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Highway Data Management in ArcGIS®

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Highway Data Management in ArcGIS

An Esri White Paper

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Introduction

Esri is in the software development phase of creating a new highway data management solution. This document presents a vision of how that solution will help highway departments more easily exchange information between users and systems, overcoming the challenges of maintaining and integrating both spatial and nonspatial data that is broadly distributed throughout an agency.

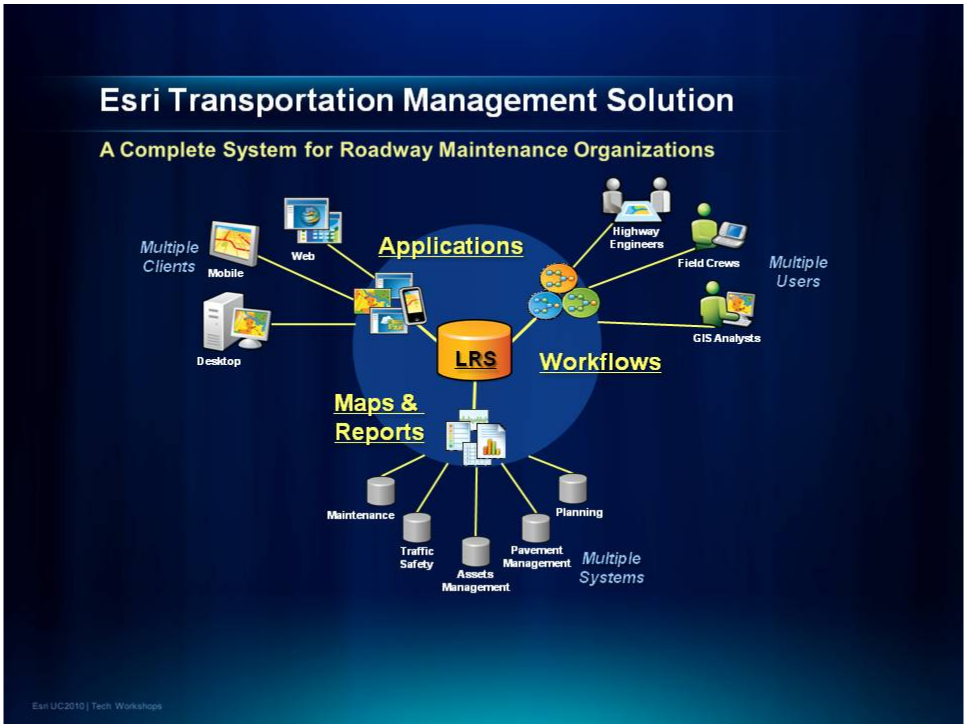
Highway departments manage and maintain a broad spectrum of information about their highways. This information is generally distributed throughout the agency, and each dataset is often maintained in its own separate system. Furthermore, these datasets might each relate to the highway in a different way. The public safety group, for example, might maintain crash data based on mileposts located along the highway. The pavement group, on the other hand, may locate pavement sections based on measurements taken from the point where the highway intersects a maintenance district and measured using a distance measuring instrument (DMI).

Any given highway department might have dozens of these datasets, each maintained in a separate system, many with their own methods for referencing locations along the highway. This can create significant problems when different groups within the agency need to access data maintained by other groups. Esri's highway data management solution is a multitiered approach that attacks the problem at three levels:

- Workflow
- Applications
- Maps and reports

The implementation of an integrated information and systems framework based on industry best practices and standards is an effective way to support the exchange and integration of information across business units within a transportation organization. This approach can facilitate interoperability between component systems and across business units by leveraging existing data and establishing improved processes to gather, maintain, and analyze that data. Utilizing this approach will also allow agencies with limited budgets to achieve the maximum potential from existing systems and initiatives while leaving the basic purpose and structure of each component system intact.

Figure 1
Esri Transportation Management Solution



Workflows support a wide variety of users from data collection crews to GIS analysts to maintenance crews in the field.

Applications support multiple clients through desktop, Web, and mobile implementations.

Maps and reports can be generated that leverage data from disparate datasets across multiple systems.

Prerequisites

This is an entry-level white paper targeted at highway department field supervisors, highway engineers, and geographic information system (GIS) analysts who manage and interact with highway data. The reader should have a cursory understanding of GIS and a high-level understanding of highway information.

Linear Referencing

Although most highway departments implement GIS on some level, most highway data is located along the highway through a linear referencing system (LRS). Linear referencing is a location method that uses a distance along the highway from a known starting point to locate assets. Linear referencing can be thought of as a nontraditional addressing method where the combination of a measure value, such as a milepost number, and a highway number represent the street address. In this manner, assets can be quickly located along the highway by simply identifying the highway number and moving up or down the highway until you come to the appropriate milepost. Assets that represent a single location are located using a single measure value. Assets that begin at one location along the highway and end at another are located using a from and a to measure value.

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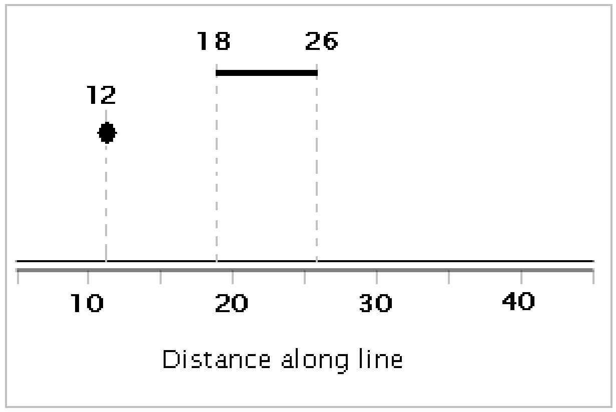
Figure 2
Linearly Referenced Asset Locations



Esri Transportation Model

The highway data management solution leverages Esri's transportation data model as described in *Designing Geodatabases for Transportation* by J. Alison Butler. The schema for the Esri® transportation model can be found at the ArcGIS® Resource Center downloads page.

