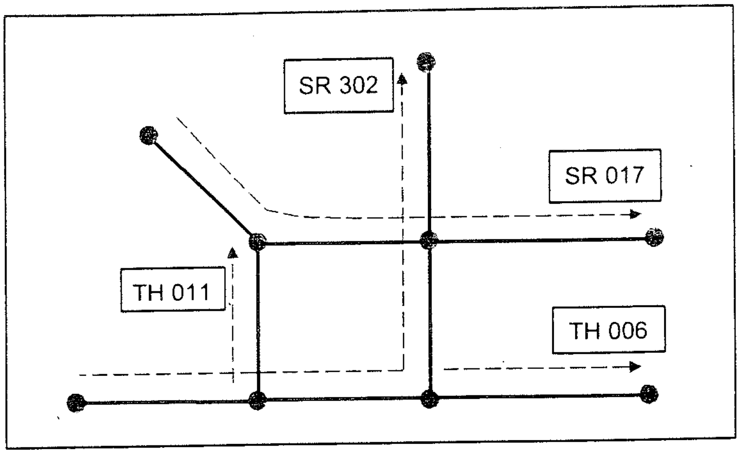


Figure 5. Named Route Traversal Organization Scheme

2. A **link-node** or **link-offset** scheme specifies attribute locations along each link of the roadway system. A separate traversal is defined for each link (Figure 6). The link identifiers are often derived from the node identifiers, hence the name 'A-node, B-node' is sometimes used for this scheme.

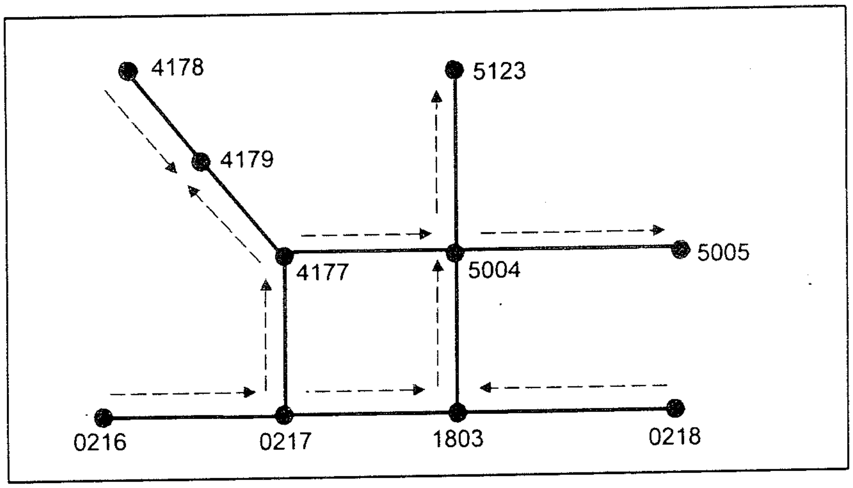


Figure 6. Link-node Traversal Organization Scheme

3. A **control section** scheme establishes a middle ground between the route-milepoint and link-node schemes. A control section method breaks roadways (usually within a named roadway) into sections that are generally shorter than numbered/named highways (complete 'routes'), but longer than single links. A traversal is defined for each control section. The control sections may be defined based on subsections of a named roadway, or based on having consistent physical characteristics, or by some other ubiquitous criteria (Figure 7). Control sections may also be defined by standard (or nearly equal) lengths (Figure 8). (The term 'control section' is sometimes used to describe a roadway section with homogeneous attribute data throughout its length, but that constraint is not assumed in this Guidebook.)

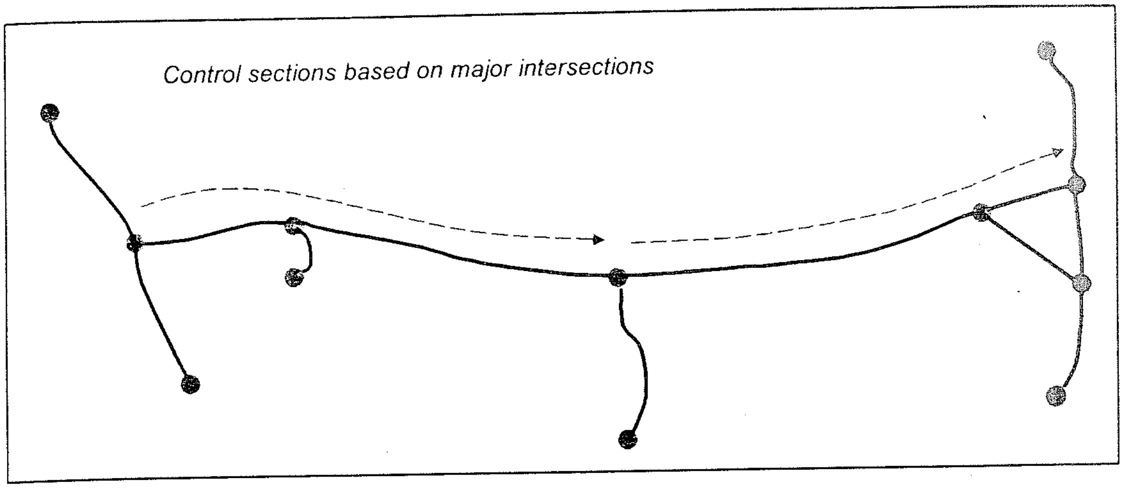


Figure 7. Control Section Traversal Organization Scheme – by Major Intersection

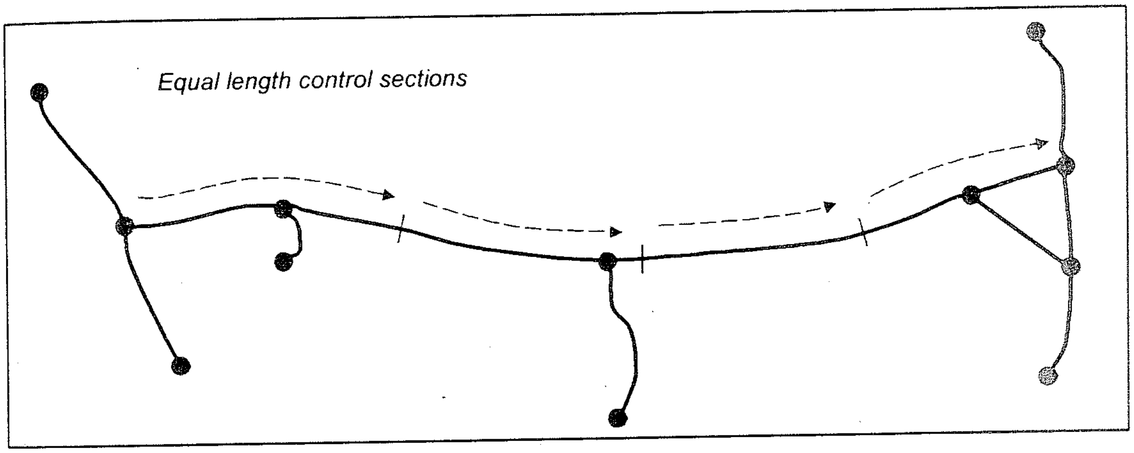


Figure 8. Control Section Traversal Organization Scheme – by Equal Lengths

Measurement along a traversal is made from either a control point or a reference point. In a GIS the distinction is important. A control point is a point at a node on the network with a known position in the GIS (with x,y or x,y,z coordinates). A reference point may not be at a node, thus measurement from a reference point is more problematic and imprecise in a GIS. In order to measure accurately from a reference point along a traversal, an artificial node may be required, thus creating topological divisions. Problems arise in both measurement systems when the roadway geometry is changed, such as when a road is realigned (e.g., straightened).

2.5 Linear Referencing Control and Event Data

Generally speaking, there are two types of data associated with linear referencing: *control tables* and *event tables*. Control tables (or files) are essential to the internal functioning of the linear LRS. Depending on the LRS design, control tables may define and record traversals, reference points, control points, the relationship between internal traversals and milepoints along numbered/named highways (where they differ), mileage equations, and the correspondence between different linear LRMs.

Event tables on the other hand contain the attribute data for the linear objects being modeled, including both point and linear events (specified by offsets along traversals). Through relational constructs, event tables may be maintained completely separately from the linear LRS and linked only when needed (for display or analysis).

Linearly referenced information can be quite complex. The type of user, whether experienced technician or peripheral operator, must be considered when designing interfaces or entire systems. Transportation data is expensive to collect and maintain, but its true value is typically proportional to how easy it is to access and utilize. Key issues include:

- Will data be kept on-line or off-line?
- What event tables will be maintained in the same system as the control tables?
- When traversals are updated (e.g., due to realignments or re-measurements), are historical event data locations rectified to reflect these changes? Or, are the historical location references maintained relative the now obsolete network, perhaps enabling reconstruction the traversal network at any historical time?
- How will 'external' databases that rely on linearly referenced locations, but which are managed separately from the LRS control tables, be kept synchronized with updates to the LRS?

As an example, Idaho's linear LRS maintains active and inactive dates for each traversal in their system throughout its 20 year history and can thus rebuild the traversal structure for any time period. Historical records such as accidents are always referenced back to the network that was valid at the time the event occurred. In contrast, PennDOT keeps only current traversal information in its control files, and re-calibrates all historical event information following any traversal updates.

2.6 Integrating Linearly Referenced Data

A major challenge for managing transportation data is the integration of linearly referenced data from different sources, and stored by different linear referencing methods. Many state DOTs have managed over the years to set up multiple linear referencing systems within the same agency. Practically speaking, the integration of data based on different linear referencing systems has not been problematic until recent years because data sharing between divisions or institutions was relatively rare. However, new information exchange techniques have simplified the information sharing process while advanced applications like intelligent transportation systems (ITS) are demanding greater integration.

There are several principal ways to minimize sharing difficulties or to otherwise bring disparate linear LRS measures together:

- Adopt a common linear LRS datum, as suggested by the GIS-T Pooled Fund Study
- Develop custom procedures and routines for each desired conversion
- Maintain anchor points and data as closely as possible to geodetic reality
- Develop a set of translation and data conflation tools to transcribe information between linear LRS and other spatial data structures.

The methods that will prove to be best for integrating different linearly referenced databases will remain under debate for some time. However, a closely related issue is the search for a standardized data exchange format. The Federal Geographic Data Committee (FGDC) is in the process of setting such standards, including linear LRS exchange formats. The ITS community is directly involved because ITS will simply not succeed without such standardized exchange formats. The European Geographic Data Format (GDF), another standard format for roadway data, has been adopted by many commercial providers of street centerline data and provides another method of data exchange. Although these standards are only briefly discussed in this manual, anyone entertaining the design of a spatial transportation database should be apprised of the state of standards development for transportation data.

2.7 Linear Referencing and GPS

The Global Positioning System, or GPS, provides a method for collecting geographic coordinates to an accuracy of several paces on the ground or better. It has been argued that the high accuracy of GPS-based methods of data collection combined with the decreasing cost of data storage will do away with the need for linear LRS methods. However, this argument seems to neglect some advantages of linear referencing, such as its history of use, its appeal as a simple method for data collection and reporting, and its practicality given financial and technical constraints. There are also difficulties in using GPS for the collection of roadway attribute data – for example, the need for a stable, highly-accurate base map and standardized methods of GPS data collection across the agency. These requirements are usually not met in state DOTs today. In addition, greater volumes of data must be collected, maintained, retrieved and analyzed, all of which involve greater costs. GPS data collection certainly promises to greatly improve the accuracy of transportation data, but it seems likely that GPS will enhance the functions of linear referencing rather than replacing them. The relationship of GPS to linear referencing is further discussed in section 6.1.

2.8 The Relationship of Linear Referencing to Business Practices

Linear referencing is an essential component supporting modern business practices of transportation agencies. Analysis of the transportation system and development of efficient management and maintenance systems requires the integration of diverse data about the transportation network. Transportation data are typically managed by different divisions within an agency. The integration of these diverse databases is generally accomplished through the *locations* of features and characteristics along the transportation network. As noted by Vonderohe et al. (1997), "the greatest incentive for policy concerning LRS is cost savings realized from data integration, data sharing and reduction of chaos."

3. The Case Studies

3.1 Use and Limitations of the Case Studies

The four case studies in this Guidebook were selected as leading indicators of the methods and techniques of linear referencing, and for how they have addressed specific linear referencing issues and problems. The focus was on state Departments of Transportation, given their leading role as practitioners of linear referencing. Further criteria for selecting the case studies is discussed below. While it is difficult to capture the representative experience of all state DOT's with four case studies, the selected case studies do serve well to provide ample material representative of current practice in linear referencing.

The objective behind selecting the four representatives was to provide an analysis of issues from which other transportation agencies, large and small, could learn. Although the general design and operation of LRS is paramount, the planning, policy, and implementation tasks are also key subject areas. New techniques in data collection, data warehousing, integrating transportation information systems (ITIS), and the ability to analyze and distribute information simply cannot be ignored. Indeed, GIS-T and ITIS applications built even within the past decade can substantially benefit from these on-going revelations.

For example, newly designed applications in LRS, GIS-T, and ITIS must be flexible enough to readily accommodate changing software and data collection techniques. Software itself is evolving towards a fully open architecture through object linking and embedding such that sub-applications are modular. Preserving the potential for future growth requires an ability to accommodate change. This decade has marked a fundamental transition where GIS and LRS practices no longer dominate transportation data management, but have become subservient tools beneath greater visions of ITIS.

When an agency contemplates a major revision of its LRS (or of any significant ITIS or GIS-T application), there is a wealth of supplemental knowledge and information from which they may benefit. In addition to this Guidebook, the attached annotated-bibliography is a good place to start locating these resources. As well, researchers should not neglect direct contacts with other transportation agencies. Many of the difficult and expensive lessons have been learned, and are best revealed through personal contact.

3.2 Selecting the Case Studies

Several factors were considered for the selection of the four case studies. Of course, one of the driving issues was the agency's willingness to participate. Many of the states considered had champion projects to highlight before the transportation community, while others were deeply involved in project development and unfortunately unable to assist in this research at this time. There was also interest in assessing implementations in different geographic areas, and to assure variation in the size, extent, level of use and general nature of the transportation network. All of these issues have directly impacted LRS development and implementation. As well, it was considered desirable to select case studies whose systems had not been widely reported elsewhere, so as to provide the most new information to the transportation community.

As discuss above, there are several linear LRS methods and techniques that may be blended to provide the best service for a given transportation agency. These methods directly effect the ease with which traversals are updated, the types of historical data that may be stored and retrieved, and how different infrastructure components are recorded.

Other functional characteristics used to select the case studies included:

- Type(s) of linear referencing methods in use: traversal-milepoint, link-node, or reference point
- How special cases are handled: ramps, divided highways, one-way pairs, etc.
- Extent of roadways implemented: state system, ramps, local roads, etc.
- Support of multiple linear referencing methods
- Detail and variety in how traversals are defined (traversal organization scheme)
- How historical data are managed (due to realignments, new roads, etc.)
- Attribute storage schemes (table structures)

Equal to these functional characteristics are the managerial policies necessary during LRS implementation. For example:

- Level of GIS implementation (use of different vendors preferred)
- Level of data integration through linear and other location referencing
- Completed, ongoing or planned revisions to an existing linear referencing system to meet new needs (especially, development of LRS to support enterprise business practices).

3.3 Overview of the Case Study Findings

The heart of every linear LRS is its traversal organization scheme. Although a framework for traversal organization was introduced in section 2.4, this section provides an overview of how each case study participant implemented their own linear LRS. Table 1 offers a general comparison between the four case studies.

Table 1. Summary of Linear Referencing Implementation by the Case Studies

	ITD	MoDOT	PennDOT	WSDOT
Principal linear referencing method	control section (incorporating historical changes)	base-offset (named route/ milepoint)	control section (roughly equal length)	base-offset (named route/ milepoint)
Years in use	20	1	10	50
Number of linear referencing systems in use	1	2 (includes 1 legacy system)	1	2
Extent of roadways	Minor collectors and above, with rest areas	All public roadways, some private drives	State routes (no local, county or city roads)	State system (no local, county or city roads)
Ramps included	Yes	Yes	Yes	Yes
Treatment of divided highways	Single control section (some exceptions where lengths differ)	Separate traversal ('travelway') for each direction of travel	Separate traversal for each direction of travel, both oriented in mainline direction	Separate traversal for each direction of travel
Mileage equations	Yes	No	No	Yes
GIS	Intergraph/MGE	Arc/Info	Intergraph/MGE	Arc/Info

Each of the four case studies is briefly summarized below. A more detailed comparative analysis is provided on a topic-by-topic basis in sections 4 and 5, including how different types of roadways are handled and their relationship to the underlying network centerlines.

3.3.1. Idaho Transportation Department (ITD)

ITD has used a single, enterprise LRS for nearly 20 years, the MACS/ROSE (Milepost and Coded Segment/Road Segment) system. A mainframe application is used to manage the LRS control files and integrate key event databases. The LRS is based on the concept of 'Segments', which are underlying control sections to which all linear data are referenced (by milepoints and dates). MACS/ROSE includes a number of interesting (and some unique) features:

- Traversals correspond to 'Segments', which are defined based on the physical roadway, and thus are not based on any roadway attributes. The Segment code is a random 6-digit alphanumeric identifier.
- Time is an integral part of the LRS. Unique segments are identified by a composite key, including a Segment code, begin/end milepoints, and effective and expiration dates.
- The system inherently manages historical data, by use of effective and expiration dates in the LRS control files and in event tables.
- When the original system was established (1978), single Segments generally corresponded to numbered highways, and could be hundreds of miles long. Currently, some Segments are more fragmented, due to updates to the system (realignments, changes to highway designations and, to a lessor extent, re-measurements).
- Milepoint control files maintain known milepoint values at various features along Segments.
- Route control files group Segments (and portions of Segments) into routes that correspond to numbered highways, federal aid funding categories, scenic/historic byways, etc.

The MACS/ROSE system was originally created with intelligence built into the coding of its Segments: the original Segment codes corresponded to highways as numbered in the field. However, it was soon recognized that this offered no advantage over a legacy 'route and milepoint' system that MACS replaced. Therefore, 'intelligent' Segment codes were replaced by arbitrary Segment codes tied to physical roadway sections that remain constant regardless of changes to highway numbers.

The MACS/ROSE unit of the GIS Section, Planning Division, has full responsibility for the MACS/ROSE enterprise LRS. Responsibilities include assignment of Segment codes, data input and updates, assuring system integrity, notifying users of system updates, providing user access to the system (at different levels), developing custom reports, point of contact for system information, developing user guides, and recommending system policies and enhancements. The MACS system was developed in-house, as a refinement of an existing LRS, using database design principles typical of the time (1975-77). NCHRP Synthesis 21 (Baker and Blessing, 1974) was instrumental in the refinement of ITD's existing LRS and the design of MACS/ROSE.

The Intergraph/MGE GIS has been used for a rudimentary implementation of the MACS/ROSE LRS, using an Informix database. The implementation was done primarily to demonstrate the potential use of GIS. The base map has not been kept fully up to date, but is used to generate custom maps on a case-by-case basis, generally using customized data sets provided to the GIS section. Only current Segments are included in the GIS base map; effective and expiration dates have not been incorporated, which poses a problem for historical events. For example, a Segment's milepoints might be revised due to a realignment. The old Segment would be expired, and a new one added with a new effective date. An accident coded as falling on the old Segment might now be displayed by the GIS along the realigned Segment.

There are a number of minor enhancements desired of the MACS/ROSE system, and a business plan is currently being formalized to make these revisions. For example, system refinements could enable users to reference common highway numbers and names for data input and reporting, rather than the current practice of locating roadway attributes by reference to Segment codes (which are random identifiers).

3.3.2. Missouri Department of Transportation (MoDOT)

The Missouri Department of Transportation is developing a Transportation Management System (TMS), an automated system that includes a collection of applications to integrate multiple management systems (in Phase 1: bridge, pavement, safety, congestion, traffic monitoring and inter-modal inventory). TMS will serve as the MoDOT enterprise transportation database, with the following goals:

- incorporate legacy databases through custom loading routines
- provide data access and maintenance tools to other offices
- enable query and reporting through a common interface (Impromptu and ArcView)
- move toward migration of systems to be directly incorporated in the enterprise database.

At the heart of the TMS is the Travelways system, providing a standard location referencing system and methods for locating the events and features of interest to MoDOT. Traversals correspond to numbered or named routes as signed in the field.

The Travelways system supports several location referencing methods, including:

- Log units (milepoints or kilometer points, based on an enterprise linear referencing system)
- Distance from a known point along a traversal
- GPS coordinates (not currently used, but supported for future use)
- Address geocoding (based on TIGER addresses).

Several special features of the Travelways system include:

- Extensible to all modes of travel along linear features (roadways, railways, waterways, airways, etc.)
- Separate traversals defined for both directions of travel on all bi-directional Travelways
- Complete management of historical data
- Transaction-based management within a relational database (Oracle), fully integrated with a GIS base map
- Common access to the centrally maintained enterprise system by all MoDOT offices
- Integrated management of core roadway attributes (e.g., functional class, etc.).

To aid in the transition to the Travelways system, a previously used LRS (the 'old system') is currently supported within the TMS application. This 'old system' is only supported to aid in the one-time conversion of data from legacy systems to TMS and to aid in interfacing from legacy systems to TMS until the legacy systems are replaced. It is considered a strong point to develop and support a single, enterprise-wide LRS, rather than accommodating multiple LRSs and translations between them.

The 'old system' had a number of limitations which, given newly available technology, warranted development of a completely new enterprise LRS. These limitations included, for example:

- The older mainframe system maintained three concurrent log systems ('basic', 'geometric' and 'current'), and some offices and Districts effectively maintained their own LRSs (generally with differences in milepoints, not routes). Updates were not synchronized between different offices, so that they each maintained different log miles.
- There was no consistent management of historical data.
- Interchanges were not fully represented (routes met at a single 'point', regardless of divided highways), so that all accidents or signs at an interchange would be coded to the same point.
- Where routes left and re-entered a county, the milepoints would restart where they left off, creating two points on a route with the same milepoint (the same was true for alternate routes on overlapping route sections).
- Milepoints were reset to zero where a highway changed between divided and undivided.

As stated in one interview, data analysis in the old system could be "80% determining and rectifying location, and 20% analysis."

The new system rectifies these limitations and provides for systematic integration of all management systems. Centralized management of updates to the system will simplify record keeping by individual offices. As well, the Travelways LRS will be completely coded in the GIS base map, and direct query of the database will be provided through a GIS (ArcView) interface.

Although the TMS is currently in development, key functionality has been demonstrated through a prototype. The system is the result of two years of analysis work followed by approximately 15 months of concentrated development (as of November 1997). The Office of Transportation Management Systems (OTMS) is responsible for all transportation management information systems. This includes the GIS and the Travelways sections. The Travelways system was developed using the Composer CASE tool (Sterling Software, previously owned by Texas Instruments). Composer was used to develop the logical data model, as well as applications that enforce the data model integrity and embedded business rules.