The Esri transportation model is a reasonably comprehensive data structure that implements many key elements of highway information and proposes both a maintenance model and a publication model. There are only a handful of concepts required by the highway data management solution; however, the following are most relevant:

- A single line feature class stores the highway geometry.

- Segment-level attributes are stored in a Segment table apart from the geometry.

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Figure 3
Centerline Segment Relationships

Simple feature class
Centerline

Geometry *Polyline*
Contains M values *No*
Contains Z values *No*

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length
OBJECTID	Object ID						
Shape	Geometry	Yes					
RecordDate	Date	Yes			0	0	8
RecordStatus	Short integer	Yes		dRecordCode	0		
EntityStatus	Short integer	Yes		dEntityCode	0		
FromDate	Date	Yes			0	0	8
ToDate	Date	Yes			0	0	8
Comment	String	Yes					100
RoadwayID	String	Yes					12
Shape_Length	Double	Yes			0	0	

Relationship class
CenterlinesHaveSegments

Type *Simple*
Cardinality *One to one*
Notification *None*
Forward label *Centerline*
Backward label *Segment*

Origin feature class	Destination table
Name *Centerline* Primary key *RoadwayID* Foreign key *RoadwayID*	Name *Segment*

No relationship rules defined.

Table
Segment

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length
OBJECTID	Object ID						
RecordDate	Date	Yes			0	0	8
RecordStatus	Short integer	Yes		dRecordCode	0		
EntityStatus	Short integer	Yes		dEntityCode	0		
FromDate	Date	Yes			0	0	8
ToDate	Date	Yes			0	0	8
Comment	String	Yes					100
CountyID	Long integer	Yes			0		
SegmentID	Long integer	Yes			0		
RoadwayID	Long integer	Yes			0		
RCLink	String	Yes					10

- Route definitions have a many-to-many relationship with segments.
- The relationship between routes and segments is maintained through a separate SegmentSequence table.

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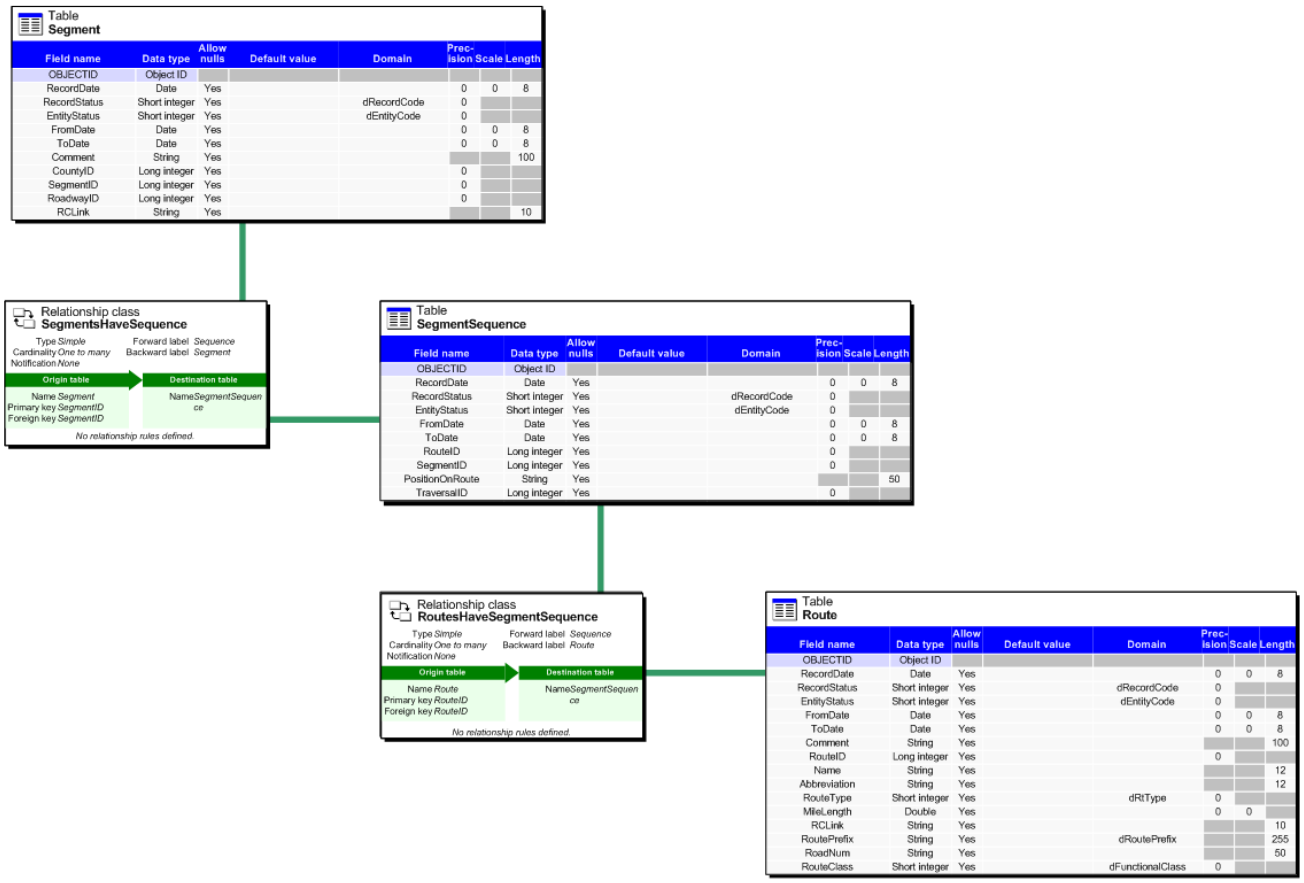
Figure 4
Segment Route Relationships



Advanced Linear Referencing

The highway data management solution implements advanced linear referencing functionality.

- Multiple linear referencing methods (LRMs)
- Dynamic route representation
- Time-aware LRS
- Rule-based event behavior

Multiple LRMs

Support for multiple linear referencing methods is a minimum requirement for a modern highway data management solution. Traditionally, there have been two approaches to managing multiple LRMs within a linear referencing system: users either store multiple route geometries or they store transformed route measure values within the business tables. Often, large highway departments will implement a combination of approaches for addressing multiple LRMs.

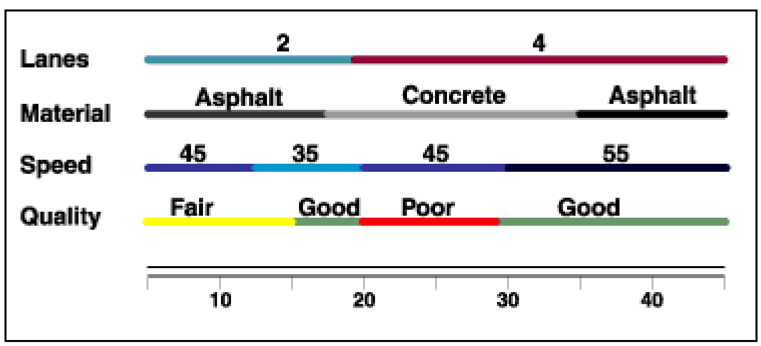
Storing multiple route geometries is problematic because each geometric feature set that is stored must be maintained. They can quickly become out of sync with one another, creating problems with accuracy and currency in any given set of routes.

Storing transformed measure values in business tables is also problematic because many business tables are maintained by non-GIS systems that use a particular LRM. To support the storage of transformed measures, it is necessary to duplicate the business tables and use complex transformation algorithms to keep measure values in sync. This problem is further complicated when incidents are reported using different measuring systems than those being stored.

A third approach that has gained acceptance in the transportation industry is to store a logical linear network in the database using a standard LRM, called a reference datum, and calculate LRM equivalencies on the fly. This approach allows users to store data using one LRM, maintain it using another, and perform analysis of business tables that are referenced using yet another LRM.

Esri's highway data management solution employs this third approach. The LRS manages the LRM equivalencies for the user so end users never have to worry about how the data is stored. Data can be integrated on the fly for display and analysis without the need to extract tables from their external systems and load them into ArcGIS. If the LRM is registered with Esri's LRS, the data can be displayed and managed. Users can quickly find answers to questions about pavement conditions and traffic counts at incident locations regardless of the fact that they are accessing four different datasets, stored in four different systems, each referenced with its own LRM.

Figure 5
Depiction of Linear Assets in a Straight Line View



There are two basic types of LRMs, those based on interpolation and those based on a set distance from a known origin. Interpolation LRMs reference a location measure as an interpolated value between the endpoints of a line or between two control features called calibration points. Mile marker and DMI LRMs are based on interpolation. LRMs based on a distance from a known origin are called referent offsets. A referent offset can be an offset from a station marker, such as those used at the start location of a highway maintenance project, or simply referenced as a distance from some other asset that can be seen on the highway. Nearly all LRMs are a derivative of one of these basic types.

Esri's highway data management solution supports both types of LRM and can support any number of derivatives. Some examples are as follows:

- Project stationing
- Address ranges
- Distance from GPS location
- Road inventory miles
- Kilometer markers

It is not uncommon for incidents to be reported using a referent offset LRM yet be stored and managed using an interpolated LRM. Esri's highway data management solution supports this type of LRM management, transforming LRM values seamlessly.

Dynamic Route Representation

Another key challenge facing highway departments is that different business units have different definitions of what a highway is. The planning group may look at a highway in its entirety from one end of the state to the other. The maintenance group, on the other hand, may break out highways by maintenance district or county boundaries. In many cases, the way one group describes a highway is meaningless to the other. For example, many highway departments employ an anchor point and anchor section approach to managing highways. One way of creating a unique anchor section identifier is to concatenate a unique state and county code, such as the Federal Information Processing Standards (FIPS) code, to a unique integer value within each county. The number might look something like this: 3605503026. Unless this numbering system has been widely socialized throughout the agency, it is meaningful to only a handful of users within the highway department and completely meaningless to anyone else.

Esri's highway data management solution overcomes this problem in two ways. First, routes are defined in the data model. The Route table supports multiple definitions of a single route and multiple route systems within the same geodatabase. Using a single piece of geometry, assets can be referenced against any route definition that exists in the database using any registered LRM.

The second way that Esri's highway data management solution addresses the need for multiple route representations is through the creation of route features dynamically based on the users' definitions of a route. To accomplish this, asset tables are used to refine the definition of a route. Any route definition that is stored in the Route table can be further amplified to accommodate any linear event table registered with the LRS. A simple example is dynamically breaking the highway at city limit boundaries to eliminate confusion when incidents are referenced against ambiguously named assets.

Perhaps a more powerful example of dynamic route representation is the management of assets and incidents at a lane level without the need to store lane-level geometry. In figure 6, lanes are stored as a business table having information concerning the number of lanes on the highway, the width of the lanes, and which lanes fall on what side of the highway. Crashes are stored in the database with a highway number and milepost measure reference along with the number of the lane in which the crash occurred.