3.3.3. *Washington State Department of Transportation (WSDOT)*

WSDOT uses the Transportation Information and Planning Support system (TRIPS), a mainframe application, to manage the Department's core transportation data. Within TRIPS, the State Highway Log contains roadway data and mileage statistics for all State Highways (over 7000 miles). It is designed to provide a record of current highway system information and a source for computing distances between major points.

The State Highway Log includes the following key elements:

- The highway network maintained by WSDOT is referred to as the State Route System. Each State Route is treated as a continuous traversal. This comprises *increasing* and *decreasing* routes (traversals) representing each direction of travel.
- Route system IDs are stored as twelve-character codes with mainlines identified by the basic State Route number ('002', for example).

- There are the two main linear referencing methods used by WSDOT:
  - The State Route Milepost (SRMP) method uses reference points along routes, and has jumps and gaps in the route milepoints due to changes to road geometry over time
  - The Accumulated Route Mileage (ARM) method records the current, actual distance from the beginning of each individual route.
- The State Highway Log contains conversion equations to cross-reference SRMP and ARM values.
- Field data collection is referenced to the SRMP, although actual measurement may be from a permanent structure such as a bridge. Data collection methods include data collection vans with DMI and videolog. Field measurements are generally taken to the nearest 1/100-mile, i.e., 52 ft. (consistent with a mapping scale accuracy of 1:32,000).
- Transportation data are stored by State Route, Increasing or Decreasing route system, Section ID and SRMP value.
- The TRIPS System Realignment File tracks all changes by date and by route. When a realignment occurs the accumulated route mile value (ARM) changes, but the SRMP remains the same. A new ARM value is added to the beginning of the realigned section and all measures after this point are adjusted.

In the SRMP method, Sections are defined between convenient measurement locations, such as intersections and bridges. Sections are generally less than one mile long. Some roadway characteristics are associated with Sections, which are indirectly linearly referenced by the begin and end milepoints of each Section along its respective route. In addition to the SRMP and ARM referencing methods, other minor methods in use throughout the Department include control sections, HPMS links, engineering stations, addresses, and simple text description ("the I-90 project").

A GIS application was developed to integrate the State Highway Log with GIS base map to map and display transportation data. The application is known as MADOG (Mapping, Analysis and Display Of Geographic data). Its implementation is a specific extension of the capabilities of the State Highway Log in GIS. Developed in the ArcView GIS, MADOG extends the capabilities of the WSDOT LRS in a number of ways:

- Provides a graphical user interface for the query, display and mapping of transportation data
- Add routes for *ramps* to the two existing referencing methods
- Provides a visual means of viewing the locations of SRMP and ARM values
- Enables referencing of data by linear referencing on the map, which can then be stored in MADOG (e.g., accident locations)
- Stores events either at a point or along a line - dynamic segmentation automatically displays events along routes
- Integrates other GIS data sets such as hydrology, administrative boundaries, local roads, etc.

The State Highway Log and MADOG systems are independent of each other. MADOG is a GIS query and display tool that utilizes State Highway Log data but is not used for data management or update.

The TRIPS system contains many other data sets provided by District and Headquarter sources. This is not directly linked to the State Highway Log but an interface can be provided to Divisions or Districts who wish to correlate pavement data, etc. There is no automated method for performing the correlation at this time. However, TRIPS system is being migrated from ADABAS mainframe database to SQL Server RDBMS, and the data model design will allow State Highway Log data to be integrated with other data sets. This new system is called TARIS (Traffic Accident and Roadway Information System) and should be implemented in 1998.

The State Highway Log is managed by the Transportation Data Office, part of the Planning and Programming Service Center (PPSC). The Transportation Surveys Section of PPSC is responsible for updating and maintaining the roadway portion of the TRIPS system. The Roadway Data Section of the Planning and Programming Service Center provides roadway geometrics and attributes for reports.

GIS activities are distributed throughout the Department. The Geographic Services Office of the PPSC implemented the LRS in GIS and developed the MADOG application. Application development is the primary responsibility of the Management Information Systems (MIS). GIS development is coordinated by a GIS Implementation Team made up of staff from various units throughout the Department.

Issues related to linear referencing currently under consideration by WSDOT include:

- Validation of LRS locations using GPS
- Inventory of attributes along the network using GPS and DMI
- Updating the LRS in the GIS
- Resolving temporal issues
- Integrating other jurisdictions' referencing methods
- Restructuring the LRS and attribute data into a relational database, and
- Developing a data dictionary.

3.3.4. Pennsylvania Department of Transportation (PennDOT)

The Pennsylvania Department of Transportation (PennDOT) manages approximately 41,000 miles of State Routes (SR). There are 25,000 bridges (structures whose span is eight feet or greater) in the system and more than 47,000 records in the SR geographic information system (GIS) segment base. The surface transportation system is administered through 11 district offices overseeing 67 counties.

Prior to 1986 a minimum of 12 LRMs were maintained for state operations; for example, railroad crossings, HPMS, maintenance management, pavement condition surveys, and traffic monitoring. Each of these systems required some use of the others and there was a snowballing time lag through the entire update procedure. A task force (5-10 individuals) was formed to integrate all systems into a single function that was computer compatible and did not require the use of mileage equations. Once a consensus system and business plan was developed, a small pilot program was implemented to forge procedures and identify implementation problems.

In 1986, all roadway transportation, maintenance, operations, safety, planning, and all related functions were placed beneath a single linear referencing system titled the Pennsylvania *Roadway Management System* (RMS). This marked the transition from the legacy system of old Legislative Routes to State Routes (SRs), a transition necessary to bring all users beneath a single LRS that was fully manageable in a computerized environment.

The resulting LRS utilizes control sections uniquely identified by a hierarchical coding scheme (county code, State Route number and segment code), with events located at milepoints along the control sections. Individual sections are approximately 0.5 miles in length, and are identified in the field by reference posts (or 'field information paddles'). As the network evolves, the reference posts are relocated as needed.

All state routes have been implemented with control sections coded in the Intergraph/MGE GIS base map (based on USGS 1:24,000 topographic maps). As a rule, the GIS does not carry ramps unless the USGS quad sheet illustrates the same (there has been little customer demand for products with ramps displayed). A well-defined business process assures coordination of updates between the GIS section and the mainframe linear LRS control tables.

Of particular note is the overall stability of the single LRS and its impact on coordinated operations among diverse functions. Thirteen distance measuring instrument (DMI) vans routinely collect field data to verify existing features and add new features during a four-year update cycle. PennDOT is thus in their third revision cycle and nearly all field uncertainties have been removed. As the instrumented vans collect information, new data are merged nightly in mainframe batch loads and integrated with a straight-line diagram (SLD) and section/offset LRM. A system of field calibration points helps to anchor traversal sections to minimize GIS event floating. The PennDOT GIS section receives regular reports of new, deleted, or changed features, at which time the Intergraph-based GIS data is updated.

PennDOT's Bureau of Maintenance and Operations is responsible for the computer system in which the LRS is stored, while the Bureau of Planning and Research is responsible for GIS. Planning and Research is the PennDOT's research program, managing academic partnerships and the local technical assistance program, transportation systems information, highway travel data collection and performance statistics, cartographic products including all official transportation systems, maps, and geographic information systems development.

The following chapters describe and analyze various aspects of linear referencing using the four case studies as specific references.

4. Linear Referencing and GIS

Linear referencing and GIS-T are exceptionally powerful tools that form the nucleus of most state-of-the-art transportation management systems. GIS, with the extensions of dynamic segmentation, provides a powerful tool for the analysis and display of linearly referenced data. Traversal systems can be generated by semi-automated means, built on top of the links of the GIS road network. Prior to dynamic segmentation, the wealth of information stored in event tables was displayed primarily on straight line diagrams, in printed log listings, or on manually generated maps by time-consuming processes. The ability to *visualize* the wealth of data stored in one or more event tables is what first made GIS such a desirable tool for transportation planning and analysis. Subsequently, GIS has been used not just for visualization, but increasingly for spatial analyses involving linearly referenced data.

At first look, the marriage between the two was "made in heaven"; however, some fundamental incompatibilities have emerged. In fact, these incompatibilities have motivated in part research efforts such as the NCHRP Project 20-27(2) generic linear referencing data model and the Dueker-Butler enterprise model (further described in sections 7.2.1 and 7.2.3). This is not to say GIS and linear referencing cannot complement each other—they do work very well together and new innovations promise even brighter horizons. Nevertheless, incompatibilities between the two must be fully understood. This section brings these issues to light, together with the guiding experience of the four case studies.

4.1 The Difference Between Linear and Geodetic Referencing

Linear referencing lays out roadway events (and event end points) like knots along a string. Developing organizational and management tools from linear referencing schemes is an intuitive process. Best of all, a map is not even required. Theory aside, linear referencing is a one-dimensional representation of a reasonably one-dimensional feature—for example, a road. All that matters is the traversal name, reference point, offset(s) and the event.

At the same time, there are limitations to the accuracy of linear referencing as it is typically implemented in a GIS environment. These limitations are due to the fact that linear referencing is one-dimensional (offset along a traversal), whereas topographic information is three-dimensional (x,y,z). GIS is still primarily geared to two-dimensional data storage and analysis, which raises issues regarding the hills and valleys a road passes through, and relating linear locations to the rest of the world. This lack of topographic referencing is not generally a defect, as linear referencing was not primarily designed for this purpose. In a sense, if the linear measures of reference points have been determined by an accurate distance measuring instrument (DMI), then these measures will have incorporated the roadway's three-dimensional shape. However, this type of three-dimensional topographical information does not usually exist within a GIS road network data layer.

In contrast to linear referencing, GIS can store geodetic information because all GIS software is capable of at least two-dimensional referencing (x,y). There are some problems however. Looking at Figure 9, three views of the same road are illustrated. In the 'linear view' of the 1.2 mile long road, five events have been located using a DMI. We know the road is 1.2 miles long because the DMI measured this distance. The only thing we do not know is the path of the road relative to the rest of the world. The GIS view offers the bird's-eye roadway with twists and turns, the benefit of the second dimension. What is missing now is an appreciation of how long the road really is. Any DMI distance up and down hills is lost as it is impressed (or projected) onto the flat GIS coordinate space, so when the GIS measures the road length, it only comes up with 1.1 miles. The roadway zig-zag is visible but the true distance along the path is lost. A cut and fill CAD profile view would be able to recapture the true DMI distance because the third dimension is fully represented at each point along the roadway line.

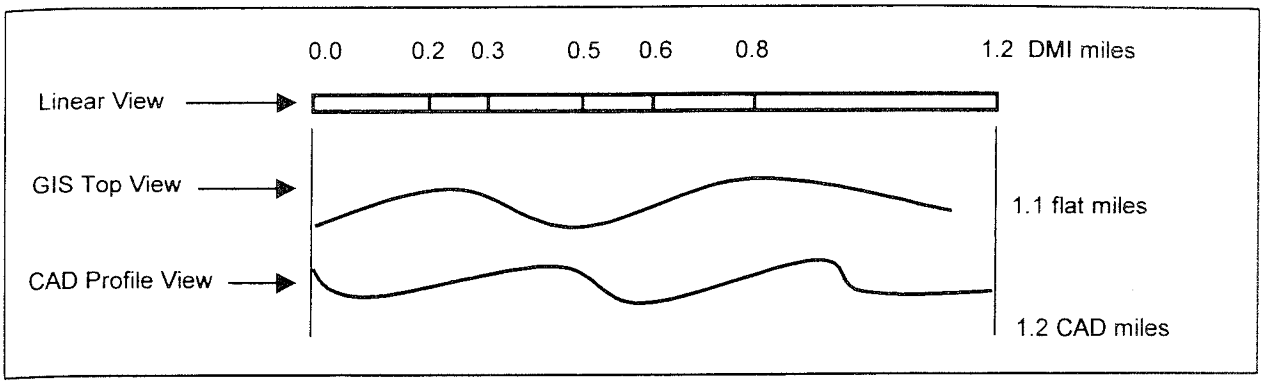


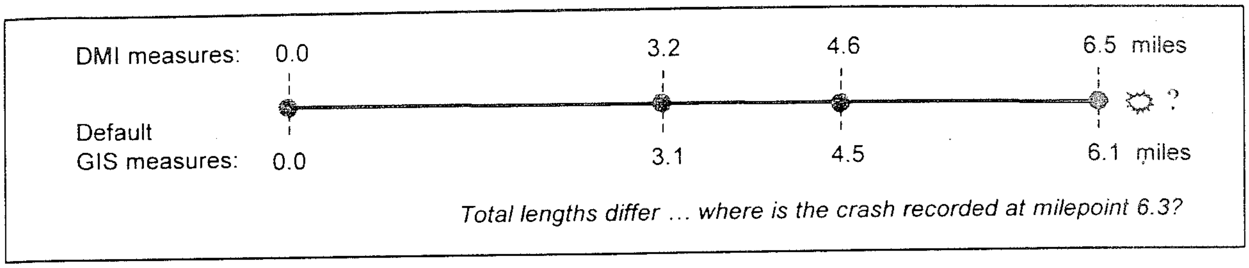
Figure 9. GIS Distance Lost to Changing Elevation

Practically speaking, transportation measures are not widely affected by this problem. For a 10% slope, the difference between horizontal and surface distance is just 0.5%. Except for in exceptionally steep terrain, the error is probably less than the error found in the original DMI measure. A greater source of error is due to GIS link lengths that have been substantially generalized from the true roadway alignment, as is the case for 1:100,000 scale data.

There are other difficulties concerning linear and geodetic measures. Take a patrol car making an accident report. Using non-differential GPS the accident may be located to no better than 300 feet. Let's assume the officer also has time on his hands and performs a skillful surveys of the accident's location to within 1 inch. Both these measures are absolute positions, and because linear referencing is a relative positioning technique, data integration is difficult. USGS 1:24,000 scale maps are accurate to about 40 feet, and so whatever accident coordinate we plot (300 ft or 1 inch accuracy), the chances the accident is going to appear on the roadbed are slim. All these issues come to play when linear and geodetic referencing are considered. Current practice in integrating these different types of measures has had limited success, given the limited accuracy of most digital base maps, yet it is adequate for many tasks. The need for greater accuracy could change, for example, when ITS-enabled vehicles require positioning accuracy at the lane-level, and thus research continues in this area.

4.2 Implementing Traversals in GIS: Coding and Calibration

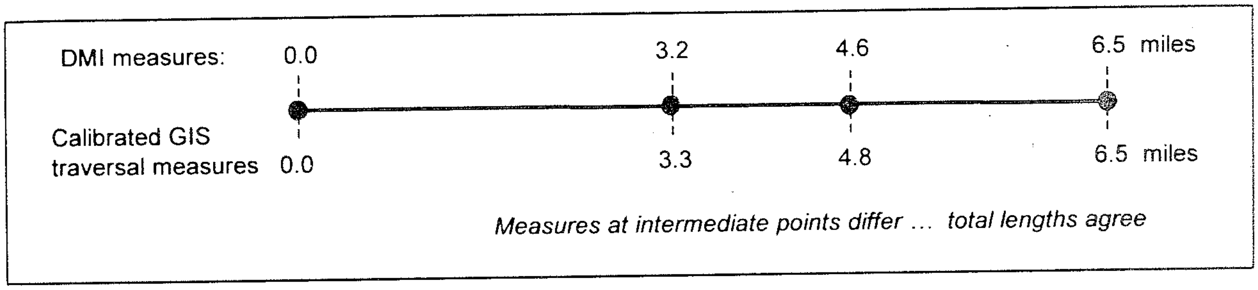
So what does this all mean? First let's consider how linear referencing is linked to GIS. The simplest technique is to define a traversal as a collection of GIS links, then associate 'begin' and 'end' measures with each node along the traversal as determined by the lengths of the GIS links. Differences between the GIS and DMI lengths are inevitable and tend to be greater the longer the traversal, as reflected in the figure below. For the figure below, a crash that occurred at milepoint 6.3 would not appear in the GIS data – it would have 'floated' right off the traversal.



Total lengths differ ... where is the crash recorded at milepoint 6.3?

Figure 10. Comparison of DMI and Default GIS Measures

A more accurate implementation of the linear measures occurs if one *calibrates* the entire GIS traversals to their known DMI mileages. Most GIS packages that support dynamic segmentation can do this automatically once the DMI measures are associated with the traversals. In the example of the figure above, the calibration would be from 0.0 at the first node to 6.5 at the last node, with linear interpolation between the two. As pictured below, although the full length now agrees with the DMI length, the interpolated intermediate measures still differ from the DMI measures.



Measures at intermediate points differ ... total lengths agree

Figure 11. Comparison of DMI and Calibrated Traversal Measures

To a large degree, this level of calibration provides suitable, basic functionality. The crash at milepoint 6.3 will now be displayed in the GIS. However, the more the GIS link distances differ from the DMI distances used by the linear LRS, the more any stationary events will tend to 'float' up and down the GIS roadway graphic. This is particularly annoying if the traversal lengths are re-measured and updated between inspection cycles, as events will float to new locations following every update (a common complaint). Most DMI measures are considered good to 1/100th of a mile (50 feet per mile). At this level of accuracy, event floating may be amusing, but functionally is not necessarily a problem.

The degree to which events float from their true locations depends mainly on the accuracy of the GIS link lengths. Floating may be greater for longer traversals, but calibration to the traversal level will mitigate this factor. Another factor is the fidelity with which the traversals have been (or can be) coded in the GIS data. For example, the GIS data may include detailed interstate interchanges with all ramps represented, whereas a legacy LRS may define a single traversal for divided highways that conceptually meet at a single point (Figure 12). The traversals may include reference points where they intersect, but it is not clear where the corresponding node should be in the GIS data. Situations like this one have motivated the refinement of legacy LRSs, or at a minimum the adoption of separate traversals for opposing travel directions on divided highways.

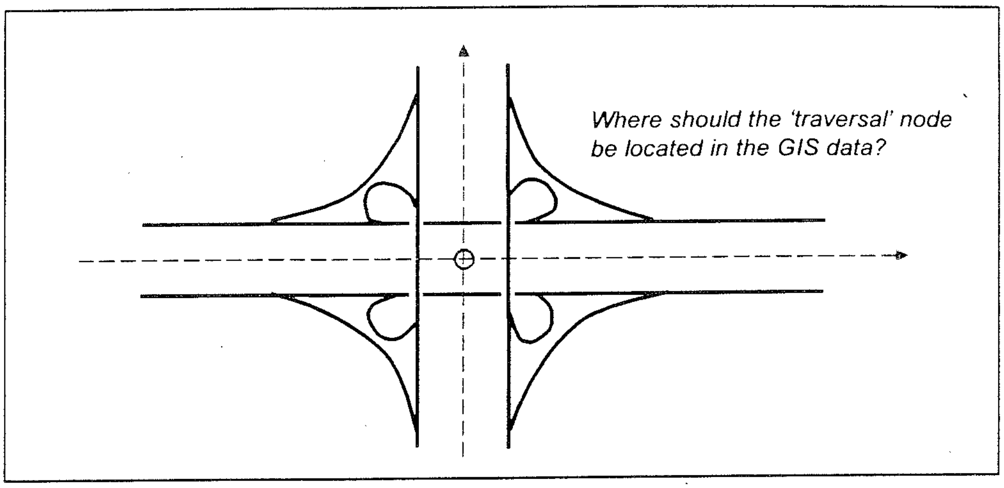
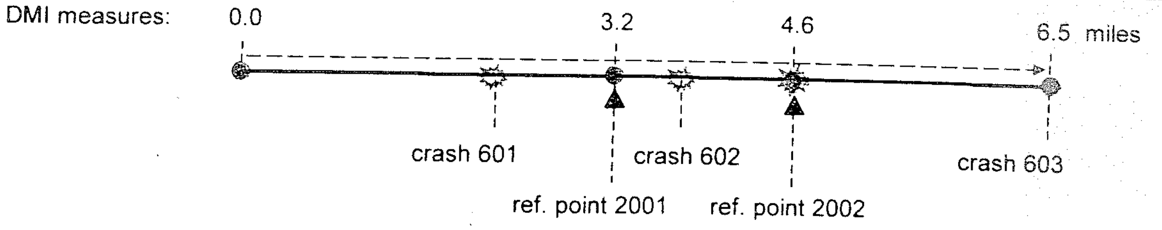


Figure 12. Interstate Interchange with Single Traversals for Divided Highways

The next level of calibration is to establish control points at intermediate nodes along each traversal, so that measures are calibrated between each pair of successive control points. This is generally a labor-intensive task, and a common practice is to establish calibration points only at major intersections and perhaps other suitable reference points (e.g., bridges and railroad crossings), at perhaps with some maximum separation. The density of control points can be increased up to the point where accuracy needs are met. Of course, the LRS must include accurate, stable measures to be used for the control points, which is not always the case. This level of calibration is likely to meet nearly all transportation data analysis needs.

One method of increasing accuracy in event locations displayed in GIS is to use a reference point method (supported by some GIS software). In this case, an event is located by an offset along a traversal from a reference point (Figure 13, below; see also section 2.3). In the GIS, each reference point is coded with its unique identifier. The lengths of the GIS links making up the traversal must also be calibrated to real-world lengths in the correct units. Generally, this is done by coding each reference point with its known measure along the traversal, and using it as a control point for calibration. Alternatively, entire traversals are only calibrated to their known lengths, and the reference points are only coded with their identifiers. In either case, there is less of a tendency for event locations to float, for even if the measures along a traversal are updated, the offsets from the reference points remain the same.



crash id	traversal id	ref. point id	offset	attribute 1	...
601	1234	2001	-1.0		
602	1234	2001	0.4		
603	1234	2002	0.0		
...	...	...	...		

Figure 13. Crashes Located by the Reference Point Method in GIS

Another method for minimizing the degree to which event locations float (and the need for calibration) is to establish relatively short control sections, each of which is a separate traversal. The PennDOT LRS, with control sections of approximately 0.5 miles each, has this advantage. Of course, calibration to a maximum distance between control points will accomplish the same purpose. (Another advantage of control sections is that fewer events need to have their locations updated when a control section is updated.)

Although not needed for the vast majority of transportation applications, even greater precision in traversal calibration can be obtained with higher-end GIS software that supports three-dimensional coordinates and calibration by 'true' one-dimensional surface length. An alternative is to associate the true surface length with each GIS link (which can be done in some GIS software by overlaying the road network layer on a digital elevation model of suitable accuracy), then to use the true surface lengths as weighting factors in the calibration between control points.

Most GIS software packages that support dynamic segmentation contain a suite of calibration tools. They tend to be imperfect in action, and may require substantial manual input and manipulation, but for the most part they are adequate for the job. If not provided by the software tools, further calibration can usually be obtained with additional custom quality control measures or manual checking.

4.3 Overview of GIS Implementation of LRS by the Case Studies

All four case studies link their linear referencing methods to their GIS by matching 'begin' and 'end' measures to the GIS equivalent to the traversal. Events do float between LRS updates to varying degrees, but none of the case study DOTs considered this to be a critical problem. However, the problem of floating events is a well established at some DOTs and is a strong motivator for LRS refinement.