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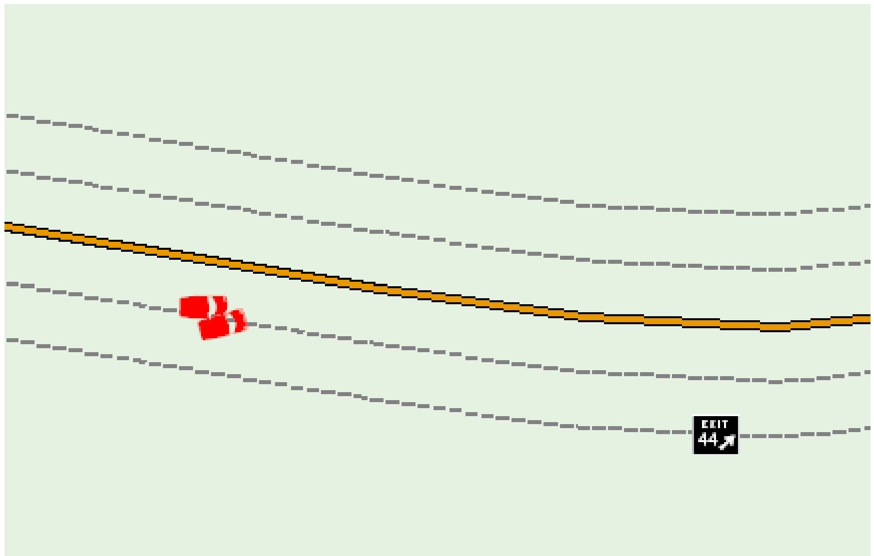
Figure 6
Lane-Level Asset Location Using Dynamic Routes



The important thing to note here is that this is not simply a cartographic representation of lane-level data. The lanes are represented in an actual ArcGIS feature class, and each lane is a feature with its own geometry and its own m-values. This means that not only can you visualize data at the lane level, you can also perform spatial analysis and run geoprocesses against lane data. All this is accomplished without the need to store any additional geometry in the geodatabase.

Time-Aware LRS

Temporal awareness is a problem that faces many organizations, not the least of which are highway departments. Storing information using a system date and time stamp is fine for tracking edits in an RDBMS, but this approach captures the state of the database, not necessarily the state of the highway system. Highway departments require the ability to add planned roads and assign assets and incidents to them before they are opened. Departments also need to retire roads while retaining the ability to reference incidents that occurred on those roads at some point in the past.

Esri's highway data management solution leverages the ArcGIS temporal data functionality such that highways can be captured and assets assigned to them before they are actually built. This approach also addresses a common problem of data currency where planned roads are not entered into the geodatabase until they have been opened to traffic. In these cases, it is typical for a certain time lag to occur between the opening of the road and its entry into the geodatabase. By entering the highway during the planning stage, ArcGIS can turn the road "on" and retire any superseded roads automatically at the planned opening date.

Figure 7 shows a section of highway as it is currently built with a portion overlapping another highway where the two converge.

Figure 7
Original Alignment with Overlapping Highways

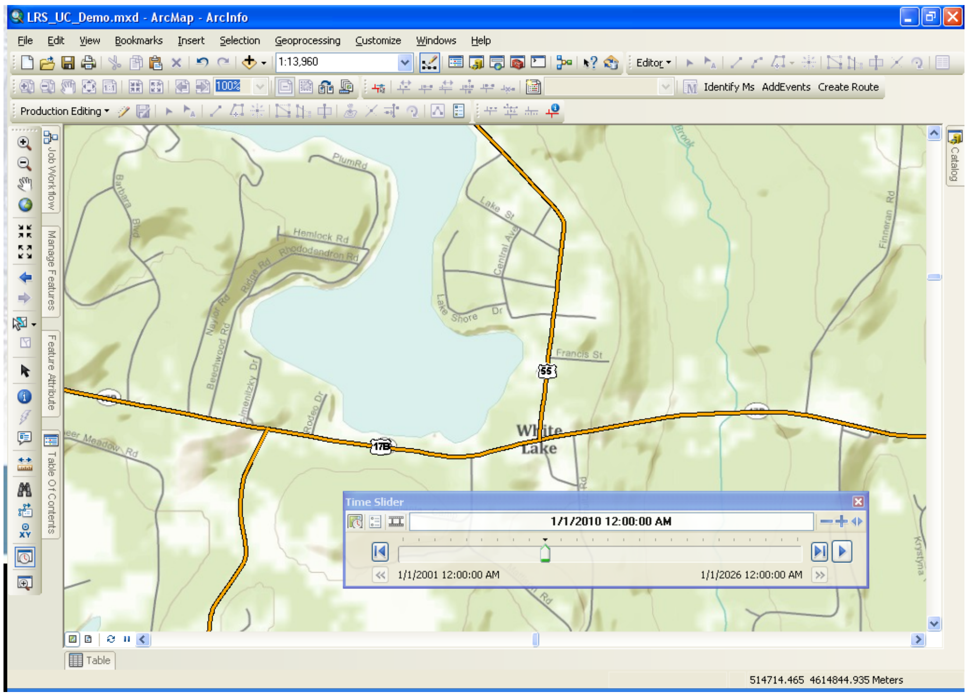
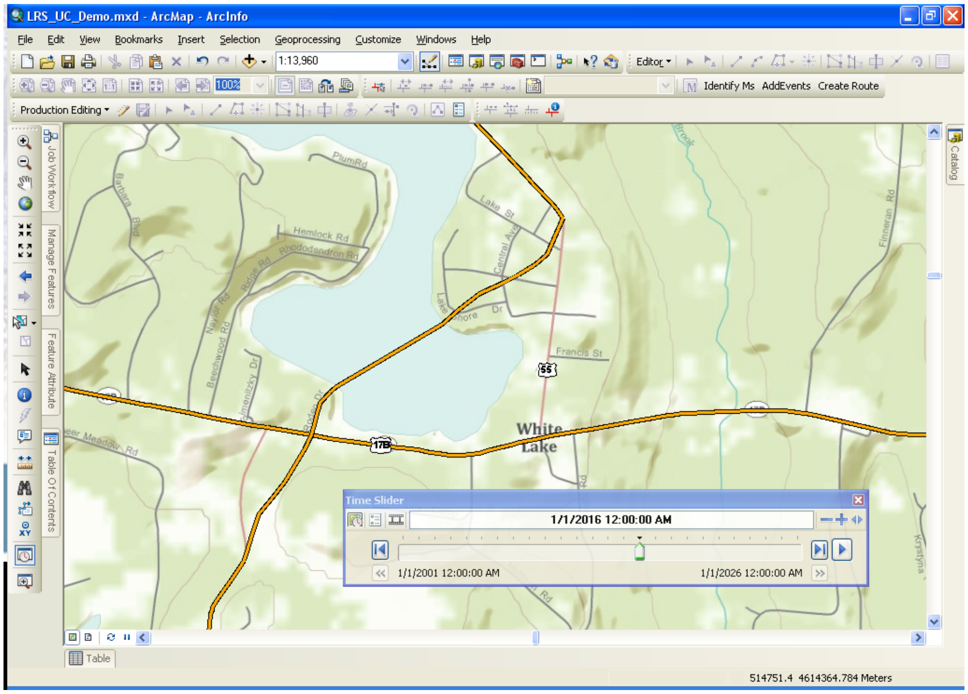


Figure 8 shows the same section of highway at a future date when a planned overpass will have been built. Based on from and to dates stored in the database, ArcGIS temporal tools automatically display the overpass as active and the superseded sections as retired based on the date shown on the time slider.

Figure 8
Future Alignment with an Overpass Replacing the Overlap



More information on temporal data can be found on the Esri Resource Center pages.

Rule-Based Event Behavior

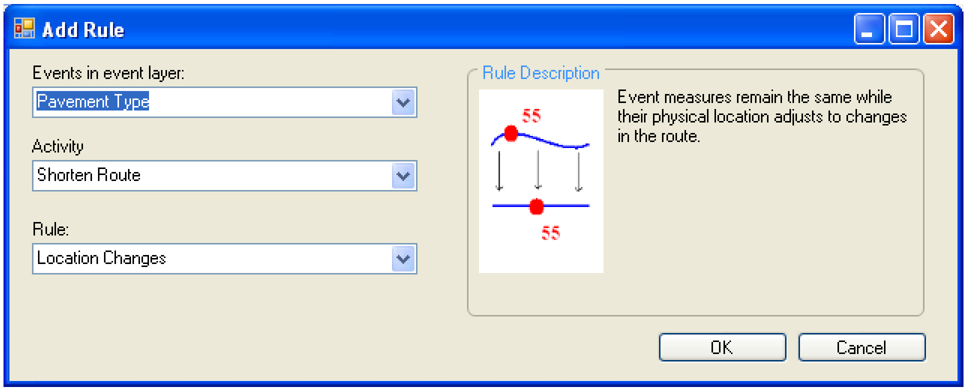
Perhaps the most difficult problem facing anyone who uses linear referencing is the unpredictability of event behavior when the underlying route geometry changes. In a typical LRS, when you edit the route and change its length, the event automatically readjusts itself to have the same relative location along the route. In many cases, this is exactly what you want to happen. If a speed limit along Highway 20 is 55 mph from mile marker 14 to mile marker 26, you want that speed limit event to retain its relative location should you make minor adjustments to your highway geometry based on more current aerial photography.

In other cases, this is not the behavior you want. What happens, for example, when you shorten a road? In the real world, the portion of the road to be closed is completely destroyed along with any physical assets that reside on it. You want your database to reflect the same conditions, but in a typical LRS, the events on the closed portion of the highway tend to snap to the end of the portion that is still active. What you really want is for these events to be retired, but it is usually left up to the user to go back and edit the event tables manually after the geometry edits have been completed. Situations such as these can lead to a number of data quality issues that tend to accumulate over time.

Esri's highway data management solution solves this problem by allowing the user to preconfigure event behavior within the LRS before any geometry is edited. The solution is completely workflow driven, which means that how events behave depends on what it is that you're doing when they are impacted.

The highway data management solution allows users to create rules that trigger specific event behaviors based on the type of edit being performed. If a highway is being shortened, for example, the solution allows you to set up rules such that the system will automatically adjust the to measures of events that should continue to the end of the highway or retire events that are orphaned by the road closure.

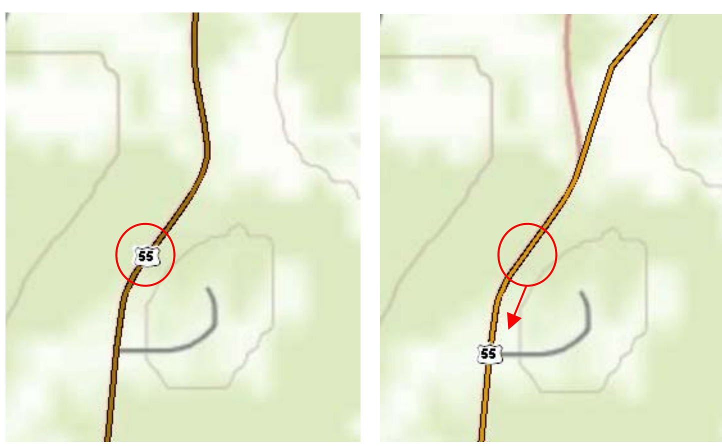
Figure 9
Building Rules for Event Behavior