A simplified view of PennDOT's manual quality control calibration business practice is shown in Figure 14. Field crews collect new DMI linear field measures during a four-year inspection cycle (Block 1). In Block 2, field measures are checked electronically in a batch process and placed into the LRS. These new measures are then extracted into a control load and entered into the GIS quality control cycle (Block 3). The GIS staff sifts through control load paper output looking for inconsistencies between the new LRS measures and GIS network distances as in Block 4. Problems are reconciled and appropriate changes made in Block 5. The ultimate quality control occurs during field use where the data are most familiar (Block 6).

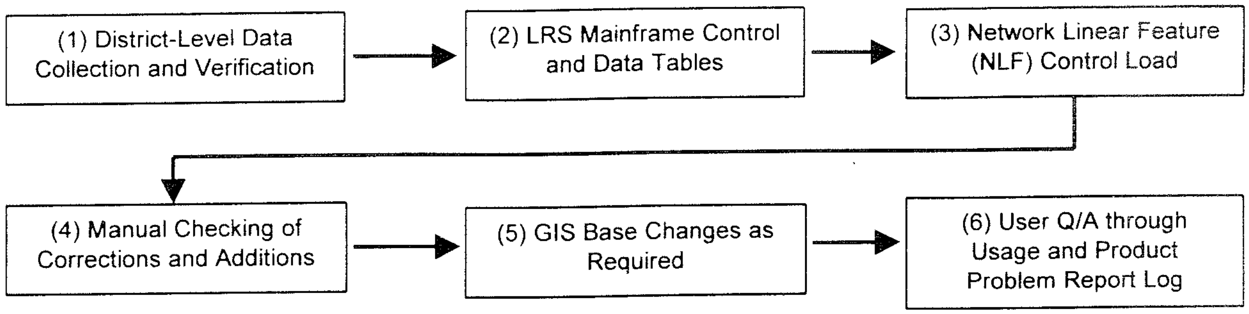


Figure 14. PennDOT's Manual Calibration Business Process

Further detail on the implementation of linear referencing in GIS by the case studies is provided along with other implementation issues in section 5.

4.4 Dynamic Versus Static Segmentation

Dynamic segmentation is a method of locating events along the traversals of a linear network with no previous segmentation of the network (Figure 2, page 15). The term is generally (but not always) associated with the application of linear referencing in GIS. In its essence, this technique uses measured offsets from fixed and known reference points to place attribute features on roadways (the essence of linear LRS). This method does not create new topological divisions (i.e., nodes) in the road network; linear events can begin and end at any points along a given traversal. Dynamic segmentation may be considered an "engine" to implement one or more linear reference schemes on a network representation.

A key advantage of dynamic segmentation is that it enables *visual network overlay* of attribute data to be performed "on the fly" by linking the GIS data to event tables stored in an RDBMS. Note that this is a *visual* overlay; overlays for query and reporting in tabular format are more complicated (discussed in section 6.4). This dynamic overlay also avoids the need to store the larger; more difficult-to-maintain, attribute tables associated with a fixed, or *static*, segmentation of the roadway. All dynamic segmentation really does is implement a linear referencing method along GIS links, and other than event "floating" due to inadequate calibration, it is the perfect tool to combine linear referencing and GIS functionality.

Under *static segmentation*, a unique data record is maintained to store a set of attributes for a single highway segment of defined location and length. There are two principal sub-classes of static segments:

1. *Fixed-length segments* are used by some transportation agencies. Highway routes are broken up into segments of an equal length small enough (e.g., 0.01 miles) so that they may be considered roughly homogeneous with respect to their attributes.

2. *Variable-length segments* are defined on the route whenever at least one of a selected set of highway attributes changes in value. The actual number of segments for a given stretch of roadway depends on the attributes contained in the table and how often each such attribute changes in value.

In general, dynamic segmentation is a more compact way of storing transportation data, and many agencies have employed this method given the benefits of linear referencing. However, some state DOTs continue to employ static segmentation with success. Static segmentation can also be useful in a data warehouse environment. As discussed in section 6.4, the data structures of dynamic segmentation may hinder the ability to perform ad hoc queries of multiple event tables.

4.5 Inconsistencies Between Linear Referencing and Network Representation

Some inconsistencies between linear referencing and network representations were introduced above, in cases where linear measures differ from computer measurement of the GIS line graphic. Generic data models for linear referencing are attempting to accommodate this problem through the use of anchor points and anchor sections (see section 7.2.1). Rather than using GIS nodes to begin and end traversals, use of known real-world positions (i.e., anchor points) have been suggested: intersections, bridges, etc. Anchor sections would connect anchor points and contain the DMI or real world distance—rather than the GIS determined line length. Dueker and Butler are also developing a model where linear LRS events may locate on more than one transportation feature (see section 7.2.3). For example, if an accident occurs at an intersection of two roads between a trolley and a bicycle path, which traversal will carry the accident? Transit route, bike route, Main Street, or Elm? At the present time, most of these issues may only be accounted for through the use of established standard operating procedures.

4.6 Conflation

One solution to the disparate data integration problem is a process called conflation. Consider two GIS network layers (e.g., road centerline coverages) that overlay but do not match up. Conflation is the process of combining two GIS networks and their respective attributes. The process is often limited to transferring attributes from one network to the other (typically with better spatial accuracy), although user-selected criteria may guide the process of merging the networks. Most often, the process is decision-intensive and requires manual supervision. In GIS networks that include traversals, the traversals and their associated information may also be combined or transferred. Conflation can therefore be used to integrate two or more linear referencing methods.

Unfortunately, once a data set has been conflated to a more accurate base map, other maps may no longer fit correctly. For example, take roadway and surface waters data developed at the same time from the same source, say USGS 1:24,000 scale maps. On the maps, bridges span streams and rivers in their 'correct' locations. Lets say this particular state DOT had recently developed a GIS roadway network accurate to 5 meters through the use of a GPS receiver (e.g., LANDGPS) mounted to their DMI van. Once attribute data from the old USGS 1:24,000 maps have been conflated to the more accurate GPS base, the bridge structures will shift away from the streams and rivers (the "bridge over the river" problem). The road base accuracy has improved while the accuracy of previously developed overlay information has not.

4.7 Case Study GIS Development and Use

At one time, accurate digital data were not readily available and personnel lacked the necessary training to efficiently build a GIS database. A great deal of digital data is now available. Further, building or upgrading map lines is possible through the attachment of differential GPS to videolog or data collection vans.

The table below compares the use of GIS between the four case studies as well as some of their applications, followed by a brief description of each case study's use of GIS.

Table 2. General Comparison of Case Study Use of GIS

Use of GIS	ITD	MoDOT	PennDOT	WSDOT
GIS used	MGE	Arc/Info	MGE	Arc/Info
Source map scale	1:100 k	1:100 k	1:24 k	1:24 k
General accuracy	Not assessed	Not assessed	40 ft	40 ft
Map source	USGS maps	TIGER	USGS maps	USGS maps
GIS used for data display & mapping	Yes	Yes	Yes	Yes
Can GIS be queried to build reports	Not in business process	In development	Yes	Yes
Point at a GIS and get a linear measure	No	In development	Yes	Yes
Quality control of GIS data	None established	Automatic process	Formal hand process	None established
Integration and analysis of different event tables	No	Through ITIS	Yes	Yes
Conversion capabilities between multiple linear referencing methods	Not needed	Yes	Not needed	Yes through MADOG
GIS integrated with videolog	No	In development	In process	Yes
Do linear LRS and GIS lengths differ?	Yes	Yes	Yes	Yes

Idaho Transportation Department: ITD uses Intergraph/MGE for a rudimentary implementation of their MACS/ROSE LRS coupled to an Informix database. The implementation was done several years ago, primarily to demonstrate the potential use of GIS. The base map has not been kept fully up to date, but is used to generate custom maps on a case-by-case basis, generally using customized data sets provided to the GIS section. Only current Segments are included in the GIS base map. The structure of effective and expiration dates for building historical traversals has not been incorporated. This has presented a few problems, such as having an accident coded in an expired Segment incorrectly displayed by the GIS along the realigned Segment.

Missouri DOT: MoDOT's GIS base map is primarily derived from TIGER data, with the geometry of divided highways, interchanges and other special features added as needed. Some centerline data have been integrated from more accurate sources (e.g., St. Louis roads based on GPS data). Routes are being coded manually and with semi-automated tools. Beginning and ending measures (based on logbooks from the 'old system') are being entered for each arc. Full quality control includes traversal calibration, roadway naming alignment following conflation, and manual spot checking. By fully integrating the GIS data with the Oracle database, the update process for the Travelways system will be simplified while assuring greater data integrity. The GIS implementation has also enabled data visualization of both legacy data and newly integrated data that was not previously possible on the enterprise scale. Current plans are for 100 GIS workstations to be rolled out to central and District offices for use with the system.

Washington State DOT: WSDOT built their GIS from rectified Microstation CAD imported into ARC/INFO. The CAD linework was cleaned, topology added, and attributes for SR ID, ARM begin and end, and direction (increasing/decreasing) attached. Traversal systems were next established using ARC/INFO MAKEROUTE. The coverages were then un-projected into geographic coordinates (latitude/longitude) at three levels – county, region and state LRSs. The MADOG application, comprising AVENUE scripts and the ArcView GUI, accesses the coverages with the routes. Point and linear event data can be referenced by the LRS, e.g., GPS data. Distribution to the Districts and Headquarter users is through ArcView.

Pennsylvania DOT: When PennDOT built their GIS, the map base was hand digitized from 1:24 k quadrangle maps. In fact the base map is synchronized with the 1:24 k USGS map series, and only after a new road actually appear on the USGS map does PennDOT formally add the roadway to their GIS. The GIS section also carries additional information on dams, hydrology, types of roadway routes, and US traffic and ramps. As a rule, the GIS data does not include ramps unless the USGS quad sheet illustrates the same. Generally, there has been little GIS need or customer demand for products with ramps illustrated. GIS section has always provided hardcopy maps of state routes and other segment information; and also made LRS available in a usable form through an ability to display data. The greatest success story followed as the district offices came online with GIS. Once the districts had full access to GIS themselves, the demands for standard products from the state GIS office dropped substantially. As a result, the GIS section could devote more time to applications development, which was also consistent with the desires of the district offices.

These overviews only briefly describe the implementation of linear referencing in GIS by the case studies. The following section addresses various implementation issues with specific reference to the case studies, including more detailed topics on their use of GIS.

5. Linear Referencing Implementation Issues

The primary goal of this Guidebook is to provide information that will aid those who are refining existing LRSs, or developing new LRSs to meet new missions or business requirements. In this section, a broad spectrum of linear referencing implementation issues is explored, largely through the experience of four state Departments of Transportation as reported through the case studies. Included in this section are issues related to:

- Coding traversal identifiers
- Use of separate traversals for each travel direction
- Special Cases for Defining Traversals (divided highways, ramps, overlapping traversals, etc.)
- Use of Mileage Equations
- Location Accuracy
- Linear Referencing for Local Roads
- Determining Location and Distance: Field and Office Practices
- Linear LRS Maintenance and Quality Control
- Management of Historical Data
- Multimodal Integration

5.1 Coding Traversal Identifiers

Section 2.4 described traversal organization schemes, the means by which traversals are defined from the underlying links of a transportation network for linear referencing. Unique identifiers (IDs) must be assigned to the traversals that can be used for referencing locations in event tables.

There are three main options for traversal identifiers:

1. A random code
2. An identifier based on the road number or name and further distinguished, as needed, by road type (mainline, spur, ramp, etc.) or political subdivision (e.g., county)
3. A combination of these, where a random code is used for data storage, but a logical road name identifier is available for data entry and reporting.

Two arguments are often made for use of a random code as a traversal ID. First, not all roads are numbered, and road names may inadvertently be entered incorrectly. Second, road numbers, names, types and political subdivisions are subject to change over time, which would consequently change the traversal ID (and perhaps the links which comprise a traversal). Any roadway attributes referencing the traversal would need to be updated to use the new ID. For a parts inventory database, this would be analogous to defining part numbers based on each part's manufacturer, and then having to change a part's number because the manufacturer changed its name. In database terms, this would be a change to a foreign key that would violate the referential integrity of the database. Thus, as the argument goes, the traversal ID should be independent of the road attributes, including its name, type and political subdivision.

Despite their advantages, random codes are difficult to use, especially for those who record the locations of events in the field or in the office. Therefore, there is a strong motivation to provide user-friendly and familiar names for traversals, with so-called 'intelligent' coding scheme. This is particularly the case where traversals are defined based on roadway numbers or names. The use of road names as external identifiers is further discussed, including institutional issues, in Dueker and Butler (1997).

Missouri DOT: The MoDOT Travelways system solves the problem of traversal identifiers by using both random and 'logical' traversal IDs. Traversals are defined by named or numbered roadways, with a corresponding logical Travelway identifier consisting of three components:

- Travelway designation (US, MO, etc.),
- Travelway name (usually the posted number or name), and
- Travelway direction (N, S, E, W, and R = reversible travel directions).

Additional identifiers may include the state name, district number, county name or city name, as needed, to assure uniqueness. For local roads (county roads and city streets), the Travelway name is the full road name. Note that direction is required since separate traversals are defined for each direction of travel (described further in section 5.2). Naming conventions for MoDOT ramps are detailed in section 5.3.2.

A unique, random number is then used as an internal identifier for each travelway to assure integrity of the physical Transportation Management System (TMS) database. If a roadway name or any other component of the traversal ID is changed, the internal identifier remains the same. A 'name history' table in the Travelways system keeps track of any changes to the traversal logical IDs. The unique internal identifier also corresponds to the traversal ('route') identifier in the GIS.

TMS on-line applications will allow users to choose travelways by selecting the logical names from lists. For data conversions and interfaces to legacy system, the legacy data must include the correct designation and names (direction can be determined/assumed as primary if the other two items are given).

Note that for external users (outside of the TMS), this system requires that the lengthy logical identifiers be used. As an alternative, systems or applications independent of TMS could make use of the same internal identifiers (and tools for their use) as provided in TMS.

Idaho Transportation Department: A traversal in the ITD LRS corresponds to a MACS/ROSE Segment, uniquely defined by a 6-digit random Segment ID. The definition of traversals becomes more complicated when historical data are considered, as will be discussed in section 5.9.

Pennsylvania DOT: PennDOT utilizes control sections which are uniquely identified by a hierarchical coding scheme, that includes a county code, State Route number and segment code. For example, section '50SR0011.S01', where:

50 = County code
SR = State Route
0011 = State Route Number
.01 = Section number.

Washington State DOT: Transportation data are stored by State Route (increasing or decreasing), Section ID and State Route Milepost (SRMP) value. Traversals are therefore defined by Sections. The State Route ID's are stored as 12 character codes comprised of a State Route number (3 digits), a 'roadway type' (2-character code for ramp, spur, etc.), and a 'roadway qualifier' (6 characters) to distinguish multiple roadway types on the same route. Together with the State Route number, these descriptors uniquely identify any piece of highway in the state. The 'roadway type' includes a direction indicator (increasing or decreasing) for selected roadway types, as shown in the table below. The roadway qualifier may be a street name, the name of a ferry ship, or a milepoint where a spur leaves a mainline, thus the traversal IDs might be subject to change if any of these values were updated.

Table 3. WSDOT Roadway Type Codes

Blank	Mainline	P1 – P9	Off ramp, increasing direction
AR	Alternate Route	Q1 – Q9 On	Ramp, increasing direction
CI	Collector-Distributor increasing	R1 – R9	Off ramp, dencreasing direction
CD	Collector-Distributor decreasing	S1 – S9	On Ramp, decreasing direction
CO	Couplet	RL	Reversible Lane
FD	Frontage Road decreasing	SP	Spur
FI	Frontage Road increasing	TB	Transitional Turnback
FS	Ferry Ship	TR	Temporary Route
FT	Ferry Terminal	UC	Under Construction
LX	Crossroad within interchange	YC	Wye-Connection
PR	Proposed Route		

Other examples: In an 'A-node B-node' link-node system, links are typically named based on the node identifiers. For example, the Maine DOT TINIS system uses 4-digit codes for nodes, then names links by concatenating the low-node and high-node numbers. Likewise, link directions are always from low-node to high-node. This creates a problem when two links connect the same two nodes, in which case they would have the same identifier. To avoid non-unique link IDs, a dummy node must be added along one of the two links (Figure 15). It is best to avoid the fragmentation of the network by such dummy nodes and the associated complications to data collection and coding.

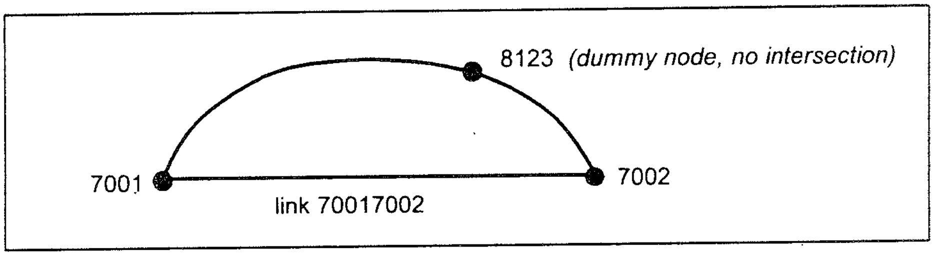


Figure 15. Dummy Node in an A-node B-node Link-node Scheme

5.2 Use of Separate Traversals for each Travel Direction

The use of separate traversals for opposing travel directions, for both divided and undivided roadways, is a major consideration for design of a linear LRS. Traditionally, each named or numbered roadway is considered a single facility, and thus a single traversal is used for the 'primary' direction of travel (often eastbound and northbound). With this traditional approach, the number of traversals would depend on the traversal organization scheme, with direction oriented as follows:

- Route-milepoint method: a single traversal might represent the entire route, eastbound or westbound, or there might be a separate traversal within each county, each oriented in the primary direction of travel.
- Control section method, there would typically be a single traversal for each control section oriented in the primary direction of travel for the associated roadway.

- With the link node method, it is less likely that the orientation of each link corresponds to a primary direction of travel.

Several problems are associated with using a single traversal for both directions of travel:

1. The opposite directions of travel may have different lengths, especially for partially or fully divided roadways (including one-way pairs).
2. Some roadway attributes and events are associated with a single direction of travel, such as 'right shoulder width', HOV lanes and the locations of crashes and signs. Although travel direction can be coded as an attribute, tying such events directly to a direction-specific travelway simplifies their retrieval.
3. Data may be collected in the non-primary direction of travel, as by a videologging vehicle, in which case the recorded mileages are not easily converted to the milepoints of the primary direction.
4. Recording of some roadway-related data, such as accident locations, is more intuitive when specified as a positive distance from an intersection (or other reference point) in a certain direction, which could be along the traversal in the desired direction (although this would not work for offsets in the wrong direction down a one-way street).
5. End users may wish to have data reported with milepoints increasing in the non-primary direction.

Of these problems, all but the first have typically found solutions that generally meet end user needs, through database coding techniques and conversion routines. However, the problem of having different lengths for opposing directions has the greatest impact on transportation data management, especially for data that are distance-sensitive such as that found in pavement management systems.

There are, of course, problems associated with using traversals for both travel directions:

1. Data entry may be more complicated for direction-specific events, for which travel direction may not have been coded in the past.
2. Determination of milepoints is more complicated in that each location on a dual-direction roadway has two milepoints, one for each direction of travel. A printed listing of milepoints might have to include milepoints for both travel directions.
3. Analysis of roadway data is more difficult where data for both directions is involved, since the correspondence between locations (milepoints) must be established for opposing travel directions.
4. When reporting information along a roadway, it may be preferable to list all roadway events in a single listing by ascending milepoints in the primary travel direction, which would require conversion of non-primary direction events to the primary direction milepoints.
5. Rules must be established to assure that roadway miles are not inadvertently double counted.
6. Rules must be established for reverse-direction lanes, for which the direction of travel changes at different times of day.
7. To aid data entry and access, automated routines may be needed to convert between milepoints in opposing directions, and to transfer selected data from one travel direction to the other.
8. While data query and access applications can be programmed to account for the nuances of dual-direction travelways, ad hoc query of a transportation database would be considerably more complicated for end-users.
9. Greater effort is required to maintain the linear LRS and the corresponding GIS data layer.

10. The linear referencing control tables and the corresponding GIS data will require nearly twice the number of traversals, which may impede data access performance (particularly for data display in the GIS).
11. Conversion to other location referencing methods is more complicated.
12. Migration from single-direction to dual-direction traversals usual requires significant changes to business practices, development of support tools and user training.

Given the complications of implementing dual-direction traversals, a common solution is to implement separate traversals for all divided highways, and for the divided portions of otherwise undivided roadways. As an option, separate traversals may be defined only for the divided portions of roadways where the difference in length between the two travel directions exceeds some tolerance.

With regard to the generic data model for linear LRS, Vonderohe et al. (1997) discuss issues of modeling bi-directional and multi-lane facilities, including the representation of such facilities by anchor sections and anchor points.

Missouri DOT: The Travelways system includes separate traversals ('travelways') for each direction of travel. The milepoints for each direction increment in the direction of travel, and may have different lengths. Southbound and eastbound directions are designated as primary, and are used to record all data that are not direction-specific. Data access and entry procedures are aided by routines to automatically provide the corresponding milepoint in the opposing travel direction (interpolating between intersections where the lengths differ). Although the MoDOT Transportation Management System is not yet in use, end users were generally looking forward to the additional functionality to be provided of dual-direction traversals, knowing that many data entry and management concerns would be addressed by the functionality of the integrated Transportation Management System.

In the field, MoDOT uses 'log books' listing the milepoints of roadway features are used to help determine event locations. The design of the log book for the new LRS has not yet been determined, and these may be more complicated than the previous single-direction log books for end users that will now need to reference locations along non-primary directions. However, this complication is offset by new functionality in the Travelways system that will enable specification of location as an offset from a known reference point.

Washington State DOT: The TRIPS system distinguishes between 'increasing' and 'decreasing' traversals for certain types of roadways (see Table 3). On these roadways, events can be referenced to the desired side of the road. The milepoints in the decreasing direction are the same as for the increasing direction, thus each point on a roadway has a single milepoint. In the GIS, a separate set of traversals (an Arc/Info route system) exists for the decreasing direction traversals.

Idaho Transportation Department: The MACS/ROSE system defines traversals only in the primary direction of travel, including for divided highways. However, there are cases where the separate directions have very different lengths, in which case different traversals ('Segments') have been created.

Pennsylvania DOT: In the PennDOT LRS, there is a traversal for each control section ('Segment'). Separate traversals (Segments) are defined for opposing travel directions on divided highways and for one-way pairs (couplets). Each segment has its own length and associated offsets, although all offsets increment in the direction of mainline travel. Undivided roadways are represented by single-direction traversals.

5.3 Special Cases for Defining Traversals

In this section, a number of special cases for defining traversals are addressed, most of which relate to the topological intricacies of the roadway network and the growing need among transportation agencies for more detailed information about the transportation network. For each special case, options for linear LRS implementation, the relationship to underlying GIS network centerlines, and the strengths and weaknesses of various options are discussed.