Depending on the type of activity being performed, different things happen to the highway data. Esri's highway data management solution controls this automatically based on a predefined set of rules for event behavior. When assets are registered with the LRS, their behavior can be controlled explicitly by linking them to these activities. When a given activity is completed, event measure values are automatically updated according to these predefined rules. The types of event behavior that can occur are as follows:

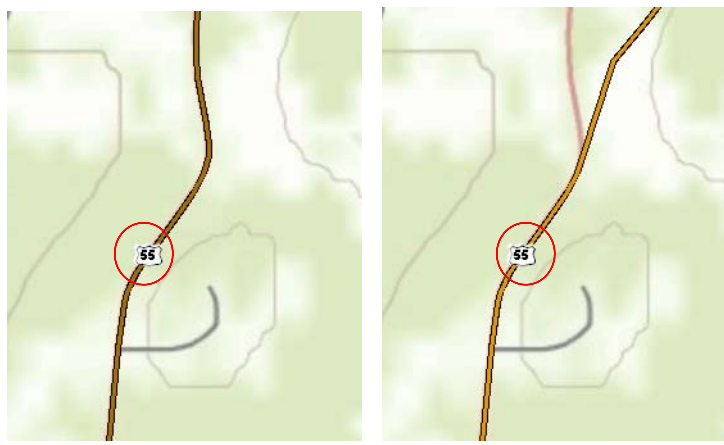
- Assets can move based on changes to the length of the highway, keeping their original measure values.

Figure 10
Asset Moves with Change in Length of Highway



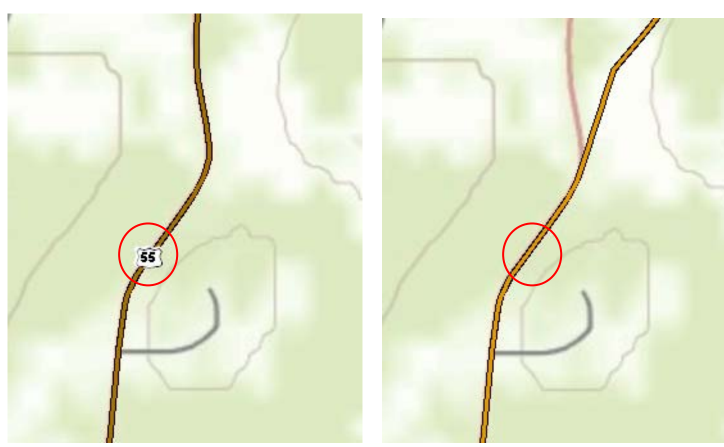
- Assets can retain their physical locations while their measure values are updated to reflect the new relative location along the highway.

Figure 11
Asset Location Stays the Same



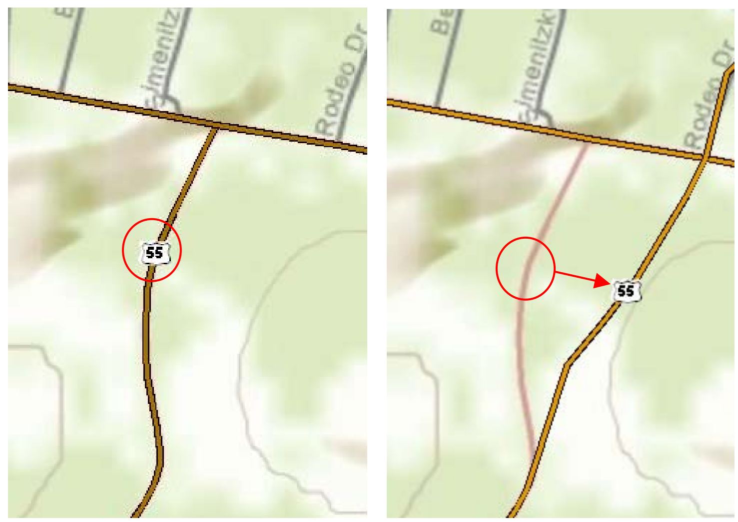
- Assets can be retired.

Figure 12
Asset Is Retired



- Assets can snap to a new route location.

Figure 13
Asset Snaps to the New Route



Workflows

Workflow is critical to a location management system. Everything that happens to highway data depends on what people are doing and why they are doing it. A *workflow* is a generalized term that encompasses projects, the various activities that make up those projects, and the individual tasks required to complete the activities. Tasks can be performed with Web, mobile, and desktop applications.

Figure 14
What Is a Workflow?

Activities generally assume three generic user roles, but the highway data management solution actually contains five:

- LRS administrator—This is a user who has administrative privileges to the geodatabase and the ability to access systems that manage asset data. The LRS administrator configures and manages the LRS.

- Field supervisor—A field supervisor is an individual who is typically not a GIS specialist but has the authority to assign work. The field supervisor creates projects, adds activities, and assigns work to field crews. Once field data collection is complete, the field supervisor reviews the data and posts updates to the LRS. A typical activity begins and ends with a field supervisor.

- Field crew—The field crew role represents users in the field who collect and validate data against the real world. These are typically not GIS users but have access to and training in the use of mobile data collection devices such as GPS.

- GIS analyst—The GIS analysts are the strong GIS experts who validate data and update the LRS. When a field supervisor posts updates to the LRS, these updates are posted in a redline format, meaning they don't actually impact the underlying LRS until the GIS analyst validates the changes. Once the changes have been validated, the GIS analyst updates the LRS, which causes a series of batch processes to run that resequence route geometry and manage event behavior.

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- Highway engineers—Highway engineer is a generic role of user who interacts with highway data. This covers a broad spectrum of users across the highway department and represents individuals who need to discover information about the highway but don't necessarily need to update route geometry. Highway engineers may perform such tasks as generating reports, making simple maps, and performing LRS analysis by overlaying assets and GIS data.

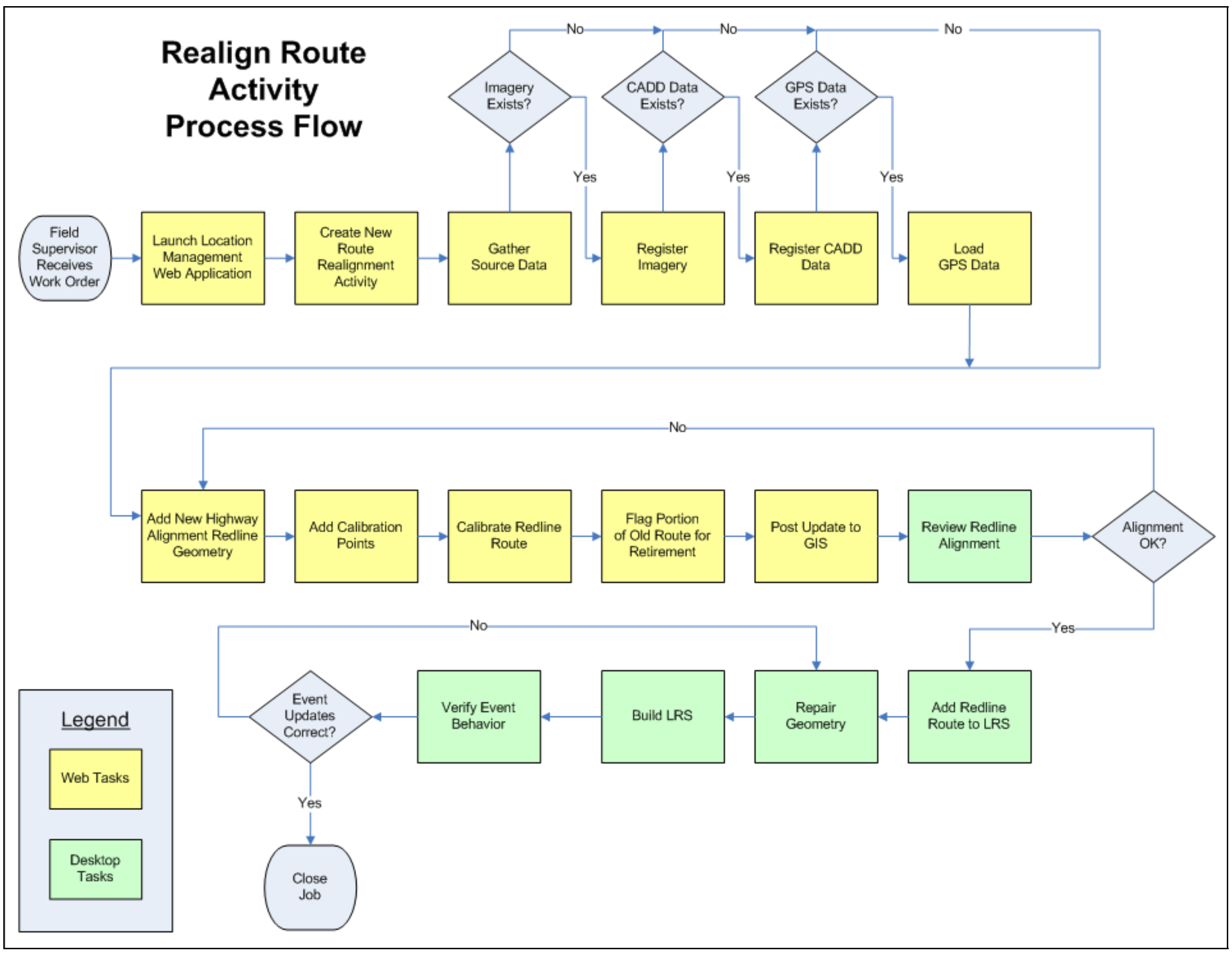
When a highway department undertakes a major project, it involves many agencies and requires a great deal of logistical support to ensure that everything is where it needs to be when it needs to be there. The highway data management solution is no different. Just as highway projects are orchestrated throughout the department, the maintenance of the highway data must follow suit. The highway data management solution handles the logistics of the data maintenance just as the project support team would handle the logistics of the construction project.

A typical highway data maintenance workflow follows the pattern of a highway project. Once planning has been completed, work is assigned, data is collected, database updates are redlined, the redlines are validated, and the updates are made to the appropriate datasets.

Figure 15
High-Level Workflow

During a route realignment activity, a field supervisor receives a work order or some other notification to perform work. The field supervisor uses the Web application to create a realignment activity in the location management system, gathers source data, and performs a redline function to enter the route. Once the redline route is complete, the field supervisor has a calibrated route feature upon which assets can be located, but no changes have yet been made to the underlying linear referencing system. The field supervisor then posts the redline route to the GIS, where the GIS staff verifies the geometry and intersects it with the underlying LRS. The GIS staff then builds the LRS by clicking a Build LRS button, and the new route is added to the route definitions, superseded route geometry is retired, and event measures are updated according to the event behavior rules associated to the route realignment activity for each event layer.

Figure 16
Route Realignment Activity Process Flow



Several generic highway data maintenance activities are preconfigured and provided with the solution.

Collect As-Built Geometry

During this activity, field crews collect the geometry of roads that have already been built but have not yet been added to the LRS. Field collection is typically performed via a Global Positioning System and provided to the field supervisor as a shapefile. Assets along the target roadway are collected at this time.