5.3.1. *Divided highways*

Different transportation agencies use different definitions for a 'divided' highway, and various methods are used to represent divided highways through linear referencing. Divided highways are often defined as having a median barrier, perhaps exceeding a certain width and/or length along the roadway (short medians at intersections may be excluded). The level of access control may also be taken into consideration for defining divided roadways. The methods used for representing divided roadways are often related to the format of logical identifiers for traversal and the use of separate traversals for bi-directional facilities (see sections 5.1 and 5.2).

For divided (and undivided) roadways, a principal 'mainline' direction is typically defined (for example, in the eastbound or northbound directions of travel). In the case of roadways with bi-directional traversals, this mainline direction is used for coding data that is not direction specific. If a single traversal is used for divided highways, the mainline direction is generally used for the determination of milepoints; in this case, any difference in length for the non-mainline direction of travel is ignored.

Pennsylvania DOT: A highway is considered to be divided when a median is present, or when there are three of more lanes with at least a painted divider. One segment is assigned to each direction of travel, but offset always increment in the mainline direction. Further, all segments will belong to the same State Route.

Idaho Transportation Department: The MACS/ROSE system generally does not include separate traversals for divided highways. In some cases where the non-mainline direction is of a substantially different length, a separate traversal ('Segment') has been defined, but this is not systematic. Some end users indicated a desire for more accurate length information by use of separate Segments for divided highways.

Washington State DOT: WSDOT has no set definition for a divided highway. Separate traversals are defined for each direction of travel, for many undivided as well as divided roadways.

Missouri DOT: 'Divided' highways have opposing lanes of traffic physically divided by a 4-foot or greater flush median or some form of barrier defined by the AASHTO manual. In the Travelways system, separate traversals are defined for all bi-directional roadways.

At a minimum, a linear LRS should include definition of separate traversals for divided highways, one-way pairs or other facilities where the length differs above a suitable tolerance for the different travel directions. Consideration is typically given to creating separate traversals at least for fully controlled or limited access highways.

5.3.2. *Ramps and approaches*

Highway ramps present a location reference problem because they represent a transition between two routes, and are not unambiguously a part of either of them. Where ramps are included in a linear LRS, they are typically defined as separate, independent traversals. They are usually associated with one or both of the connected routes either through the ramp naming convention or by their attributes. A standard is usually set for unambiguously locating the begin and end points of a ramp.

Table 4. Implementation of Ramps by the Case Studies

	ITD	MoDOT	PennDOT	WSDOT
Ramp traversal definition	Separate traversal for each ramp	Separate traversal for each ramp, for each direction of travel	Separate traversal ('9000' series Segments)	Separate traversal
Ramp end points	At painted gore point	The physical, permanent gore (edge of pavement), if discernible, otherwise the painted gore	Physical gore point	Point of taper
Acceleration/ deceleration lanes	Part of ramp, to end of painted line	Not part of a ramp, lanes are another travelway attribute	Part of the roadway, not the ramp	Part of the ramp
Implemented in GIS	No	Yes	Only for ramps included in the GIS data	Yes

Idaho Transportation Department: Where a ramp merges with an acceleration/deceleration lane, the end of the painted dashed line is used as the end point for the ramp. Although these locations may change when the gore is repainted, this has not been reported as a problem given the type and accuracy of data collected. Also, ramps are related by an attribute to one of the connected highways (typically, the highway with the highest functional class, or lower number within the same class).

Missouri DOT: Ramps are named based on the roadways they connect (e.g., 'Ramp 54W to 63N N'). Some roadways that appear to be 'ramps' in complex interchanges may actually carry the 'mainline' route (travelway) through the interchange. For example, in the figure below, US 63 N overlaps US 54 W and 'splits off' at the associated ramp. Therefore, the travelway 'RP US 54 W TO US 63 N N' is built along this link, but the link also carries the route for mainline US 63 N (the primary travelway).

Pennsylvania DOT: Ramps begin at the gore point in the PennDOT Roadway Management System. Acceleration and deceleration lanes are treated as an additional lane count within the State Route attribute table. However, field maintenance crews maintain the ramp area including the acceleration and deceleration lanes. Consequently, time and material allocation to ramp-related projects are somewhat perturbed, being allocated in part to a separate ramp Segment, and in part to separate lanes of another Segment. Both management and field personnel see this as a system problem, but the physical database cannot accommodate true field practice.

Washington State DOT: The Related Roadway Type discriminator (part of the traversal identifier) indicates an 'on ramp' or 'off ramp', and increasing or decreasing direction.

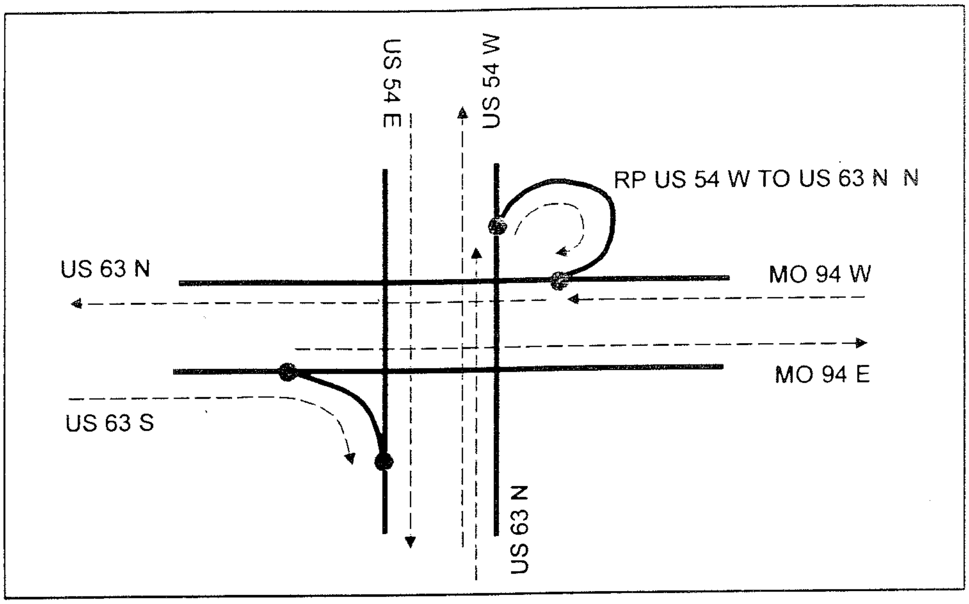


Figure 16. Ramp Names and Coding for the MoDOT Travelways System

5.3.3. *Non-contiguous traversals*

Traversals are not necessarily contiguous throughout their length, and there are several cases where this may occur depending on how traversals are defined. In cases where named routes, some transportation agencies have chosen to have a single traversal on the overlapping section. In the example in Figure 17, the traversal for Route 5 has a gap where it is overlapped by Route 27. A problem exists in this situation if the milepoints along Route 5 are continuous, in which case the two intersection nodes as pictured would have the same milepoint for Route 5. This situation should certainly be avoided, since a given traversal and milepoint should have a unique location. A preferable system is to have continuous traversals that overlap (described further in the next section).

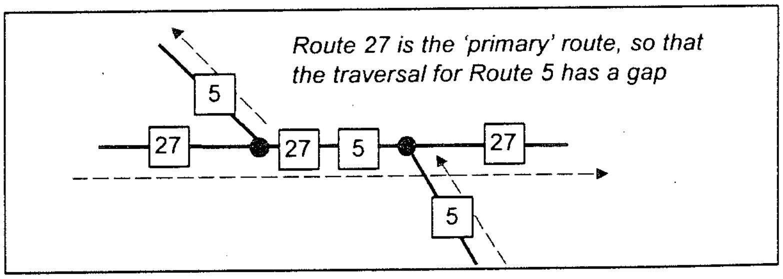


Figure 17. Gaps in Traversals for Overlapping Routes

Gaps in traversals may also occur if traversals are identified by county (or other political division), and a highway leaves and re-enters a county (Figure 18). If a single traversal is used within the county, as pictured, and the route has continuous milepoints, then the same problem occurs as for the previous example (the two nodes along the county boundary would have the same milepoint). This situation should be avoided by one of several methods:

1. Use continuous traversals which are not distinguished by county (preferable, where practical)
2. Use continuous milepoints which are not reset at county boundaries, even though the traversals are defined by county
3. Assign separate traversal names to discontinuous sections within each county (e.g., by a numeric discriminator).

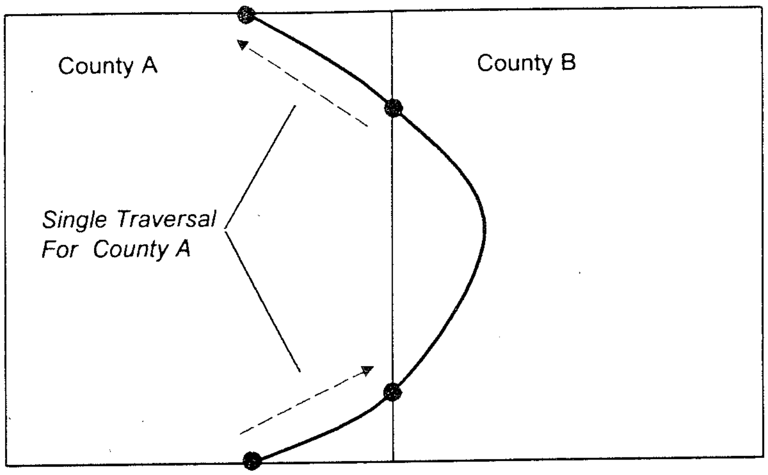


Figure 18. Gap in a Traversal that Exits and Reenters a County

Many would argue that traversals should not be defined based on political divisions (or on any other attribute of the roadway), but this becomes a practical consideration which often depends on how the data are maintained, particularly when transportation maintenance districts are responsible for recording or performing updates. The issue of non-contiguous traversals is generally not a concern for control section or link-node traversal schemes.

The case studies: MoDOT and WSDOT use continuous traversals corresponding to numbered or named roadways and which are not distinguished by county or other political division, thus they do not have non-contiguous traversals. (MoDOT currently supports a county-based route-milepoint system for compatibility with legacy practices, but the milepoints are continuous so that locations are not ambiguous). PennDOT and ITD use control sections that are always contiguous.

Regarding the capabilities of GIS, the robustness with which non-contiguous traversals are handled at present differs between the vendors' dynamic segmentation products. Over the long term, this should cease to be an issue as these packages handle such routes more intelligently.

5.3.4. Overlapping traversals

As described in the previous section, traversals may overlap one another, which is typically the case when they are defined based on numbered routes (Figure 19). When this occurs within a single linear referencing method, the location of a point on the overlapping segment may be ambiguous: which traversal is it on? Although either traversal could be used, it is much preferable for purposes of analysis and reporting to have a single method of specifying the location of any point on the network. To resolve this situation, one traversal is designated as 'primary', to which all event data are referenced for the overlapping section. The primary and alternate route designations may be indicated either on straight line diagrams, or in 'log' listings for each route.

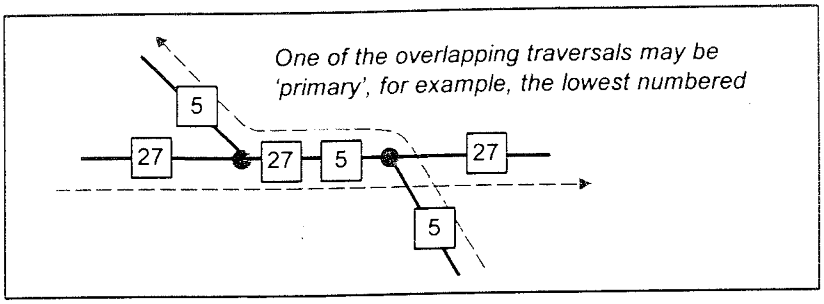


Figure 19. Overlapping Traversals

The case studies: The rules for designating the primary traversal vary between agencies. MoDOT designates the primary route by the Travelway designation (Interstate, US, etc.), then by lowest number (or letter) within each Travelway designation (undivided roadways support two traversals, one for each direction, but these are not considered to be overlapping). In Idaho, control sections are non-overlapping (for any given date). However, the MACS/ROSE system also maintains control files for the milepoints along numbered highways and these support overlapping routes for which the measures increase for both primary and alternate routes over common sections. In PennDOT it is general practice for control sections to begin and end at the points where overlaps occur, which ensures a unique 'address' at each end point. WSDOT selects a primary route by functional class, to which all event data are referenced for overlapping sections.

As mentioned, designation of a primary traversal (and a unique measure for each point on the network) is important for data analysis and reporting purposes. However, it may be very useful to enable data entry by alternate (non-primary) traversals. For example, in the Missouri DOT Transportation Management System, data loaded from another system may include event data specified along an alternate route, in which case it is automatically re-referenced to the primary route in TMS. In this way, data can be collected by familiar means based on routes as signed in the field, but the application assures data are stored by primary traversal.

Note that in the case of PennDOT, cumulative route offsets (for numbered highways) are not continuous across overlapping sections so that an alternate will have the same offset at both the beginning and end points of the overlap. If PennDOT were to enable data input by cumulative route offsets, rules would have to be established to assure that point events were not referenced to ambiguous offset locations.

Support of alternate traversals on overlapping sections can be useful for data reporting as well as for data entry. It can be useful to enable query of roadway events by any user-selected traversal (or 'route') such that the results are reported along the selected traversal, whether or not it is the primary traversal. For example, if 'snow plow' routes were defined as alternate traversals, then it would be useful to print a listing of roadway features and conditions in milepoint sequence along a snow plow route, extracting data that is referenced internally to the primary traversals. This functionality is being implemented in the Maine DOT TIDE system (currently under development).

Some systems have been developed which support alternate, overlapping traversals (or routes), but only a limited number. It is preferable that an unlimited number of alternate traversals be supported, so that additional traversals can be defined as needed for special purposes.

5.3.5. One-way pairs

A one-way pair (or 'couplet') occurs when an undivided roadway temporarily splits into two one-way sections. This presents a complication to linear referencing when a single traversal is used to represent the undivided highway and a method is needed to separately represent both one-way sections. A common solution is to use a single traversal in the mainline direction of travel, and to define a separate traversal for the one-way portion (or portions) in the opposing travel direction.

The case studies: MoDOT support separate traversals for both directions of travel on undivided roadways, thus each leg of a one-way pair is its own traversal with milepoints increasing in the direction of travel. WSDOT defines a separate traversal for the one-way section, using a separate 'couplet' roadway type as part of the traversal identifier. In Idaho, if the one-way leg is over 0.01 miles a separate Segment (and hence traversal) is created. For PennDOT, an additional control section (Segment) is created for the separate one-way section, with milepoints increasing in the mainline direction (as for divided highways).

5.3.6. Layered or tiered roadways

When two roadways are layered or tiered, one on top of the other, they can be handled like any other roadways within a given linear referencing method. If the two roadways are for opposite travel directions, as on some bridges, then they can be handled like any other divided highway. However, when the linear referencing is to be implemented in GIS, this poses a 'network pathology' (Sutton and Bespalko, 1995), where the network features are difficult to represent or display in a GIS. The tiered roadways may be presented by a single line in the GIS, in which case both traversals would be carried on the same line. This could pose a problem, however, if both traversals happened to be primary. In any case, techniques are needed to provide unambiguous data display and graphical query in the GIS environment.

The case studies: None of the case studies included specific examples of layered or tiered roadways. All would define separate traversals for each roadway.

5.3.7. Service roads

Service roads parallel one or both sides of a limited access highway and provide a buffer between the limited access and local roadways. As separate structures, these would typically be designated as separate traversals.

The case studies: ITD, MoDOT and WSDOT define a separate traversal for each service road. PennDOT would only include the service road if it were a State Route.

5.3.8. Individual lanes (including HOV lanes)

Lane-specific information is typically stored as attributes of the roadway, rather than defining separate traversals for individual lanes. This is adequate for most purposes, but may present a problem when high-occupancy vehicle (HOV) lanes are considered. HOV lanes are typically separated from other lanes by a barrier, and are often represented separately in transportation models. There are some advantages to maintaining a correspondence between the traversals in a linear LRS and the network elements of a transportation model, particular for simplifying data exchange between the two.

The case studies: For all of the case studies, separate traversals were not defined for HOV lanes.

5.3.9. *Associated facilities (truck runoff ramps, rest areas, etc.)*

Ideally, an LRS should enable location referencing within all facilities associated with the transportation network (rest areas, points of entry, truck runoff ramps, etc.). For example, an accident in a rest area would be located within the rest area, rather than on the mainline route at a point corresponding to the rest area. To provide this functionality in a linear referencing method, separate traversals would need to be defined within each such facility.

The case studies: At ITD, rest areas and points of entry (from Canada) are separately mapped at a high level of detail (for end-users), with Segments assigned for each section of roadway within each facility. PennDOT defines Segments for these special use structures (with a special '9000 series' State Route number). MoDOT will not include such facilities in Phase I of the Travelways system, but the linear referencing methods would be easily extended to account for these (with additional naming conventions). WSDOT locates such facilities as features along roadways, but does not define separate traversals within each facility.

5.3.10. *Rotaries*

The representation of a rotary within a linear LRS depends on the desired level of detail. In the past rotaries have often been represented as a point intersection, but this does not necessarily provide the desired level of detail (e.g., for a sign inventory or for maintenance work). Furthermore, this may not correspond to the detail of the GIS data. For example, consider a rotary for two intersecting highways and their corresponding traversals (Figure 20). In this case, a link of the rotary has no corresponding traversal, thus there is no way to specify locations along this link.

Where full representation of the rotary is desired, a suitable approach would be to define a separate traversal for the rotary circle, which would be the primary traversal overlapping any other roadway traversals on the rotary.

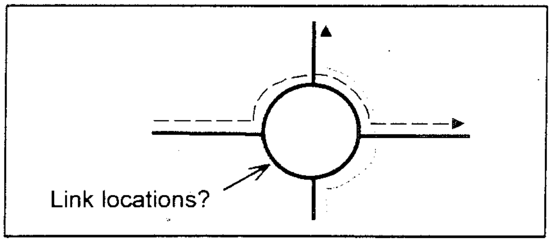


Figure 20. Rotary with Link not Accounted for

The case studies: In Idaho, in the one case where a temporary rotary was established, a single control section 'Segment' was established for the entire circle of the rotary. At MoDOT, the rotary circle could be a separate Travelway, with overlapping Travelways for each incoming roadway (the situation has not yet occurred). PennDOT handles a rotary like other intersections, with no separate control section for the rotary circle. At WSDOT, the situation has not occurred.

5.3.11. *Cul-de-sacs*

The representation of cul-de-sacs becomes an issue primarily where local roads are concerned. A cul-de-sac may be fully represented or simplified as a point, often depending on the size of the cul-de-sac and the method used to inventory the roadway. In cases where local roads are added to an existing system, the presense of a cul-de-sac may depend on the resolution of the GIS data used as a data source.

The case studies: In Idaho, Segments for cul-de-sacs may end in the middle of the cul-de-sac, or may follow the flow of traffic around it. For PennDOT none exist in the State Route system, and for WSDOT these have not been addressed.

In MoDOT, traversals are established for both directions of travel around a cul-de-sac. The southbound or eastbound direction of the cul-de-sac 'stem' is considered the primary travel direction, thus counterclockwise around the cul-de-sac is primary. For local roads, the inclusion of cul-de-sacs initially depends on the accuracy of the GIS base map, which in turn depends on the accuracy of the TIGER line work that was merged with the road network coverage by conflation.

5.3.12. Proposed roadways

Proposed roadways are often inventoried and may be included as official mileage for budget purposes. Therefore, they are typically included in roadway inventory databases and are assigned traversals and associated (approximate) milepoints. Regarding implementation in GIS, proposed roads may be included in a single road network coverage, or they may be managed in a separate coverage for convenience (as most users do not want to see proposed roads).

The case studies: For all of the case studies, traversals may be defined for proposed roadways. In the Idaho MACS/ROSE system, a record can be added for a proposed (planned) roadway, with a future effective date. The planned road will not be included in reports until after the effective date. Proposed highways have not been added to the GIS base map. PennDOT enters proposed roads as approximate ('dashed') lines in the GIS, until they appear as permanent features on the USGS quad sheets. At MoDOT, it is undecided at this time if centerlines for proposed roads will be added to the roads layer, or to a separate coverage. A 'band' may be added to the coverage for planning corridors.

5.4 Use of Mileage Equations

Historically, one of the major difficulties with linear referencing has been the problem of updating 'downstream' measures when a traversal is updated (i.e., due to a realignment or re-measurement). For example, consider the figure below in which a traversal is realigned (shortened) by 0.1 miles between milepoints 1.0 and 3.0. If the downstream measures (3.0 to 10.0) are all updated (to 2.9 to 9.9), then all references to these traversal milepoints would need to be updated, including any event tables, reference posts or reference points, log books, straight line diagrams and 'equation signs' in the field (e.g, as used by ITD). These updates can be a daunting process, especially in the past when manual methods were used.

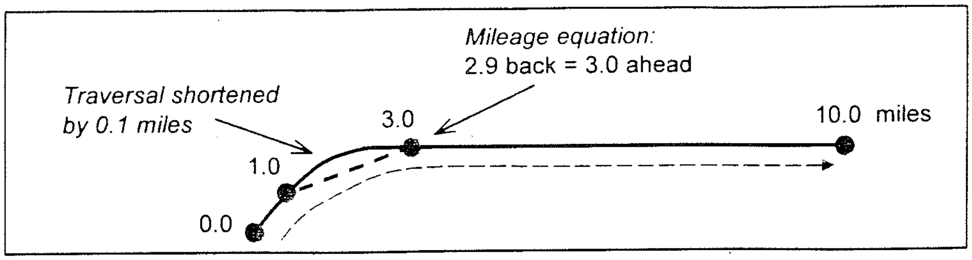


Figure 21. Updates to 'Downstream' Traversal Measures

To avoid these cascading updates, mileage equations have historically been employed so that downstream traversal measures would remain unchanged. In the above example, a mileage equation of '2.9 back = 3.0 ahead' would be established at the original milepoint 3.0. The obvious shortcoming of this system is that the milepoints are no longer continuous, and the equations must be taken into consideration for any reports or analyses based on the sequential linear measures. Another serious difficulty occurs when a traversal is lengthened, in which case a mileage equation might be '3.0 back = 2.9 ahead', a situation which leads to non-unique linear locations (a common solution is to establishing a separate traversals for the lower and upper portions, often by a naming discriminator).

Mileage equations served an important purpose in the past, when the task of updating references to traversals was overly complex. However, they are generally avoided today given the automated techniques that are now available. In fact, the Ground Transportation Subcommittee of the Federal Geographic Data Committee has recommended that mileage equations not be used in linear referencing systems (FGDC, 1994).

The case studies: Both ITD and WSDOT use mileage equations. Notably, their LRSs were created 20 and 50 years ago, respectively. At ITD, where LRS updates are common, both system managers and several end users noted problems with the complexities of mileage equations and expressed a desire to eliminate them in any future system revision. MoDOT's newly developed enterprise LRS does not use mileage equations. PennDOT does not require mileage equations, and the design of their short control sections (about 2500 feet) was in part to avoid the need for these.

5.5 Location Accuracy

Accuracy in linear referencing can be measured in several ways, particularly when GIS is taken into consideration. Consideration may be given to the accuracy of:

- 'Official' traversal lengths (named routes, control sections or links)
- 'Official' linear measures for reference points or control points
- Event offsets as measured in the field.

Note that these are all concerned with the accuracy of distances measured along traversals. These are all *linear* accuracies, where a distance or offset is always relative to a known point along a traversal.

When implementation in GIS is considered, the accuracy with which point and linear events are displayed becomes a concern. In GIS, linearly referenced locations are linked to the network lines and displayed in *geographic* coordinates, generally in 2 dimensions. The *geographic* accuracy of a feature location is measured relative to its Cartesian (x,y) coordinates. In GIS, linearly referenced data may be displayed along with other types of GIS layers, thus it becomes important that a bridge (located by linear reference) be displayed on a river (a GIS layer), and that an accident location be displayed correctly relative to an intersection.

The distinction between *linear* and *geographic* accuracy is important and sometimes overlooked. The overall accuracy with which linearly referenced data are displayed in a GIS depends on the:

- Linear accuracy of the event offsets
- Accuracy of the linear referencing control (traversal lengths, reference point offsets, etc.)
- Accuracy with which the GIS traversals have been coded and calibrated, and
- Geographic accuracy of the GIS network lines.

A GIS base map developed (with thorough quality control) from 1:24,000 scale base maps will have an accuracy of about 40 feet. However, the locations of event data displayed in the GIS may be much less accurate than this depending on the linear accuracy of the data.

Many transportation agencies have standards or guidelines for linear location accuracy. For example, all linear measures might be taken to the nearest 0.01 miles (52 feet), including traversal lengths. It is common for individual feature types to have their own accuracy requirements, and to have different linear accuracy requirements for urban and rural areas.

Idaho Transportation Department: By administrative policy, "all official roadway feature locations are maintained to the nearest 0.01 miles." If a route is re-measured and found to differ from the old length, a difference of less than 50 feet (0.01 miles) is ignored. Within the accident records system, the linear accuracy of each accident location (specified by Segment/milepoint) is assessed based on the information provided on the accident report, and the estimated "plus or minus" inaccuracy is recorded with the accident record. The accuracy with which features are displayed in GIS is poor at larger scales, but this has not been a problem as most maps are at very small scales.

Missouri DOT: Most data are currently recorded to 0.01 miles, while some (e.g., functional class) are recorded to 0.001 miles. Beginning and ending measures are being coded for each GIS link on the state system (mainly from 'old system' log books, with measures recorded to the nearest 0.01 miles). Key points (e.g., county boundaries, where overlaps start/stop, where divided facilities begin/end) are being updated to 0.001 miles. Milepoints for local roads are being determined from GIS centerline lengths.

Pennsylvania DOT: The linear measurement accuracy for PennDOT is about 40 feet. If a Segment (control section) is re-measured, there is a minimum tolerance below which the official length would not be changed, but in general practice the tolerance is ignored and user experience applied. Because the system is re-calibrated Segment by Segment, making such changes is not considered a problem.

Washington State DOT: WSDOT has a linear accuracy tolerance of 0.01 miles (52.8 feet). If a traversal is re-measured and found to differ from the old length by less than 200 feet, the length is not updated.

5.6 Linear Referencing for Local Roads

The incorporation of local roads into existing or new LRSs has become a major concern of some state DOTs and other transportation agencies. Depending on context, 'local roads' may include roads that do not fall under the state's jurisdiction, or they may include roads that do not receive federal aid. Interest in local roads is due to a number of reasons, including:

- Recording of crash locations on local roads
- Support of public transportation data
- Closer integration with local transportation planning organizations
- Maintaining an inventory of all roads receiving state aid
- Fulfillment of a general mandate to "manage the state's transportation system."

First among considerations for incorporating local roads are the development and maintenance costs. Development includes extending the linear referencing method to the local roads, and may include integrating local roads in the GIS network (by conflation) and coding the GIS network for dynamic segmentation. Maintenance considerations include how changes to the local road system will be reported or verified, and perhaps how data will be exchanged with local agencies. Where local roads are incorporated, they often have lower accuracy requirements and are less frequently updated.

Depending on the type of LRS, incorporation of local roads into an existing system can be a substantial undertaking. For example, the addition of local roads to a link-node scheme would require that many existing links be split (where they intersect local roads), creating new links in their place. All event data referenced to the old links would need to be updated to the new links. LRS design should include consideration of the impacts of and procedures for incorporating local or other roads in the future.

The case studies: In Missouri DOT, local roads are currently being integrated with the state base map by conflation of the 1995 TIGER data. As new nodes are added, their milepoints are being calibrated. Travelways are being defined on local roads based on their road names. Idaho's LRS currently includes only a few local roads, but it would accommodate local roads without modification. WSDOT and PennDOT do not include any local roads in their LRSs (PennDOT is incorporating some local roads in its GIS base map, where they are used as a backdrop).

5.7 Determining Location and Distance: Field and Office Practices

A key component of a linear LRS is the method used to determine linear locations, either in the field or in the office. Various tools and techniques are typically available to field and office staff to determine and record the locations of features and characteristics along traversals. Indeed, one measure of success for a linear LRS is the ease of data collection. A common finding of the case studies is that end-users want to be able to easily record event locations by familiar means, preferably by common roadway numbers and names as signed in the field.

5.7.1. Use of mileposts and reference posts

Physical signs are often used in the field to enable determination of linear locations. Mileposts typically display the actual mileage from the beginning of a traversal (aiding travellers as well as data collectors), while reference posts may display a code for which the corresponding offset can be determined from office records. A realignment that changes a roadway's length may necessitate changing the locations of all 'downstream' mileposts, depending on the business practices of each organization (e.g., milepost locations may be updated only if the change in length exceeds a tolerance). Some agencies have abandoned use of mileposts due to maintenance costs and development of other means for determining locations.

Pennsylvania DOT: PennDOT uses reference posts (or 'field information paddles') installed when the system was put into place in 1986. The paddles are routinely adjusted as necessary as the network evolves.

Idaho Transportation Department: Mileposts were set for major highways when the original system was implemented in 1978. The mileposts have not always been maintained in their correct locations. It is understood that the true milepoints differ from those posted in the field. However, the mileposts are useful for determining an approximate location in the 'milepost log', from which the accurate milepoints can be determined (the milepost log listing includes the correct milepoints for mileposts, for example, 'milepost 23.0' might have a milepoint of 22.962. By policy, if a milepost cannot be placed within 50 feet of its true location, it should not be installed.

Missouri DOT: Some mileposts were established long ago (mid-1960s?), mainly on interstates and US routes. These are not used in Phase 1 of the Travelways system, but they may be used as reference markers in the future (with associated accurate milepoints, as for ITD).

Washington State DOT: Mileposts are established along State Routes and are maintained by the central office. They are considered to be accurate.

5.7.2. Determination of traversal/section lengths

The case studies: WSDOT, PennDOT and ITD all relied primarily on distance measuring instruments (DMIs), such as those mounted on videolog vans, to determine the lengths of traversals or the linear offsets for and control points. Where DMI data were not available, distances could be taken from engineering design plans (although this was not preferred as design plans often differ from the 'as built'). The MoDOT Travelways system relied initially on mileage records from the legacy system for state system roads, which were generally taken for engineering stationing records. County road mileages have been based on DMI-based inventories, while local road lengths have generally been determined by the GIS centerline lengths.

5.7.3. Determination of event locations

In the course of data collection and inventory, field and office personnel use various means for determining event locations. The case studies illustrate the principal options.

Pennsylvania DOT: PennDOT is unique among the case studies in their use of Straight Line Diagrams (SLDs) as a means of showing the locations of key roadway features and their associated linear measures. The SLDs depict a great deal of information about roadway features and their locations. A substantial problem for their LRS stems from the user's interpretation of the actual SLD (particularly for elaborate intersections). The symbology is complex and different interpretations ensue based on user experience. In the field, event locations can be recorded as an offset from a referencing marker 'paddle'. DMIs are also used for determining offsets along control sections.

Idaho Transportation Department: Segment code maps are used for the state highway system by the maintenance districts. Some roadways have a complex sequence of Segments, due to the many realignments that have occurred over the past 20 years, which results in a very complex milepost log printout. Many users would prefer to be able to reference locations using common highway numbers rather than Segment codes. In the field, staff can record locations by noting the distance to nearby intersections, bridges, mileposts or other reference markers. Segment numbers and milepoints are then determined in the office using the milepost index and log for each state or federal highway.

Missouri DOT: Log books list the milepoints of static features (used as reference points) along all routes. Users will be able to record locations as an offset from a 'static' feature (the only 'static feature' available for Phase I of TMS is intersections. Future releases hope to support using the logs of other static features stored in the database such as bridge ends, signs, etc.). The use of separate Travelways for both directions of travel created additional overhead, in that much data needed to be populated in both directions. To minimize this overhead, a routine was developed to automatically transfer data from one direction to the other. End users found this method to be very effective.

Washington State DOT: Permanent physical points (e.g., a bridge), may be used as reference points for determining the distance of an event such as an accident. The bridge location has a State Route Milepoint (SRMP) and an Accumulated Route Mile (ARM) value, so the accident location can be automatically correlated with SRMP and ARM for that route. In the office, the Highway Route Log has a "feature" field that indicates attributes such as bridges, city limits, intersections, markers, etc., with the associated ARM and SRMP values. Another listing (not in the official highway log) details additional roadway attributes such as storefronts, stream crossings, driveways, hamburger stands, etc., and the associated milepoints of these features.

5.8 Linear LRS Maintenance and Quality Control

Maintenance of the linear LRS includes performing any necessary updates to the linear referencing control database and to the GIS data (these may or may not be fully integrated). An overview of various methods used to ensure the quality and integrity of the linear referencing control and GIS databases is described below for the case studies. Management of historical data is discussed in the following section (5.9).

Idaho Transportation Department: Quality assurance and control (QA/QC) is performed for some event tables within the MACS/ROSE LRS (verifying that a linear event table covers the entire network), but no routines exist to check the event tables of other operational systems. When event data are added to the MACS/ROSE system, routines verify that Segment codes are valid. The GIS base map is updated internally by the GIS Section of the Planning Division. GIS updates are not yet synchronized with updates to the mainframe LRS control tables, and only minimal QA/QC has been performed on the GIS data at this time.

Missouri DOT: The Travelways Maintenance Application (specifications completed, but to be developed) will perform updates directly in the GIS (ArcStorm or Arc/Info) and transfer the updates to the appropriate Oracle tables of the Travelways system. This process will assure full synchronization between the GIS and linear referencing control databases.

The MoDOT GIS base map is under development. Quality control does or will include full QA of routes (e.g., start and end points), assuring road names agree during conflation, spot checking, performing 'frequencies' to identify invalid codes, etc. Mismatches have been identified between field-measured and GIS lengths, but not systematically. GIS centerline lengths are compared with the county road inventory 'log mile' lengths as part of ongoing QA/QC procedures. Discrepancies between the LRS and the GIS base map coding exist, but are currently being resolved in the base map.

Washington State DOT: As for the other case studies, internal routines are used to verify LRS integrity, such as that linear events cover the entire network (where applicable), or to verify that all event traversal IDs and milepoints are valid.

A process has been developed for updating the GIS base map where a change in an accumulated route milepost (ARM) value is detected and the new value is inserted as the link attribute; the cartographer must then manually adjust the cartographic representation. The GIS base map in not kept fully synchronized with the LRS – routines have been developed to keep them reasonably synchronized, but there is some temporal disagreement between them. Random, informal "checks" are made of the GIS base map against the published road log, although no formal system for validation has been established.

Pennsylvania DOT: An LRS batch process scans all records to ensure mandatory fields are complete and to verify that all event table Segment IDs and milepoints are valid. GIS is further used to verify spatial completeness with selected plots. Maintenance procedures for the GIS data, including synchronization with LRS control tables, were described in section 4.3.

5.9 Management of Historical Data

Management of historical data is fundamental to the business of transportation agencies, because it is through analysis of trends and cumulative effects that investment into the transportation system can be optimized. Historical data management is also one of the main challenges of linear referencing, given that location is the key to data integration while location references change over time (e.g., due to realignments, re-measurements, renaming of traversals, etc.). Furthermore, updates to the LRS may be difficult to convey to separately managed, 'remote' operational data sets, due in part to reliance on remote data managers to update their own databases, and on the vertical organization of transportation systems within an agency. It is not surprising then that historical data management is often fragmented or incomplete within an LRS and that full access to and analysis of historical data is often limited.

5.9.1. Synchronization of linear LRS control and event databases

Updates to the linear LRS control database involve several different types of updates, including:

- Correction to traversal lengths or control point measures (no physical change to the network)
- Realignments (modified network, often affect 'downstream' traversal measures)
- Addition of roadways (which may extend existing traversals)
- Abandonment of roadways (which may impact portions of traversals and their measures)
- Introduction of a new node along a route (may impact an existing traversal).

Updates may occur even when there has been no physical change to the network (e.g., a correction to milepoints along a route). These updates may take place in the LRS control database, on straight line diagrams or other paper records. In addition, any updates to the LRS may require corresponding updates to any event tables that reference the updated portions, by rectifying the linear references to agree with the updated LRS control database. Alternatively, event tables may be date stamped so that they will now reference historical records in the control tables.

It is common for event tables that are integrated with LRS control files in a uniform application to be automatically rectified when updates occur to the LRS. In contrast, a problem often exists for 'remote' event tables (e.g., pavement management system, sign inventory, etc.) which are managed completely separately from the LRS control database. For these, it is not uncommon that an update to the LRS control tables is not automatically reflected in the remote database, in which case the event tables will no longer be "synchronized" with the LRS control. In this case, if the event data is linked to the current LRS as coded in a GIS base map, locations may either be displayed in incorrect locations or not displayed at all. Furthermore, any analysis involving historical data would likewise be impacted. Synchronization of LRS control and event databases is therefore a central problem for managing historical linearly referenced data.

5.9.2. *Use of periodic archives of historical data*

Various techniques have been applied for managing historical linearly referenced data with different levels of functionality. At the lowest level, users would be able to access archived "snapshots" of data related to the transportation network. This could be accomplished, for example, by saving annual or semi-annual snapshots of event data, along with the synchronized GIS network on which the LRS is implemented. Archived historical data sets enable display and overlay of historical data from different dates on a common map. As well, users can generate summary statistics for different dates, and compare those summary statistics (for example, to compare the percentage of state highways having sufficiency ratings below a given tolerance as of different dates).

However, while periodic snapshots provide basic access to historical data, this system has several limitations. First, a complete copy of the GIS network and related event tables must be stored with each dated version, although much of this data will be redundant (most of the physical network and many of the roadway characteristics are static from year to year). Second, data stored for different dates cannot easily be directly compared, road segment for road segment, since each version of event data is referenced to a different network. Visual comparison is possible by displaying data from different dates on the same map, but even this method is limited by the complexity of symbology needed to display two complete networks and their related attributes (or events). Full comparison of archived data from different dates would require that the two networks be joined by conflation, so that any linear features modified between the two dates could be identified, along with any updated measures for the linear LRS. Finally, any event data sets not stored with the periodic archive could be difficult to synchronize with a specific historical network. For these reasons, periodic archives have quite limited functionality.

5.9.3. *Enabling segment-level comparison of historical data*

A higher level of functionality would enable 'segment-level' comparative analysis of data from different points in time. With a segment-level comparison, conditions at two different times are compared along arbitrary roadway segments. This would enable queries of the type, "identify highway segments which had condition A at a given date in the past, but which now have condition B." A query of this sort requires that the system be able to compare each segment of the current network with its corresponding segment on a historical network.

Once highway segments have been classified based on how they have changed over time, they can be mapped using a single symbol to identify the degree of change. For example, maps or reports could be generated which indicate how pavement conditions have changed over the past 5 years for each highway segment (e.g., better, same, or worse). This functionality can be contrasted with the simpler system where past and present conditions are mapped together, and the user must decode the combined symbology to determine how different road sections have changed over time.

Regarding statistical analysis, a segment-level comparison (between different dates) provides much greater flexibility for reporting changes over time than is afforded by the use of archived data sets. Summary statistics generated at different points in time provide results such as, "The portion of the state highway system in 'poor' condition has decreased from 15% to 12% over the past 5 years." Additional detail can be provided by segment-level comparative analysis, such as, "Whereas 5% of state highways in poor condition were improved to acceptable levels, only 2% deteriorated from acceptable levels to poor condition." A map could then be generated highlighting those highway segments that had deteriorated or been improved.

To enable segment-level comparison, the system must be able to reference event data from different times to common linear measures along the network. Any changes made to the LRS between the dates of the two data sets must be accounted for. In a named route/milepoint system, LRS updates might include a correction to traversal measures, or a change in a traversal identifier due to a realignment in the middle of a traversal. In a link/node system, link identifiers may change as new nodes are introduced. For any type of LRS, changes to the underlying linear control elements (routes, links and/or measures) will require some sort of rectification between the event data sets in order to compare past and present conditions at the segment level.

5.9.4. Management of historical centerline alignments in GIS

In order to display historical data referenced to historical traversals, it is necessary to store the historical traversals (and alignments) in the GIS. This can be managed by storing historical traversals in a separate GIS layer, which can be combined with the current network as needed for performing historical analyses. Alternatively, all historical alignments and traversals can be stored in a unified GIS database that is fully synchronized with the linear referencing control database (or fully integrated with it). Due to the relatively recent support of linear referencing in GIS and the typical separation of GIS from other information systems functions, it is more common for the GIS data to be maintained only for the current road network. As the tools for managing linear LRS in GIS become more sophisticated, it is likely that full management of historical alignments in GIS will become more common.

5.9.5. Experience from the case studies

This section summarizes management of historical data as practiced by the case studies. A comparison of the impact of LRS updates on different linear referencing methods is provided with the general comparison of linear LRMs in section 7.

Idaho Transportation Department: Historical data is managed in ITD's MACS/ROSE system by a special type of control section uniquely identified by:

- a Segment ID
- the begin/end milepoints, and
- the effective and expiration dates.

The effective and expiration dates serve to keep track of and manage any updates to the LRS over time. Event data stored on-line in the MACS/ROSE system also has effective and expiration dates, so that historical events can be related to the correct control section. A 'Segment' may include many of these control sections, and at any given point in time each segment is completely represented by non-overlapping control sections (although historical control sections may overlap).

The definition of a traversal is complicated in the MACS/ROSE system by the way historical data is managed. A traversal may correspond to an entire 'Segment', which has unique milepoints at any point in time (although they may not be continuous). Alternatively, the traversal may correspond to a control section distinguished by effective and expiration dates. These 'control section' traversals would be required for display of historical data, whereas full 'Segment' traversals would be adequate for current data. GIS software that supports dynamic segmentation generally does not have any direct support for historical data, thus the control section effective and expiration dates would have to be incorporated as part of the traversal identifier.

Event data within the MACS/ROSE system is automatically synchronized when updates occur to the LRS (records are expired and created with new effective dates as needed). Keeping LRS updates synchronized with event databases external to the MACS/ROSE system is managed by several procedures. Notification of updates is sent to a standard list of data set managers, who must update their own data sets. Diagrams are produced for complex realignments. By administrative policy, corrections to milepoint errors shall be made once (or twice) a year during a specified month(s) so that other MACS/ROSE data users can make the necessary changes to their systems at the same time.

One problem with the current system is that it fragments the underlying segments in a way that presents difficult complexities for location reporting on time sheets. In rare cases, when updates occur to the MACS/ROSE LRS, the corresponding update is handled differently in the operational data set. This is the case, for example, with the maintenance management system database, where there is a strong desire to avoid LRS updates which complicate recording of locations for maintenance activities (required on time sheets). There is a desire to avoid representing a single route by multiple Segment codes, to minimize the number of equations used, and to avoid use of positive equations (which create overlaps and thus require use of new Segment codes). A complex update which involves creation of several new Segment control records (such as that described in section 4.9.8) might be performed in the maintenance database by maintaining a single record and putting a single equation at the end of the altered Segment. Other operational systems generally comply with MACS/ROSE update procedures, although others mentioned the issue of complexities in the update process on their operations.

ITD plans to migrate to a distributed RDBMS platform in the next two to three years. It is believed that many of these operational issues (e.g., time-sheet reporting, duplicate mileposts on routes, and equations) can be more easily and effectively dealt with once this migration is accomplished.

Missouri DOT: Historical data is fully managed in the MoDOT Travelways system such that historical conditions can be recreated for any point in time. This full management of historical data was an essential component of the information system design. The procedures have been designed and tested, but have not yet been implemented in the full Transportation Management System (TMS).

An update process has been defined and is currently in the detailed design phase. A 'Travelway Maintenance Application' will be developed to maintain the Travelways system's Oracle tables directly from the GIS, assuring that the Oracle and GIS data are fully synchronized at all times. When any element of the LRS is updated, the affected Travelway Sections and Locations are deactivated (by setting 'deactivate' date fields), and new Sections and Locations are created as needed (with 'activation' date fields set accordingly). It is envisioned that historical alignments will be stored in the GIS as well, but it has not yet been determined how the updates will be stored (e.g., combined with current alignments in a single coverage, or in a separate coverage).

A formal system for notifying users of Travelway changes will be developed, communicating the type and nature of changes made. This may include access to a browser of a Travelway Change table, enabling users to view the sequence of changes over time (by route, by District, etc.). External users might be notified of changes by e-mail, posting to a web page, or other means. Notification will be needed to make users aware of travelway changes, in case they are then required, due to business rules, to make changes to their data. However, for data stored within TMS, updates to locations (e.g., changing log units due to realignments) will be taken care of in the Travelways Maintenance procedure (to be developed).

Pennsylvania DOT: The PennDOT business procedure for historical data is set up to fully re-calibrate all data, historical or otherwise, to the relative offsets as Segments are re-measured or realigned, each and every time the LRS is updated. Consequently, the location references for all on-line event data are fully rectified to the current linear referencing control. For example, if a Segments milepoints are updated with new measures, then any events that referenced the old milepoints would be updated to reference the new milepoints. The reconstruction of historical route information is technically not designed into the system. For example, if a route is turned back to a local authority, there are no provisions to collect and preserve historical data should the route ever be returned to the state. Likewise, no historical alignments are explicitly stored in the GIS data.

The business procedures for synchronizing the GIS with the LRS are described in Figure 14, section 4.3. A well-delineated system for notification users of LRS updates is in place and considered germane to operations. Based on the information provided, end users must update their event data sets accordingly.

Historical data are available on line for five years, while other data are preserved off-line. For most foreseen business practices, most needs have been met using the existing data structure.

Washington State DOT: When updates are needed, automated procedures are used to realign the LRS based on construction contracts and other legal documents. Accumulated mileage values are adjusted from the point of realignment.

When updates occur to the LRS, TRIPS tables are automatically updated by the realignment process. However, TRIPS is updated daily whereas the LRS application in the GIS MADOG application is defined by the State Highway Log, which is published annually. Thus, the GIS coding of the LRS is up to one year behind changes in TRIPS. Historical alignments are not stored in the GIS data.

5.10 Multimodal Integration

One impediment to transportation planning is the separation of information by different transportation modes. The extension of a single linear referencing system form roadway networks to railways, waterways, airways and other modes of transportation would enable greater consistency in the management and integration of their associated databases. In particular, integration of these different modes would aid the management and analysis of transit information, which often involves transportation by multiple modes.

Conceptually, extension of linear referencing methods to other transportation networks is quite straightforward – traversals and any associated linear referencing control elements would be defined as for roadways. Not surprisingly, special rules provisions would be necessary in some cases. For example, travel by air and open water is not constrained to linear features. More practically, traversal identifiers must accommodate other transportation modes. As well, multimodal LRSs would likely include a new entity for ‘intermodal transfer point’, where passengers or goods are able to transfer between modes. However, the essential methods of linear referencing are easily applied to any linear network.

The case studies: The MoDOT Travelways system was designed to accommodate non-roadway modes of travel in the future (only roadways are supported in Phase 1). Linear referencing methods for all four case studies are readily extended for other network features. The WSDOT system would require an extended set of ‘related roadway types’ to accommodate any new modes.

6. Relevant Technologies and Applications

A variety of technologies and applications are related to or impact the use of linear referencing. Some of these technologies are compared across the case studies in the table below, followed by a brief description of each technology.

Table 5. A comparison of State DOT Incorporated Technologies

	ITD	MoDOT	PennDOT	WSDOT
GPS	no applications	incorporated with enterprise LRS	data fields added – vans being equipped	GPS – LRS translation mechanisms in place
Data log vans	mission essential	mission essential	mission essential	mission essential
Video log	mission essential	under development	under development	mission essential
Straight line diagrams	not used	not used	mission essential	not used
ITS/IVHS	no applications	urban freeway cameras for congestion monitoring	urban freeway cameras for congestion monitoring	urban freeway cameras for congestion monitoring
Data warehousing	no applications	extension of enterprise system	no applications	moderate use
RDBMS for LRS control	not used	mission essential	not used	moderate use

6.1 Global Positioning System (GPS)

The Global Positioning System (GPS) is a US Department of Defense (DOD) owned and operated radio navigation and positioning system. This $10 billion joint-service program began in 1972 following the integration of the US Navy and US Air Force radio navigation systems. GPS became fully operational on December 8, 1993 when the 24th functional satellite completed the planned constellation.

In essence, GPS receivers can provide the precise location of a point on the ground in terms of x,y,z coordinates (e.g., latitude, longitude and elevation with respect to a specific geodetic datum). Various accuracies can be attained, and sub-meter accuracy is now attainable on a regular basis.

The use of GPS is particularly relevant to linear referencing for a number of reasons:

1. The accuracy and permanency of geographic coordinates is appealing, especially given the problem of 'floating' locations in some linear LRSs that lack adequate location controls.
2. Data collection by GPS is becoming common, leading to new requirements for converting between linear references and geographic coordinates.
3. It has become economically feasible to greatly improve the accuracy of GIS road network base maps by GPS collection of roadway centerlines and other roadway features.
4. There is extensive interest among transportation agencies to improve GIS road network accuracy to enable integration with design plans and other civil engineering data.

5. Emerging technology now enables the more efficient storage and analysis of geographic coordinates in relational databases. Geographic coordinates may be stored in association with linear referencing measures to facilitate conversion between the two referencing methods.

It has been argued that the high accuracy of GPS-based methods of roadway data collection, combined with the decreasing cost of data storage, will do away with the need for linear LRS methods. However, this argument seems to neglect some of the advantages of linear referencing, such as its history of use, its appeal as a simple method for data collection and reporting, and its practicality given financial and technical constraints. The collection of roadway attributes that begin and end along commonly defined routes (or traversals) is a well established practice that enables different event data sets to be compared and integrated based on their locations. There are also difficulties in using GPS for the collection of roadway attribute data – for example, the need for a stable, highly-accurate, commonly used and updated base map and for standardized methods of GPS data collection across the agency. These requirements are usually not met in state DOTs today. In addition, while the costs of data storage are being lowered, greater volumes of data must be collected, maintained, retrieved, checked and analyzed, all of which involve greater costs. GPS data collection certainly promises to greatly improve the accuracy of transportation data, but it seems likely that GPS will enhance the functions of linear referencing rather than replacing them.

Some detailed information on the GPS is provided below to highlight the importance of newly attainable accuracies to linear and location referencing.

GPS ascertains ground position by first timing a radio signal from the satellite to the receiver to determine the line-of-sight distance between the two. Coupled to this timing signal is the estimated location of the transmitting satellite's stable position relative to the earth's center. A simple vector subtraction then yields the receiver's absolute position. Signals from four satellites are needed for a four-dimensional fix (latitude, longitude, elevation, and broadcast time).

Because the original use of GPS signals was for defense purposes, they are encrypted with the simple intent to prevent others from mimicking the signal. The military is not particularly troubled that there are a variety of techniques on the market that quickly and easily break through the encryption (e.g. cross-correlation and z-tracking techniques). The only true hindrance to civil GPS use is thus selective availability, which is the intentional degradation of a signal correction factor. When active, this limits civil use to no better than 100 meter accuracy. This degraded accuracy can be improved by comparing received GPS signals with the same received signals at a known point. An error difference is generated by subtracting the satellite's positional estimate from known position, hence the name differential GPS (DGPS). There are three forms of DGPS: Local Area Networks (1-10 meter accuracy), Wide Area Networks (0.5 meter), and baseline interferometry (sub-centimeter accuracy).

Wide Area Networks (WADGPS) are a new operating concept that will revolutionize the GPS usage, as 0.5 m accuracy without linkage to a base station will become the norm. Every state DOT should thoroughly research this technology before making GPS or data logger purchases of any type. Baseline interferometry is primarily used for survey applications. Position is not determined strictly by satellite distance determination, but rather through the statistical determination of the number of carrier wavelengths between the base and rover.

It is common to compare the thickness of a map line with its scale size across the earth's surface. Even at a scale of 1:2400, a drawn line would still be 4 feet thick on the earth's surface. When significant figures of angular measure are increased (Table 6), a relationship between map scale and GPS accuracy may be illustrated. As Wide Area Differential GPS (WADGPS) comes on-line, real-time accuracy to seven significant figures or 0.5 meters without fixed base stations will be common place. Databases built to accommodate GPS coordinates should be designed to carry these field widths.

Table 6. Significant Figures, GPS Accuracy, and Scale Map Line Thickness

Lat/Long Stored Accuracy	Distance at Earth's Surface	Approximate Map Accuracy Limit	GPS Accuracy Limit
1 °	100 (111) km		
0.01 °	1 km		
0.001 °	100 m	1:250,000	S/A on - no differential
0.0003 °	30 m	1:62,500	S/A off - no differential
0.0001 °	10 m	1:24,000	LADGPS
0.000006 °	0.6 m	1:1200	WADGPS
0.0000001 °	1.0 cm	1:25	GPS Baseline Interferometry

6.2 Videologging

Videologging, employed by some larger transportation agencies, provides a comprehensive solution for collection of data that can be sensed from specially equipped vehicles. Camera-equipped vehicles routinely drive a jurisdiction's roadway network to inventory conditions, sign locations, and other infrastructure features, all from a driver's point of view. Variations on the theme include:

- Integration of a Distance Measuring Instrument (DMI) for recording location by linear offset
- GPS and/or inertial positions tagged to each video frame
- The coupling of other instrument reading for roadway condition
- Real time addition of attributes through semi-automated data entry or voice recognition
- Precise location infrastructure through GPS-anchored laser-ranged offsets
- Digital storage for video-linking for GIS-T and ITIS applications
- The direct interface of video with straight line diagrams.

The integration of videologging with linear referencing may occur at various levels. At the simplest level, the video tape associated with any particular section of roadway is stored as a roadway attribute in the common linear LRS. At a more advanced level, video clips or individual video frames are linked to specific roadway points or segments by the linear LRS, enabling users to graphically select a point on the roadway network and view the corresponding video clip or frame.

Data collected with the videologging effort, such as pavement conditions, is typically converted from the linear measures recording during data collection to the common linear LRS for integration with other roadway attributes. During the data collection process, operators may calibrate the recorded measures by comparing the on-board DMI to previously recorded 'official' measures at each reference point along a traversal. The data collection routes often involve travel in the opposite direction of established traversals (if bi-directional traversals are not available), and data collection along fragments of traversals, thus routines are commonly developed for converting between linear locations recorded during videologging and the standard linear LRS.

Accurate and up-to-date sign inventories compiled from video logging generally pay for themselves from tort liability mitigation alone. The consolidation of multiple equipment types in the same dedicated video logging van is common practice, and substantial vendor literature is available on the Internet and from annual transportation conferences. Again, when fitting GPS to video logging equipment, the capabilities of WADGPS must be considered.

6.3 Straight Line Diagrams

Straight line diagrams (SLDs), or 'strip maps', are the central component of many document-oriented linear referencing methods, and generally avoid the costs of installing and maintaining signs in the field. These are most often computer-generated using primitive symbology, and may include diagrams of the roadway path together with symbols and annotation describing key intersections, distances and infrastructure points. SLDs may be loaded on laptop computers within data logging vans to aid direct input of infrastructure features into the system. Information from all roving data collection assets are then consolidated into a central location and merged with existing linearly referenced data.

6.4 Data Warehousing

A data warehouse is a large, integrated, centralized database providing access by user-friendly means to query and analyze an organization's information resources. Typically, a data warehouse integrates disparate operational databases into a unified system. In a transportation organization, a data warehouse might integrate various systems including roadway inventory, pavement management, safety, accident records, bridge structures, traffic management, vehicle registration records, etc. The data warehouse is typically read-only, with periodic data loads from the operational databases (as is being implemented by the Maine DOT), or it may be effectively developed in coordination with a transactional-based system where operational data are fully integrated and directly updated (as being developed with the Missouri DOT's Transportation Management System).

Location is the key to integrating disparate transportation databases. Transportation-related data are typically located by one or more linear referencing methods, and in some cases by non-linear referencing methods (e.g., Cartesian coordinates for point features). The integration of disparate transportation databases must enable users to pose queries that combine data derived from different operational databases, related through location, but often with different LRMs. Examples of such queries include:

- For a selected section of roadway (e.g., specified by the begin/end milepoints on a traversal), what roadways have an average traffic volume (AADT) of more than 5000 vehicles per day, with a pavement condition rating of 3.0 or less?
- What are the accident rates for reconstruction projects completed from 1990 to 1994, for the three year periods before and after completion of the projects?

Linear referencing poses a particular challenge to data warehousing. Linear LRS serves as the key to relating different databases, but does not readily lend itself to the relational model that is the standard for modern relational database management systems (RDBMS). SQL, the standard language for accessing relational databases, is based on set theory and the assumption that the order of rows in a table is arbitrary. However, the order of rows in a linear event table is important, being based on the sequence of milepoints along traversals (the same is true of time series data). By consequence, standard SQL does not include the functions needed for all desired operations on linearly referenced data.

As an example, consider roadway attributes along a single traversal from two event tables, as represented in the figure below:

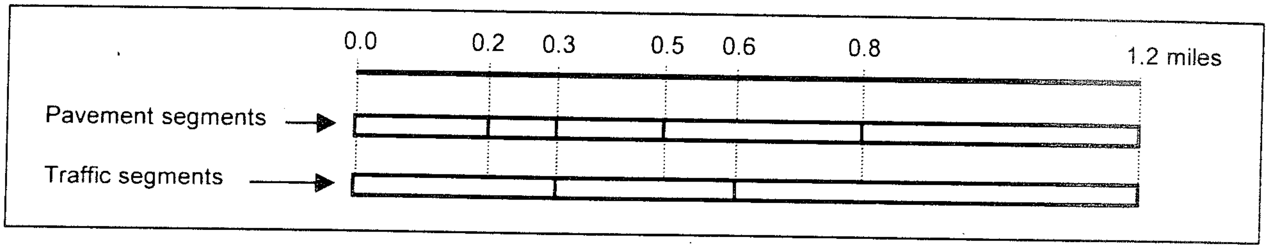


Figure 22. Sample Roadway Attribute Segments

Each segment is a length or roadway with common attribute values, for each of the respective tables. These attributes might be stored as in the sample event tables below:

Table 7. Sample Pavement Event Table

Traversal ID	Begin milepoint	End milepoint	Pavement condition	Roughness	...
123456	0.0	0.2	2.8	12.1	
123456	0.2	0.3	2.8	11.0	
123456	0.3	0.5	3.6	9.8	
123456	0.5	0.8	3.2	10.5	
123456	0.8	1.2	2.2	11.0	

Table 8. Sample Traffic Volume Event Table

Traversal ID	Begin milepoint	End milepoint	AADT 1996	AADT 1995	...
123456	0.0	0.3	5600	4800	
123456	0.3	0.6	3200	3000	
123456	0.6	1.2	6000	5800	

Now consider a query for the given traversal, from 0.0 to 1.2 miles, for a 1996 AADT of 5,000 or greater and a pavement condition of 3.0 or less. This requires the *intersection* of the two event tables, to determine where milepoints begin and end. The result set for this query would be:

Table 9. Result Set for Intersection of Sample Event Tables

Traversal ID	Begin milepoint	End milepoint	AADT 1996	Pavement Condition
123456	0.0	0.2	5600	2.8
123456	0.2	0.3	5600	2.8
123456	0.8	1.2	6000	2.2

Note that the first two records of the result set have the same attribute values, thus these two records could be *dissolved* with regard to their milepoints, as in the following table:

Table 10. Result Set with Dissolved Records

Traversal ID	Begin milepoint	End milepoint	AADT 1996	Pavement Condition
123456	0.0	0.3	5600	2.8
123456	0.8	1.2	6000	2.2

In many respects, this is precisely the sort of functionality provided by dynamic segmentation in a GIS. However, there is an important distinction. In the GIS, the overlay is performed *visually* by simultaneous display of multiple event data sets. The user must then interpret the map to ascertain which roadway segments meet the query conditions. If the user wants to see the intersected events in a new table, an event overlay operation must be separately performed, against which the query can then be posed. In contrast, the operation in a relational DBMS would perform the overlay as part of the query and produce the desired result set directly (visual display is optional).

In standard SQL, there are no operators corresponding to the *intersect* and *dissolve* functions illustrated above. In fact, the intersection of the two event tables T1 (pavement) and T2 (traffic) can be performed as in the following pseudo-SQL statement (mp = milepoint):

```
SELECT traversal _id, greatest(T1.begin_mp, T2.begin_mp), least(T1.end_mp, T2.end_mp),
           T1.pavement_condition, T2.aadt_1996
  FROM     T1, T2
  WHERE    T1.traversal_id = T2.traversal_id  AND
           T1.begin_mp < T2.end_mp  AND  T1.end_mp > T2.begin_mp
```

Although this is fairly straightforward for two event tables, extending this SQL construct to three or more event tables is an arduous task. For performing ad hoc queries, even the intersection of two event tables is too complicated for typical users. Furthermore, no such method exists in standard SQL for dissolving event records (a report can be generated that groups records by common attribute values, but would not account for any gaps in the sequence of milepoints). The problem, in essence, is that standard SQL has no method for processing records based on their order, as by comparing the end milepoint of one record with the begin milepoint of the subsequent record.

As a solution to these complications, custom applications are typically developed to perform the desired operations on event tables and to return result sets in the desired format. In addition, some vendors have provided extensions to standard SQL to perform the intersection (or union) of event tables. However, these types of extensions are usually performed separately and cannot be combined with a SQL query statement.

6.5 Spatial Data Transfer Standard

The National Spatial Data Infrastructure (NSDI) includes an initiate to forge exchange standards for geographic information. The principal result of this effort is the Spatial Data Transfer Standards (SDTS). Without such standards there are valid concerns that past investments in digital geographic data could be lost.

To divide the problem into manageable pieces, SDTS will be implemented as series of pre-defined profiles. To maximize storage, ANSI/ISO 8211 will be followed for file size reduction. The most significant profiles include:

- Topological Vector Profile (TVP) was for developed point, line, polygon, and composite vector data, including USGS Digital Line Graph (DLG) and the Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER) data files.

- Raster Profile (RP) is currently available in draft form only, but will transfer image data, digital terrain models, and other gridded data. When complete, the RP profile will facilitate USGS Digital Elevation Models (DEM) and Digital Orthophoto Quadrangles (DOQ).

- Geodetic Profiles (High Precision Point Profile or SDTS Part 6). This profile was developed by the National Oceanic and Atmospheric Administration - National Geophysical Data Center (NOAA-NGDC) and the USGS to transfer control points.

- Transportation Network Profile (TNP), developed by the Volpe National Transportation Systems Center for the US Department of Transportation (USDOT) Bureau of Transportation Statistics (BTS). Nearly all transportation data follow this profile for network-related vector data.

FGDC is also well underway in setting up LRS exchange formats, and because the establishment of viable standards is a critical path in ITS implementation, research is well established. A major center for research in this area is the Oak Ridge National Laboratories. Based on information from their World Wide Web site (Oak Ridge National Laboratories, 1997), there are three specific recommendations on ITS data transfer standards:

1. When developing an ITS spatial data interchange standard, the interchange format must take into account the special needs generated by ITS use, including international standardization, database update, metadata requirements, ITS features and attributes, and compatibility with the ITS location referencing standard. The emphasis for this will not be to create a new standard 'from scratch' but rather to make existing standards and standards under development truly useful for ITS.

2. Support development of International Standards Organization Geographic Data Format (GDF) for ITS. The ISO GDF standard will enable delivery of spatial data to all ITS customers in GDF format.

3. Implementation support and outreach. Since transfer standards by themselves transfer features, not directly usable databases, they must be tailored to meet ITS end-user needs with application-specific information on data dictionary items, recommended practices, and metadata and data quality, and usage documentation. This tailoring includes collection of this information, structuring it into useful documentation and software, and deploying it to ITS application communities.

7. Current Research in Linear Referencing

The extreme importance of linear referencing to the policies and activities of transportation agencies, coupled with the advent of GIS as a tool for integration, analysis and display of information, has prompted a great deal of research into the theory and application of linear referencing. This research has also been prompted by a number of problems commonly experienced with linear referencing, including:

- the integration of data based on different linear and location referencing methods
- the relative efficiency of different database storage schemes and access methods
- the effect of updates to the roadway network (due to realignment, re-measurement, new construction, etc.) on linearly referenced data sets
- the limitations of one-dimensional measurements as applied to real-world structures
- other related areas.

This section provides a brief overview of current research addressing these areas of concern.

7.1 Bureau of Transportation Statistics LRS in GIS CD-ROM

The Bureau of Transportation Statistics (BTS) released in 1998 a 'LRS in GIS' CD-ROM to assist state and local transportation agencies and professionals with the implementation of linear referencing systems in GIS. The CD-ROM contains about 100 scanned documents relevant to linear referencing and GIS, including many research findings. Also included are a glossary of terms (with definitions from multiple sources), and a resource guide written by BTS to provide an overview of topics on implementing LRS in GIS. Topics are linked to original source materials, and all documents are searchable by key word and author or title. More information is available directly from BTS at (202) 366-3282, on the Internet at http://www.bts.gov/gis/, or by E-mail to orders@bts.gov.

7.2 The Search for a Generic Linear Referencing Data Model

A landmark publication which spurred research in the area of linear referencing was the NCHRP Report 359, "Adaptation of Geographic Information Systems for Transportation" (Vonderohe et al., 1993). This report provides an overview of the adaptation of GIS for the management and integration of the myriad types of information used for managing and administering transportation systems and facilities (otherwise known as GIS for Transportation, or GIS-T). It includes findings of NCHRP Project 20-27, *Systems and Applications Architecture for GIS-T*, and recommends that transportation agencies develop conceptual organizing principles founded upon the notion of location as a data integrator.

A brief overview of current linear referencing data models is provided here. It is not the intent of this Guidebook to provide detailed information that can be obtained from the original sources. Practitioners of linear referencing who are involved in refining existing systems or developing new systems should be fully apprised of current research into linear referencing models.

7.2.1. NCHRP Project 20-27(2) generic linear referencing data model

A generic linear referencing data model was developed under National Cooperative Highway Research Program (NCHRP) Project 20-27(2), based primarily on the results of a workshop held in Milwaukee, Wisconsin in August, 1994. The objective of the workshop was to develop a draft consensus conceptual data model for linear referencing systems. A data model was developed in the format of an entity-relationship diagram, which describes the key elements of a linear LRS and the relationships between them. Minor refinements were made based on inputs from various sources (Vonderohe et al., 1995 and 1997).

The data model uses a single linear datum, based on anchor points and anchor sections, to associate transportation data with multiple cartographic representations and multiple network models. The datum also enables transformations between different linear referencing methods, multiple networks, and cartographic representations at various scales. The data model, at the entity-relationship level, represent requirements for a generic data model for linear referencing systems, but is not intended as a detailed specification. Much of the subsequent discussion of the model has focused on how the model should be tested or implemented.

The proposed model acknowledges that a roadway system may be represented by different cartographic representations (e.g., by different GIS layers at different scales). Likewise, many different networks may be used to model the roadway system, each with its own set of links. The model makes use of anchor points and anchor sections to establish a single datum to which all cartographic representations and network models can be referenced. Business data are not directly referenced (e.g., by milepoints) to anchor sections; instead, they are referenced to traversals, which are built upon links. Anchor points and anchor sections are further described in the glossary, and in Vonderohe et al. (1997). Some specific cases and examples of the use of anchor sections are also described in Vonderohe and Hepworth (1996).

7.2.2. GIS-T Pooled Fund Study Linear Reference Engine

As part of the GIS-T/ISTEA Management Systems Pooled Fund Study, or PFS (Fletcher, 1995), specifications and a prototype were developed for a Linear Referencing Engine (LRE). The LRE was proposed as a robust data model framework in response to perceived needs among the GIS-T community for development of a standard model that could work with different linear referencing methods. The LRE was proposed to demonstrate location transformation between multiple referencing methods. Developed using Borland's Delphi software, the LRE supported reference points, milepoints, anchor sections and traversal classes. Although the LRE successfully demonstrated the intended transformations, it did not address many of the "real world" concerns associated with linear referencing.

Phase B of the PFS included implementation of the first-draft data model developed under NCHRP 20-27(2), described above in section 7.2.1. One of the findings led to a refinement of the NCHRP generic linear referencing data model (Vonderohe et al., 1997).

7.2.3. The Dueker-Butler model

A GIS-T enterprise data model has been developed by Dueker and Butler (1997). This is a more general model than the NCHRP 20-27(2) model, in that it incorporates non-linear location referencing (e.g., by GPS), area events, more detailed cartographic entities and non-transportation features. In the paper describing the model (Dueker and Butler, 1997), an enterprise model intended to support sharing of digital roadway databases is developed in a series of steps: the basic model, adding topology, adding cartography, adding a linear datum and supporting non-transportation features. This detailed presentation is instrumental in describing the model and its intended purpose. The authors then discuss issues associated with implementing the model, including sample physical database designs.

7.2.4. *Proposed methodology for design of a linear LRS*

Vonderohe and Hepworth (1996) proposed a methodology for design of a linear LRS that will meet specific accuracy requirements. The methodology was developed from geodetic engineering principles and techniques used for designing geodetic control networks. A complete mathematical development is provided founded upon the law of propagation of random error and the statistical analyses of systems of redundant measurements.

7.3 Intelligent Transportation Systems (ITS) Locational Referencing System

The objectives of Intelligent Transportation Systems are motivating the need for seamless integration of disparate transportation data sources. ITS incorporates a broad range of technologies, but one of the key concepts is that real-time information be provided directly to the traveler to aid in navigating from point to point. Relevant information provided to the traveler would include shortest path, traffic conditions, construction projects, alternate routes, etc. These applications fall under the umbrella of Advanced Traveler Information Systems (ATIS), Advanced Passenger Transportation Systems (APTS) and Advanced Traffic Management Systems (ATMS).

A great challenge for this type of ITS is in providing location referencing information, across wide geographic areas and from different kinds of databases, by methods that can be properly interpreted and integrated by the ITS application.

Oak Ridge National Laboratory was tasked by the Federal Highway Administration to:

- review the requirements of ITS applications for spatial data and location referencing
- develop consensus positions on spatial database issues, and
- determine whether any Federal action is necessary to ensure those needs are met.

The research has recommended development of a national ITS datum, a set of nodes and links which all ITS users would have available as a standard non-planar network for referencing purposes (Goodwin, 1996; Siegel et al., 1996). The ITS datum would serve as a national network of ground control points that would anchor spatial references between different databases. Translation between different location referencing methods would be accomplished through the common ITS datum.

To work with the proposed ITS datum, the research has also proposed development of an interoperability protocol framework called the Location Reference Message Protocol, or LRMP (Goodwin, 1996; Goodwin et al., 1996; Goodwin et al., 1995). This protocol would provide a framework for standardizing location reference message formats to meet ITS needs. Multiple formats would be required to support the different kinds of location referencing that would be used by ITS applications. The LRMP is being developed under ongoing work on the ITS project.

8. Summary of Findings

This Guidebook aims to provide practitioners of linear referencing with the guidance they need to accomplish their work in a rapidly changing technical environment. The approach taken has been to combine theory with the direct experience of the four case studies, to address a multitude of issues related to the design and use of linear referencing systems. In this way, it is hoped that theory has been brought "down to earth", and current practice has been put in the context of general principles. It is also hoped that the organization of the Guidebook by topic, rather than by case study, provides a working framework for those who must evaluate either specific aspects of linear referencing or entire linear referencing systems.

8.1 The Case Studies as Models for Successful Management of Location Referencing

The four case studies provide ample experience and examples regarding the various aspects of linear referencing addressed in this Guidebook. In many cases, each DOT has its own way of dealing with a particular issue. Different solutions support different levels of functionality, and each solution has its own basis in the context of each agency's business practices.

From a broader perspective, one might ask why these four DOTs have been successful with regard to their use of linear referencing. Largely, their success can perhaps be attributed to institutional structure and support. As shown in the table below, each case study DOT assigns responsibility for managing and maintaining LRS and GIS operations to specific offices. Linear referencing poses a particular challenge to data management in that its use is generally widespread in separate offices and operational systems, yet it is subject to updates over time. Likewise, integration with other location referencing methods is increasingly important for gaining the greatest value from an agency's information resources. Effective management of an enterprise LRS requires clear recognition of the essential role of location referencing to data integration, and adequate institutional support for coordination and maintenance of the system.

Table 11. Institutional Responsibility for LRS and GIS Operations for the Case Studies

	ITD	MoDOT	PennDOT	WSDOT
Office responsible for the agency's LRS	MACS/ROSE unit of the GIS Section, Planning Division	Travelways Section, Office of Transpor-tation Management Systems	Bureau of Maintenance and Operations	Roadway Data Section, Planning and Programming Service Center
Office responsible for the agency's GIS	The GIS Section, Planning Division	GIS Section, Office of Transportation Management Systems	GIS Section, Bureau of Planning and Research	Geographic Services Office, Planning and Programming Service Center

Management of an enterprise LRS has traditionally been aligned with a central information systems office, and often with a mainframe-based roadway characteristics database. In contrast, GIS is often associated with a planning office, which may take on responsibility for implementing and maintaining the agency's linear referencing in GIS. This separation of responsibility may complicate coordination and synchronization of updates between the LRS and GIS. Although workflow practices such as those used by PennDOT (section 4.3) can be developed to address this issue, experience elsewhere has shown that this general approach is not fully reliable. For many transportation agencies, management of LRS and GIS operations will likely be more tightly integrated in the future, if not merged altogether. Indeed, operational maintenance of the LRS may be best managed by a GIS application with the benefits of its graphical interface. The Missouri DOT's Office of Transportation Management Systems exemplifies an organizational structure where a single office is responsible for managing the LRS and the GIS, as well as the operational databases by which they are used.

8.2 General Comparison of Linear Referencing Methods

While a thorough analysis of the pros and cons of different LRMs is beyond the scope of this document, some general comments are offered to highlight the potential strengths and pitfalls of the various LRMs. Different methods will always be required to meet individual needs; however, the characteristics of each must be considered prior to implementation.

Three general linear referencing methods were described in section 2.3:

- Named route/milepoint
- Control section
- Link-node.

Built upon these fundamental LRMs, many variations in the application of linear referencing are possible, as evidenced in the case studies. Some of the key issues to consider and compare when designing or refining a linear LRS include:

- Efficiency in the number of linear referencing control elements (e.g., number of traversals, number of control points, etc.) – this may impact both performance and maintenance costs
- Stability and maintainability with respect to geometry update
- Stability and maintainability with respect to attribute update
- Storage efficiency for event (attribute) data
- Ease of coordination with separately managed, linearly referenced databases
- Availability of robust, off-the-shelf supporting software tools
- Ease of transition from the current data organization and environment
- Reliance on field sign infrastructure and associated maintenance costs
- Compatibility with current work organization (e.g., preserving the relationship with current highway maintenance jurisdiction boundaries).

Linear LRSs are challenged by the problem of managing updates to the LRS and keeping various event databases synchronized with the LRS control database (see section 5.9). These problems have led to various techniques for minimizing the impact of updates to the system, including:

- Use of control section or link-node traversal organization schemes (fewer roadway sections are impacted by a localized update)
- Use of mileage equations (avoid updating of downstream measures)
- Date stamping of all LRS updates (so that event locations don't need to be rectified, but this complicates data analysis)
- Integration of event databases and LRS control in a unified application (minimize the problem of updating and synchronizing remote event database, at least for mission critical information).

Today, using automation techniques and database technologies, these problems are much more easily managed than in the past. The apparent trend today, as evidenced by Missouri DOT's integrated Transportation Management System, is to manage linear referencing by traversals based on the numbered and named roadways that are most familiar to end users. Introduction of 'intermediate' traversal schemes (such as control sections) is avoided to minimize complications in data collection, analysis and reporting procedures. Likewise, use of mileage equations is avoided as these ultimately complicate both data management and data interpretation and analysis by end users. Updates to the LRS control and to event databases (integrated and remote) are managed through automated routines, and access to historical data is provided through the system design. Conversion between different linear referencing methods is handled by the centralized system. The increased support of dynamic segmentation and management of linear referencing by GIS adds additional support for this trend.

8.3 Outlook for the Future

Linear referencing is well established as the principle means by which transportation agencies manage data related to transportation networks. However, emerging technologies, new methods of data collection and the expanding responsibilities of transportation agencies have changed the way the linear referencing is viewed and implemented. Linear referencing is now viewed as just one type of location referencing within a larger location referencing system. The implementation of linear referencing in GIS has become the norm, and full integration between linear referencing control databases and GIS has become desirable as the display and analysis of current and historical information moves from wishful thinking to a practical reality.

The design and refinement of LRSs will continue with greater sophistication to meet new objectives. Greater data integration will enable more thorough analyses to improve the decision-making process of where to best invest in the transportation network to meet various (often conflicting) needs. Linear referencing methods, as one key component of robust location referencing sysstems, will provide an essential framework for development of integrating transportation information system (ITIS), intelligent transportation systems (ITS), and related endeavors.

APPENDIX A: GLOSSARY

This glossary defines terms used in this Guidebook. Some alternative definitions are provided to assist the reader of other publications on linear referencing.

Many of the definitions refer to 'roadways' for convenience. The reader should be aware that linear referencing is not confined to roadways, but may be applied equally well to other travelways (railways, waterways, airways), utility lines, or other linear features.

The definitions in this glossary are derived from the following sources. In some cases, the definitions provided are slightly modified or simplified from the original version, so the original source should be referred to for definitive definitions. Definitions without a citation are based on common usage or compiled from a combination of sources.

[1] Baker, W., and W. Blessing, 1974, "Highway Location Reference Methods", Synthesis of Highway Practice 21, TRB, National Academy of Sciences, National Cooperative Highway Research Program (NCHRP), Washington D.C.

[2] United States Geological Survey (USGS), 1992, *Spatial Data Transfer Standard: Part 1 Logical Specifications*, Reston VA.

[3] Vonderohe, A.P., Chih-Lin Chou, Forest Sun, Teresa Adams, 1997, "A Generic Data Model for Linear Referencing Systems", *NCHRP Research Results Digest 218*, September 1997.

Anchor point. A zero-dimensional location that can be uniquely identified in the real world in such a way that its position can be determined and recovered in the field. Each anchor point has a 'location description' attribute which provides the information necessary for determining and recovering the anchor point's position in the field. Location descriptions can vary and can be quantitative, descriptive or both. An example would be the intersection of the centerlines of Oak and Maple Streets.

Anchor points can be understood as 1-dimensional control points, in that they serve the same purpose as geodetic control points in 2 and 3 dimensions (i.e., they are the fundamental objects to which all other objects are directly or indirectly tied) [3].

Anchor section. A continuous, directed, non-branching linear feature, connecting two anchor points, whose real-world length can be determined in the field. Anchor sections are directed by specifying a 'from' anchor point and a 'to' anchor point. Anchor sections have a 'distance' attribute which is the length of the anchor section measured on the ground.

Anchor sections provide the fundamental referencing space. The collection of anchor sections in a given linear referencing system is analogous to the ellipsoid surface in a geodetic datum or the map projection surface in a 2-dimensional Cartesian referencing system [3].

Control point. A point at a node along a given traversal with a known linear measure. Control points are generally used to calibrate the linear measures along traversals. The term is sometimes used synonymously with **reference point**.

Control section. A general (and ambiguous) term for a section of roadway, with well-defined end points and a known length. Control sections may be established based on consistent linear attributes (pavement type, number of lanes, etc.), but this is not required.

Dynamic segmentation. The geographic overlay and display of attributes associated with traversals, describing events (features or characteristics) along a linearly referenced network.

Event. A feature, characteristic or phenomenon that occurs along a roadway (or traversal) and is described by attributes stored in a database, including its location specified by a linear referencing method. See **point event**, **linear event**.

Linear event. A 1-dimensional event with location specified by a two linear measures along a traversal. A linear event must reference one 'start' and one 'end' reference point along the same traversal. See **event**.

Linear measure. Another term commonly used for 'traversal measure'. See **traversal measure**.

Linear referencing method. A location referencing method in which a location is specified as occurring on a uniquely identified linear feature (i.e., a traversal or link), at a set distance and direction from another point with a known linear measure (often the beginning of the traversal or link). See **location referencing method**.

Linear referencing system. A location referencing system (defined below) comprised of one or more linear referencing methods. See **location referencing system**.

Link. A 1-dimensional object that is a topological connection between two nodes [2]. In common parlance, the term 'link' often refers as well to the linear feature that connects two nodes in a GIS centerline layer. However, a clear distinction is made for data modelling, where a 'link' is simply a topological connection, and a 'line' has shape and position and can be used for cartographic representation.

Location referencing method (LRM). The technique used to identify a specific point or segment of a roadway, either in the field or in the office [1]. As cited in [2], a linear referencing method is composed of at least one traversal and at least one traversal reference point. See **traversal**, **traversal reference point**.

Location referencing system (LRS). The total set of procedures for determining and retaining a record of specific points along a roadway. The system includes the location referencing method(s) together with the procedures for storing, maintaining, and retrieving location information about points and segments on the roadways [1].

Mileage equation. An formula used to equate two linear measures at the same point along a traversal. For example, "2.06 miles back = 2.08 miles ahead." Mileage equations are used when a realignment or re-measurement has occurred, so that 'downstream' measures do not need to be adjusted. When used, the linear measures are discontinuous and may not represent true accumulated mileage along the traversal.

Milepoint. The mileage displacement from a beginning of a linear feature to any location along the linear feature [1].

Milepost. A physical entity, ordinarily a sign, placed beside a roadway and containing a number that indicates the mileage to that point from some zero point on the roadway [1].

Node. A zero-dimensional object that is a topological junction between two or more links, or an end point of a link [3, simplified].

Offset. A distance along a traversal from a point with a known linear measure (a traversal reference point). A 'milepoint' generally refers to an offset from the beginning of the traversal.

Point event. A zero-dimensional event with location specified by a single linear measure along a traversal. A point event must reference one and only one traversal reference point. See **event**.

Reference point. A fixed, identifiable feature, such as a signpost, intersection, or bridge end-point, from which a location can be measured or referenced [1]. Reference points with known linear measures (e.g., milepoints) can often be used to calibration the linear measures along traversals in a GIS, depending on the GIS software.

Reference post. A physical entity, ordinarily a sign, placed beside a roadway and containing a number that identifies the location of the post. The identification number is generally associated with the actual milepoint of the location in office records.

Route. An ambiguous term which is often used to mean (a) a numbered or named highway (or roadway) as signed in the field, (b) a traversal with associated linear measures, or (c) both of these. See **traversal**.

Section. An ambiguous term which generally refers to a section of roadway between major roadway features (e.g., intersections). In the context of dynamic segmentation in GIS, a traversal may be comprised of sections, each of which corresponds to one link or a portion of a link, directed along the link with specified from and to measures.

Segment. An ambiguous term referring to any portion of a roadway. In the context of dynamic segmentation, a segment is a length of roadway between two specified milepoints.

Travelway. A roadway, railway, waterway or airway.

Traversal. An ordered and directed, but not necessarily connected, set of links. Coding conventions are required for establishing traversal directionality and for specifying non-connected traversals [2]. The original definition in [2] specified a "set of whole links", however the term is used slightly more generally here in that a traversal is not constrained to whole links (as is the case for common GIS software). Note that the direction of a traversal along any link may be concurrent or contrary to the direction of the link.

Traversal measure. See **traversal reference point**.

Traversal reference point. A zero-dimensional location along a single traversal that is used to reference events along the traversal. Each traversal reference point has a 'traversal measure' attribute which is used to locate it along the traversal. 'Traversal measure' is an offset measured from the initial node in the traversal to the traversal reference point [3, simplified]. See **reference point**.

APPENDIX B: ANNOTATED BIBLIOGRAPHY

Baker, W., and W. Blessing, 1974, "Highway Location Reference Methods", *Synthesis of Highway Practice 21*, TRB, National Academy of Sciences, National Cooperative Highway Research Program (NCHRP), Washington D.C.

This relatively early synthesis of location referencing methods, by Blessing and Blake, provided an overview and framework of existing practices along with definitions which continue to be used today (e.g., the distinction between linear referencing methods and linear referencing systems). (23 pp. plus appendices.)

Brown, J.N., A.L. Rao and J. Baran, 1995, "Automated GIS Conflation: Coverage Update Problems and Solutions," *Proceedings*, AASHTO Symposium on GIS in Transportation, Sparks NV, April 2-5, 1995.

Problems and solutions of combining different linear networks through conflation are discussed, including the resolution of one-to-many and many-to-one relationships between linear elements, route systems, left-right oriented attributes, etc.

Dueker, K.J. and J.A. Butler, 1997, "GIS-T Enterprise Data Model with Suggested Implementation Choices," Center for Urban and Public Affair, Portland State University, Portland OR, September 10, 1997.

A number of concepts and ideas are compiled on how a state transportation agency could use an enterprise data model to implement a GIS for Transportation (GIS-T), including the enhanced integration of ISTEA management systems. A high-level GIS data model is presented, including the elements of a linear referencing system, and implementation choices are discussed. Appendices address using road names as external identifiers, relevant relational database design principles and the Transfer Standard. Available at http://www.upa.pdx.edu/CUS/. (17 pp. plus appendices.)

Dueker, K.J. and R. Vrana, 1992, "Dynamic Segmentation Revisited: A Milepoint Linear Data Model," *Journal of the Urban and Regional Information Systems Association*, Vol. 4, No.2, Fall 1992.

Describes the general concepts of linear referencing and the application of dynamic segmentation as a means of storing location information.

Federal Geographic Data Committee, 1993, "Federal Agency Needs for Ground Transportation Networks and Network Attributes," Ground Transportation Subcommittee, September 1993.

This report presents a summary of Federal agency needs for ground transportation networks, as an initial step toward the development of an overall requirements document for spatial data related to ground transportation. Requirements described in the report are limited, as they are based on responses of just 11 FGDC Ground Transportation Subcommittee members to a questionnaire. (21 pp.)

Federal Geographic Data Committee, 1994, "Position and Recommendations on Linear Referencing Systems," Ground Transportation Subcommittee, October 1, 1994.

The FGDC Ground Transportation Subcommittee recommends that (1) a standard linear LRS be included as part of any transportation network profile established under the Spatial Data Transfer Standard, and (2) that any transportation network databases developed as part of the National Spatial Data Infrastructure include, as part of their core data, all key linear LRS attribute fields. Recommendations are also given for railway and waterway linear LRSs. (8 pp.)

Federal Highway Administration, 1993, *Highway Performance Monitoring System Field Manual*, Office of Highway Information Management, FHWA Order M5600.1B, August, 1993.

Federal HPMS submission requirements include incorporation of a linear LRS for all rural arterial, urban principal arterial and National Highway System (NHS) segments included in the HPMS database. One essential requirement of the linear LRS is that any route/milepoint must specify a single, unambiguous location.

Fletcher, D.R., 1995, *GIS-T Pooled Fund Study Phase B Summary Report*, Alliance for Transportation Research, Albuquerque NM.

The summary report for the phase of the GIS-T PFS which developed the Linear Referencing Engine.

GIS/Trans, Ltd., 1994a, *A Primer for Geographic Information Systems for Transportation, Volume 1: A Review of Linear Referencing Systems.*

This document reviews and evaluates Linear Reference Methods and associated implementation issues.

GIS/Trans, Ltd., 1994b, *A Primer for Geographic Information Systems for Transportation, Volume 2: Dynamic Segmentation.*

This document describes the 'dynamic segmentation' model for implementing linear LRSs with GIS, and includes case studies from the Pennsylvania DOT and the Vermont Agency of Transportation.

GIS/Trans, Ltd., 1995, *An Object Oriented Network Data Model for Transportation GIS, Task 1 Report, Review of GIS-T Research and Development*, Principal author John Sutton, November 30, 1995.

The objective of this study was to evaluate the feasibility of utilizing an object-oriented data model for GIS-T, including analysis of LRS-related issues. The Task 1 report includes an annotated literature review, addressing GIS-T standards, data management issues and current GIS-T research initiatives. (63 pp. plus appendices.)

GIS/Trans, Ltd., 1996a, *An Object Oriented Network Data Model for Transportation GIS, Task 2 Report, GIS-T Problems and Issues Analysis*, May 30, 1996.

This report analyzes several problems and issues encountered in GIS-T network analysis (and identified in the Task 1 Report), including network definition, linear referencing methods and network conflation. A summary of the Pooled Fund Study Linear Reference Engine (LRE) is provided. In brief, the LRE is a proof-of-concept model for converting location specifications between different linear referencing methods and a datum (i.e., a reference network). The report also evaluates options for development of an object oriented GIS-T data model. (67 pp.)

GIS/Trans, Ltd., 1996b, *An Object Oriented Network Data Model for Transportation GIS, Task 3 Report, Object Oriented Feasibility Analysis*, Principal author John Sutton, May 30, 1996.

This report applies the findings of the Task 1 and Task 2 reports from a business perspective, defining strategies for product development, and reviewing market demand and product development cost considerations. (12 pp.)

Goodwin, C.W.H., 1996, "Location Referencing for ITS," white paper prepared for Oak Ridge National Laboratory, March 7, 1996.

Provides an overview of key issues related to location referencing for intelligent transportation systems. The material summarizes work to date performed by ORNL, as tasked by the FHWA, to develop consensus positions on spatial database issues. The paper presents a practical approach to standardization.

Goodwin, C.W.H., S.R. Gordon and D. Siegel, 1995, "Reinterpreting the Location Referencing Problem: A Protocol Approach," in *Proceedings*, AASHTO Symposium on GIS in Transportation, Sparks NV, April 2-5, 1995.

The ITS community has indicated a need for development of a common location referencing method to cover a majority of ITS applications. This paper discusses interoperability requirements for ITS, critiques the "common method" approach, and recommends that multiple location referencing standards be developed and specified within an interoperability protocol framework, the Location Reference Message Protocol.

Goodwin, C.W.H., D. Siegel and S.R. Gordon, 1996, "Location Referencing Messaging Protocol Preliminary Specification," working paper prepared for FHWA Office of Safety and Traffic Operations, February 29, 1996.

A preliminary specification is provided for the Location Reference Message Protocol (LRMP), an interoperability protocol for message formats for communication location reference information for ITS applications.

Hickman, C., 1995, "Feature-Based Data Models and Linear Referencing Systems: Aides to Avoid Excessive Segmentation of Network Links," *Proceedings*, AASHTO Symposium on GIS in Transportation, Sparks NV, April 2-5, 1995.

Presents a general, feature-based data model supporting linear referencing dynamic segmentation, avoiding undesired link segmentation.

Intergraph Corp., 1995, "Dynamic Segmentation Using Intergraph's MGE Segment Manager," white paper, February 22, 1995.

A brief overview of the capabilities and uses of MGE's segment manager is provided. Available at http://205.139.151.5/iss/industries/transportation/papers/mgsmwp.htm. (7 pp.)

Minnesota Department of Transportation, 1992, *Recommendations for Location Reference Systems*, prepared by the Location Data Standards Group, May 21, 1992.

This report aimed to help Mn/DOT standardize on a limited set of location reference systems, including two linear LRSs. (31 pp. plus appendices.)

Minnesota Department of Transportation, 1994, *Recommendations for Supporting and Developing Automated Translations among Location Reference Systems*, prepared by the Location Data Server Task Force, January 10, 1994.

This report contains the findings of a Location Data Server Task Force, whose mission was to examine the feasibility of developing a location translation server for performing translations between different location referencing methods. Recommendations were made for development of applications and data for translating between different location referencing methods, and for establishing the responsibility for development and maintenance of the applications and associated databases. (About 100 pp.)

Nyerges, T.L., 1990, "Locational Referencing and Highway Segmentation in a Geographic Information System," ITE Journal, March 1990.

Nyerges, Tim, 1994, "Frameworks for Describing and Evaluating Linear Referencing Systems and Linear Data Models," unpublished draft, University of Washington, Dept. of Geography, July 15, 1994.

Data model structure issues for linear LRSs are discussed, including many literature references. A suggested terminology is given for linear LRSs and LDMs, and a framework (made up of largely key questions) is provided for evaluating linear LRSs and LDMs. Entity-relationship diagrams are presented for several optional data model structures.

Oak Ridge National Laboratories, 1997, “Spatial Dataset Transfer Standards and ITS,” ORNL Spatial Data Interoperability Project Site (http://itsdeployment.prg.utk.edu/spatial/).

Okunieff, Paula, David Siegel, Qingwen Miao, Stephen Gordon, 1995, “Location Referencing Methods for Intelligent Transportation Systems (ITS) User Services: Recommended Approach,” *Proceedings*, AASHTO Symposium on GIS in Transportation, Sparks, NV, April 2-5, 1995.

This paper discusses five location referencing methods and strategies for their implementation, then examines components common to the methods and discusses how they form the basis of a set of standards for a location referencing system for ITS user services. The system permits multiple location referencing methods and coding schemes to operate within a single framework. (16 pp.)

O’Neill, W.A. and E.A. Harper, “Linear Location Referencing within GIS,” *Proceedings*, 1997 ESRI Arc/Info User Conference.

Describes use of an ArcView application for translating between different referencing methods for the Utah Department of Transportation. Available at http://www.esri.com/base/common/userconf/archive.html.

Ries, Tom, 1993, “Design Requirements for Location as a Foundation for Transportation Information Systems,” *Proceedings*, AASHTO Symposium on GIS in Transportation, Portland OR, March 1993.

Information strategy planning efforts at the Wisconsin DOT are described, with emphasis on Location Control Management, a business area identified as needing further analysis in their Information Strategy Plan of 1991. The paper concludes that location has three logically interdependent levels: Geodetic, Geographic and Linear, and proposes that implementing these levels will allow more flexibility in managing location for meeting their business needs. In particular, a link-node LRS is proposed as a potential neutral LRS which could be developed and used for translating between other LRSs already in use. (19 pp.)

Rowell, R., 1996, “Theory and Practice in Linear Referencing at the Idaho Transportation Department,” *Proceedings*, AASHTO Symposium on GIS in Transportation, Kansas City MO, March 31-April 4, 1996.

Describes, in general terms, ITD’s linear referencing system, which includes management of historical data by date stamping location references.

Scarponcini, P., 1994, *Location Data Modeling Effort Final Report*, prepared for Minnesota Department of Transportation, Graphic Data Systems Corporation.

A detailed location data model is described and presented as a series of entity-relationship diagrams. The process for developing the data model is also described. (23 pp. plus appendices.)

Scarponcini, P., 1995, “A Method for Determining a Standard Linear Reference Scheme,” *Proceedings*, AASHTO Symposium on GIS in Transportation, Sparks, NV, April 2-5, 1995.

This paper details work performed for the Minnesota DOT to determine a standard linear referencing scheme, with the ultimate goal of arriving at a unified definition of location. Although a simplified definition of location was achieved, the paper explains why a single definition of location was not possible. Road segments were defined as viewed by different data users, including ‘simple’, ‘directed’, ‘detached’, ‘laned’, and ‘component’ road segments. A comprehensive linear LRS bibliography is included. (22 pp.)

Siegel, D., S. Gordon, C.W.H. Goodwin, 1996, "The ITS Datum Preliminary Data Structure and Content," working paper prepared for Oak Ridge National Laboratory, February 25, 1996.

This working paper describes the ITS datum, a set of nodes and links which all ITS users would have available as a standard non-planar network for referencing purposes. Associated file formats are described.

Sutton, J. and S. Bespalko, 1995, *Network Pathologies: Phase 1 Report*, Sandia National Laboratories Transportation Systems Analysis GIS Project, Document No. AH-2266, prepared by GIS/Trans, Ltd., October 31, 1995.

This paper provides examples of network pathologies, or situations where the network feature is difficult to represent in the GIS due to topology and/or connectivity constraints. (31 p3p.)

United States Geological Survey (USGS), 1992, *Spatial Data Transfer Standard: Part 1 Logical Specifications*, Reston VA.

Includes standardized terminology for linear features in a GIS network.

Vonderohe, A.P., Chih-Lin Chou, Forest Sun, Teresa Adams (University of Wisconsin – Madison), 1995, "Results of a Workshop on a Generic Data Model for Linear Referencing Systems," *Proceedings*, AASHTO Symposium on GIS in Transportation, Sparks, NV, April 2-5, 1995.

This paper is a second and final draft report on the above-named workshop. See the final report in Vonderohe et al (1997), below, which includes some revisions to the consensus data model. (34 pp.)

Vonderohe, A.P., Chih-Lin Chou, Forest Sun, Teresa Adams (University of Wisconsin – Madison), 1997, "A Generic Data Model for Linear Referencing Systems", *NCHRP Research Results Digest 218*, September 1997.

This paper is the final report on the above-named workshop. A consensus location referencing data model is described, which resulted from a workshop attended by 42 transportation professionals in August, 1994. The data model, in object modeling form, associated transportation data with multiple cartographic representations and network models through a single linear datum. Issues where consensus was reached are described, as well as remaining significant points of contention. Supported by the NCHRP Project 20-27(2). (24pp.)

Vonderohe, A.P., L. Travis, R.L. Smith and V. Tsai, 1993, "Adaptation of Geographic Information Systems for Transportation," *NCHRP Report 359*, TRB, National Research Council, Washington DC.

Findings of NCHRP Project 20-27, including recommendations that transportation agencies develop conceptual organizing principles founded upon the notion of location as a data integrator.

Vonderohe, A.P. and T.D. Hepworth, 1996, "A Methodology for Design of a Linear Referencing System for Surface Transportation, Final Report," Project AT-4567, Sandia National Laboratories.

This final report proposes a methodology for design of a linear LRS that will meet specific accuracy requirements. The methodology was developed from geodetic engineering principles and techniques used for designing geodetic control networks. A complete mathematical development is provided founded upon the law of propagation of random error and the statistical analyses of systems of redundant measurements. (83 pp.)

APPENDIX C: CASE STUDY QUESTIONNAIRE

FHWA Linear Referencing Practitioners Guidebook

LINEAR REFERENCING CASE STUDY QUESTIONNAIRE

June 1997

Brief Overview

➧ *Provides a brief, introductory overview, highlighting key points of the system and areas of particular interest to the reader. This will likely be completed after compilation of the questionnaire.*

1. Persons Interviewed

   ➧ *Record the name and position of each person interviewed. For each person, ask how he/she uses linear referencing, what experience he/she has, who else would be important to talk to about linear referencing, etc.*

2. Organizational Information

   2.1. What office is responsible for development and maintenance of the agency's linear referencing systems? Describe its responsibilities.

   2.2. What office is responsible for coordinating GIS activities? Describe its responsibilities.

3. Overview of Current Use of Linear Referencing

   3.1. Can you name and briefly describe each of the linear referencing systems currently in use in your agency?
   ➧ *Note: it's important to get the "name" by which each LRS will be referenced Detailed descriptions come in the next section.*

   3.2. We'll go over each of the LRSs in detail, but what are the major issues you face, as a department, with regard to linear referencing?
   ➧ *For example: managing updates to the LRS and historical data, integration of data using different LRSs, integration with GPS and other data types, implementation in GIS, development of referencing systems for local roads, etc.*

   3.3. What formal process, if any, was used for development of your linear referencing system(s), e.g., Information Engineering?

   3.4. Describe any current initiatives you have for revising / expanding your linear (and location) referencing.

   3.5. Do you have any standards or other documentation on your agency's linear (or location) referencing strategy and systems? ➧ *Request copies of any available documentation.*

4. Detailed Description of Each LRS

Repeat this section as needed for each LRS in use by the Agency

4.1. General overview

4.1.1. How is this LRS referred to (its "name")?

4.1.2. What type of LRS is this (route/milepoint, link/node, control section, etc.) .

4.1.3. Briefly describe how the LRS is managed (e.g., computer application, hardware/software, etc.).

4.1.4. What documentation describes this LRS (obtain copies)?

4.1.5. What documentation exists for end-users, on how to determine and record locations, standard database fields, etc.?

4.1.6. How long has this LRS been in use?

4.1.7. Has it undergone any major revisions? If so, explain.

4.1.8. Whose responsibility is it to maintain and update the LRS, and to assure correct use of the LRS?

4.1.9. Do you have any plans or contingencies for converting to metric?

4.2. Use of this LRS

4.2.1. Who in this agency uses this LRS (e.g., what management systems), and what information is referenced to this LRS:

____ General roadway characteristics system
____ Traffic management (counts, volumes, etc.)
____ Congestion management
____ Accidents
____ Bridges
____ Pavement management
____ Highway / work program development
____ Project monitoring system
____ Engineering / design
____ Construction management
____ HPMS
____ Sign inventory

____ Right-of-way
____ Videolog
____ Permit routing
____ Maintenance
____ Local road inventory
____ Rail (crossings, etc.)
____ Air / aviation
____ Public transportation
____ Other: ____________
____
____
____

4.2.2. What end-user applications (GIS or other) make use of this LRS (work program development, etc.)?

4.2.3. To what degree is this LRS used and/or maintained and updated by DOT district offices?

4.3. Route definition, coding, resolution

4.3.1. How are routes defined? What roadway sections make up a route, and how are start and end points determined?

4.3.2. To which roadways does this LRS apply (state system, county, other public roads, etc.)? ➡ *Note: specific cases like ramps and service roads are dealt with below.*

4.3.3. How are the route IDs coded? ➡ *Note: be specific concerning the meaning of individual characters and codes, the use of leading zeros, justification within the field, etc. Any documentation?*

4.3.4. How many individual routes are there (approx.)?

4.4. Linear Referencing System control

LRS control files (or tables, or diagrams) define the key components which control the LRS, and the *relationships between them. LRS control elements may include routes, links, control points, mileage equations or other components. Data tables (or event tables) are not part of the LRS control.*

4.4.1. What documentation describes the LRS control files (or tables, diagrams, etc.)?

4.4.2. Describe the control files used to manage the LRS (or reference the documentation).

4.4.3. Are mileage equations used? If so, describe their use and function.

4.4.4. Describe any other tables that comprise the LRS database, and the database structure.

4.4.5. What are the strengths and weaknesses of the LRS control database?

4.5. Field practices / data collection

4.5.1. Are mileposts or reference posts (i.e., signs) used in the field? ___ Yes ___ No If so:

a) When were they established?

b) Have they been maintained, and are there any maintenance issues?

c) Are they considered to be accurate?

d) Is there any estimate of maintenance costs?

4.5.2. How are 'correct' route lengths determined in the field (e.g., use of DMIs)?

4.5.3. What "centerline" is used to determine road length (e.g., right lane)?

4.5.4. Where exactly are the start and end points of routes (e.g., within an intersection)?

4.5.5. How are the measures (the "locations") of point and linear events determined:

a) in the field (e.g., mileposts or reference posts)?

b) in the office (e.g., Straight Line Diagrams, 'route log' or 'log mile' listings, or computer applications)? ➨ *Note: if possible, get a sample SLD*

4.5.6. If Straight Line Diagrams are used:

a) do they have route IDs on them (e.g., as used in the LRS control database)?

b) do they have milepoints on them?

4.5.7. What problems or issues are there in the field (or office) for those using the LRS for their data collection?

4.5.8. What are your standards (or practices) for linear measurement accuracy (e.g., accuracy tolerance in urban/rural areas, accuracy for different feature types, etc.)?

4.5.9. If a route is re-measured and found to differ from the old length, is there a tolerance below which the official length is left unchanged?

4.5.10. Other?

4.6. GIS implementation (if implemented)

4.6.1. What GIS software is currently used?

4.6.2. What process was used to "implement" this LRS using GIS?

4.6.3. Have all roads handled by the LRS been implemented in GIS?

4.6.4. Describe the GIS base map (centerline file) used:

a) Original source of centerlines:

b) Scale:

c) Development process:

d) Accuracy/quality:

e) Other:

4.6.5. Quality control of the GIS base map:

a) What quality control has been done on the LRS implementation in the GIS base map?

b) Have mismatches been identified between field-measured lengths and GIS lengths?

c) Are there discrepancies between the LRS and the coding in the GIS base map (e.g., differences in section lengths, problems with interchange alignments, etc.)?

4.6.6. GIS base map update procedures:

a) What update procedures are used for the GIS base map?

b) Is the GIS base map kept synchronized with the LRS (e.g., if the linear measures for a route are updated in a relational database)? If so, what procedures are used?

4.6.7. If local roads (some or all) are included, describe:

a) Source of the local roads centerlines:

b) How local road centerlines were integrated:

c) How local roads (and their routes) are updated and maintained:

d) Other:

4.6.8. To what degree have the measures in the GIS been calibrated?

4.6.9. How accurate (or inaccurate) are the locations of features as displayed in the GIS? Is this a problem?

4.6.10. How is linear referencing currently being used in the GIS:

____ Data display/mapping
____ Database query (e.g., select a location or road section on the map and get a report)
____ Determination of linear measures (e.g., to specify crash locations)
____ Automated data input (e.g., including graphic specification of locations)
____ Other custom applications (construction project information, work program, etc.)
____ Quality control of data
____ Integration and analysis of different event tables (e.g., identify accidents associated with specific pavement conditions)
____ To convert between different LRSs (➡ *Note: LRS conversion does not require GIS, but a GIS application is often used*)
____ Other:

4.6.11. What (other) issues or problems have there been with the GIS implementation?

4.6.12. What have been the (other) major benefits and successes of the GIS implementation?

4.7. Special roadway cases
How does your LRS (and GIS base map) handle each of the following special cases:

4.7.1. Divided highways

a) How are attribute locations specified along the separate travel ways (e.g., an accident which occurs in the north-bound lane)?

b) If divided highways are not specially handled, are there problems due to the separate travel ways having somewhat different lengths/measures?

c) If divided highways are specially handled in the LRS, what constitutes a 'divided highway'? (E.g., only highways with full access control? Highways with a certain type of median?)

d) Are routes defined for separate travel ways? If so, how are the measures determined, and are they correlated between the different travel directions?

4.7.2. Ramps

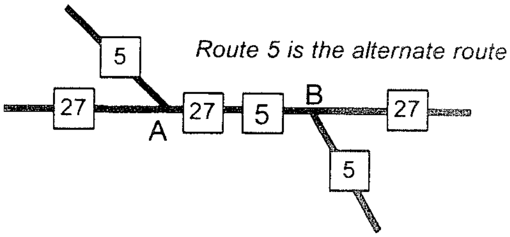
a) Are ramps included in the LRS?

b) Where do the measures for a ramp begin (e.g., at the gore point)?

c) Are acceleration/deceleration lanes considered to be part of a ramp?

4.7.3. Approaches (at intersections, including ramp intersections).
➧ *Especially, how is a 'Y' intersection handled? Is a separate route defined for one of the legs?*

4.7.4. Alternate or overlapping routes



a) For the case illustrated at right, does the LRS use coincident routes (measures increase for both routes along the common section), or is there a gap for the alternate route?

b) Are multiple road/route name aliases supported for alternate routes?

c) If a 'primary' route is designated, how is it selected?

d) Are attributes (events) along the common section associated with only the primary route, or can they be associated with either route?

e) Suppose there is a gap for the alternate route. For example, suppose the measures for route 5 stop at 2.5 miles at point A, then continue from 2.5 miles at point B. In this case, the location 'milepoint 2.5 on route 5' would be ambiguous, existing at 2 places (points A and B). Is this the case for this LRS? ____ Yes ____ No If so:

1) Has this posed any problems for you (e.g., is it possible for an accident at point A to be ambiguously located at '2.5 miles along route 5)?

2) If there are such gaps, do these potentially cause problems for analysis, such as for identifying high accident locations? For example, could a high accident location along route 5 span both legs, thus including two separate intersections?

4.7.5. If your routes are defined by county (or other jurisdiction), what happens when a route exits and reenters a county? Are there ambiguous measures (as there can be for a route with a spatial gap)?

4.7.6. One-way pairs (i.e., where a road divides into 2 one-way sections of different length)

a) If a separate route is defined for one leg of a one-way pair, what criteria determine if the leg is to become a separate route?

b) Are there any route ID coding conventions?

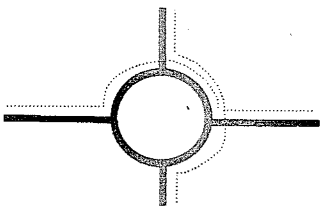
4.7.7. If local roads are included, are there any special accuracy or maintenance considerations?

4.7.8. Layered or tiered roads (e.g., a 2-level bridge).

4.7.9. Service roads (which parallel a limited access highway).

4.7.10. Individual lanes (including HOV lanes).

4.7.11. Associated facilities (truck runoff ramps, rest areas, emergency U-turns, etc.).



4.7.12. Rotaries: how is the situation illustrated at right addressed, where a portion of a rotary doesn't belong to any of the intersecting routes?

4.7.13. Cul-de-sacs: is a standard direction (clockwise or counterclockwise) used for determining the direction of increasing measures?

4.7.14. Proposed highways: if measures are assigned, how are these integrated with the base map?

4.7.15. Locations of offset features (i.e., perpendicular offset from a route).

4.8. Attribute storage schemes

4.8.1. Is there a major, centralized "roadway characteristics" database? If so, what is it called?

4.8.2. Are event tables 'linearly normalized', 'linearly denormalized', or a hybrid?

4.8.3. Are any QA/QC procedures used to:

a) verify that a linear event table covers the entire network? For example, every section of roadway falls under a single jurisdiction; is there a routine to assure the 'jurisdiction' event table covers all roadways in the system?

b) verify that all event route IDs and milepoints are valid?

c) verify point events are not coded at ambiguous milepoints (i.e., at discontinuous routes that have continuous measures?
d) other?

4.8.4. Are there any barriers to database query or analysis associated with the database structure?

4.9. Updates to the LRS and management of historical data

4.9.1. Briefly, what process is used to update the LRS (not the GIS data), due to reconstruction, new construction, abandonments, re-measurements, etc.?

4.9.2. Is there a system for tracking updates to the LRS over time? How are updates recorded?

4.9.3. Is there a system for notifying end users of updates to the LRS, so their event tables can be updated?

4.9.4. Are routes and/or events time stamped? ___ Yes ___ No If so, describe what the time stamps refer to (data entry data, effective/expiration dates, etc.), and how they are used.

4.9.5. Are historical alignments (and/or routes) stored:

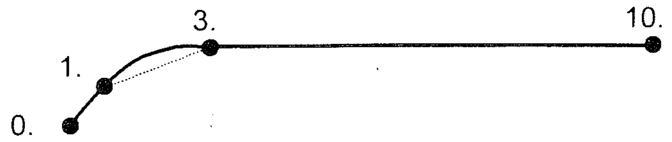
a) in the LRS?

b) In the GIS data?

4.9.6. Are there procedures for comparing the records of an event table to assure that events are 'synchronized' with the current LRS (i.e., to identify any records that reference routes or portions of routes which have been updated)?

4.9.7. Are there procedures for keeping updates to the GIS network synchronized with updates to the LRS?

4.9.8. Consider a specific example, a realignment with reduction in route length. Suppose that a reconstruction project between milepoints 1.0 and 3.0 of a 10.0-mile route eliminates 0.1 miles from the route.



a) How are the route IDs modified?

b) How are the measures (and/or routes) updated along the full length of the original route (e.g., does the original section from 0.2 to 10.0 miles now measure from 0.1 to 9.9 miles)?

c) Are field markers updated (with new measures)?

d) For on-line event tables (in the centralized "roadway characteristics" database), are the measures for events referenced to the updated route updated accordingly? If so, is the process automated or manual?

e) How are updates handled for event tables other than in the centralized database (i.e., used by different divisions)?

4.9.9. Procedures used for other types of updates. Using the questions posed above under 4.9.8 as a model, how are each of the following cases updated in the LRS, with regards to the route IDs, measures, field markers, storage of historical data, etc.

a) Roadway realignment with increase in length (any difference from the update process for a reduction in length, as in 4.9.8?):

b) Change to the route identifier (e.g., if highway jurisdiction changes from state to county):

c) Correction to route measures without any change to the roadway alignment (e.g., due to re-measurement in the field):

d) Addition of a new roadway (and route):

e) Addition of a new portion to an existing route, and the end or beginning of the route:

f) Deletion of an entire roadway/route:

g) Deletion of a portion of a route, from the beginning, middle or end of the route:

h) Creation of a new node (e.g., due to addition of a new road), in the middle of a route, with a newly-determined measure:

4.9.10. What needs do you see for managing historical data, which are not currently being met?

5. HPMS Submission

5.1. Have you developed a separate or modified LRS to meet HPMS submission requirements? If so, please elaborate.

6. Data Integration

6.1. Data transfer between information systems

6.1.1. Consider a roadway characteristic such as Average Annual Daily Traffic (AADT), which is typically used by many information systems. When new AADTs are determined, how are the new values transferred to other information systems (e.g., traffic modeling, bridges, railroad crossings, etc.)?

6.2. Integration of different LRSs

6.2.1. To what degree are your multiple LRSs integrated?

a) Are you able to translate measures from one LRS to another? For which LRSs?

b) Are you able to map features using different LRSs?

c) Are you able to perform queries with custom applications, drawing from data sets using different LRSs?

d) Are you able to perform ad hoc queries, from data sets using different LRSs?

6.2.2. What major problems and/or successes have you had integrating data located by different LRSs?

6.3. Integration with GPS and other geographically referenced data

6.3.1. Are you integrating GPS data with linearly referenced data? If so, please elaborate.

6.3.2. Does your GIS base map have link attributes? If so, what are the attributes, and how are these integrated with linearly referenced data?

6.3.3. Are you integrating linearly referenced data with any point or polygon data (e.g., for any specific projects)?

7. Use of Related Technologies

7.1. Describe any GPS activities related to linear referencing, such as:

7.1.1. Refinement of the LRS measures?

7.1.2. Refinement of the GIS base map?

7.1.3. Resolution of discrepancies between the LRS and GIS base map?

7.1.4. Data collection?

7.2. Describe any use of video logging, and the use of linear or other referencing systems for locating video footage.

7.3. Describe any use of other technologies related to linear referencing:

7.3.1. Data warehousing:

7.3.2. Intelligent transportation systems (ITS):

7.3.3. Other:

8. Relationship to Other Modes of Transportation

8.1. Are you considering the use of linear referencing to support other modes of transportation, such as for supporting analysis and modeling of transit information?

APPENDIX D: ITIS Workshop Flyer

The Linear Referencing Practitioners Guidebook was conceived largely to support FHWA ITIS Workshop, in the interest of presenting the broader role of information technology in today's transportation agency. The flyer below describes the workshop.

INSERT ITIS FLYER HERE

INSERT ITIS FLYER HERE

APPENDIX E: ITIS Workshop Frequently Asked Questions