Collect Asset Inventory

During this activity, field crews collect assets along the roadway. While this can be accomplished with a mobile device, the typical methods for inventory collection will be to use the highway data management Web application. Assets are collected as events using the LRM and route reference of the field crew's choice.

Add Planned Road

During this activity, the field supervisor or appropriate designee adds new highway geometry based on a building plan. The highway geometry is redlined by the field supervisor, and the redlined route is calibrated so that assets can be added at the same time. Default assets, such as pavement and speed limits, will be automatically generated and populated with default values.

Add New As-Built Geometry

During this activity, field supervisors add new geometry or update planned road geometry based on an as-built drawing. The geometry changes are submitted as redline features and calibrated with a base LRM, and assets are updated and/or added at this time.

Cartographic Realignment of Existing Geometry

During this activity, field supervisors update highway geometry based on new aerial imagery or as-built drawings. A cartographic alignment is a change in the route geometry where no change has occurred in the physical world. Edits may be made to route vertices, and new calibration points may be added during this activity.

Physical Realignment of Roadway Geometry

During this activity, field supervisors update highway geometry based on changes in the physical world. A simple roadway realignment may be part of a larger realignment project. During a physical realignment, new roads are added and portions of the highway that will be closed are retired. A physical realignment may be performed for existing or planned realignments.

Physical Realignment with Overlaps in Routes

This activity is similar to a physical realignment except that it deals with routes containing portions that overlap. The primary purpose for identifying this activity individually is to ensure that events along the overlapping section of the highway are managed appropriately by the system when the LRS is updated.

Physical Realignment with Gaps in Routes

This activity is similar to a physical realignment except that it deals with routes that have gaps in them. The primary purpose for identifying this activity individually is to ensure that events near the gaps in the highway are managed appropriately by the system when the LRS is updated.

Extend Existing Roadway Geometry

During this activity, an existing highway is lengthened either at the beginning or end of the highway. While it is not common for this condition to occur as a stand-alone process, shortening and extending highway sections may happen frequently as part of a larger realignment project.

Shorten Existing Roadway Geometry

During this activity, an existing highway is shortened at the beginning, middle, or end of the highway. While it is not common for this condition to occur as a stand-alone process, shortening and extending highway sections may happen frequently as part of a larger realignment project.

Retire a Portion of a Highway

During this activity, a portion of a highway is closed and its geometry must be split and retired. This activity may be performed as part of a larger realignment project or as a stand-alone activity when a road is simply closed.

Merge Portions of a Highway

During this activity, two highways are merged into one. Assets assigned to a portion of the highway to be merged are either assigned to the target highway or retired. While this activity can happen during a large realignment project, it more commonly occurs when highway names are changed administratively.

Change the Jurisdiction of a Highway

During this activity, a highway portion is changed based on its interaction with an administrative or other type of boundary. When business rules indicate that highways are split based on administrative boundaries, portions of the highway and their associated assets must be reassigned when those boundaries change.

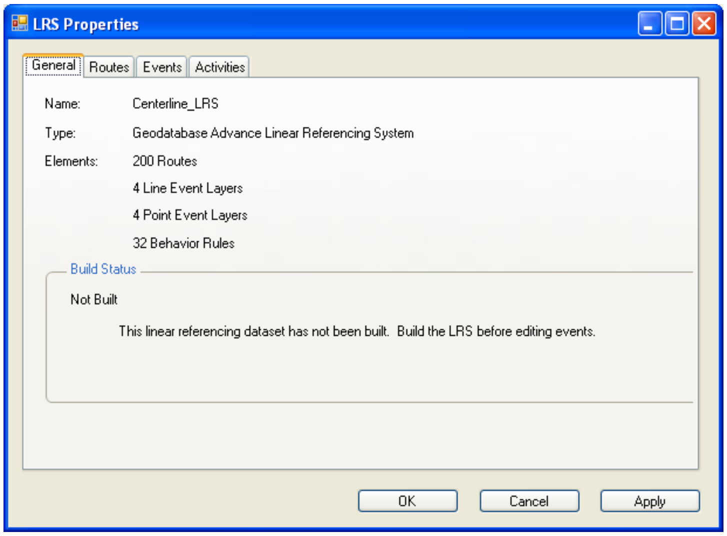
Applications

Esri's highway data management solution includes a suite of applications for managing and maintaining highway data. To be fully effective, a highway data management solution has to reach the broadest possible distribution of users. To support a wide variety of users distributed throughout complex organizations, the solution leverages applications on the desktop, on the Web, and on mobile devices. The primary focus is on the Web, leveraging ArcGIS Server and Esri's REST API.

Desktop

Desktop applications are focused around configuring and managing the LRS. A database configuration tool (DCT) provides a simple interface for defining routes, registering events, and adding event behavior.

Figure 17
Database Configuration Tool



Desktop editing functions are provided from the Highway Data Management toolbar to ensure the fewest possible number of mouse clicks are required to integrate redline route geometry with the LRS. A Build LRS button automatically resequences route geometry, updates LRMs, recalibrates routes, and manages event behavior with a single click.

Web

The primary focus of the highway data management solution is on the Web. This provides a simple mechanism for distributing highway data to the broadest possible audience. It also provides the most flexible software installation platform since the majority of users will not be required to install any software except a standard Web browser that supports either Adobe® Flash® 10 or Microsoft® Silverlight®. From the Web application, users can view and update asset data, print maps, and generate custom reports. Field supervisors can create jobs, assign work, redline changes to route geometry, and verify data quality. Field crews can conduct asset inventories, add new asset data, and update existing assets.

Figure 18
Prototype Web Application

Mobile

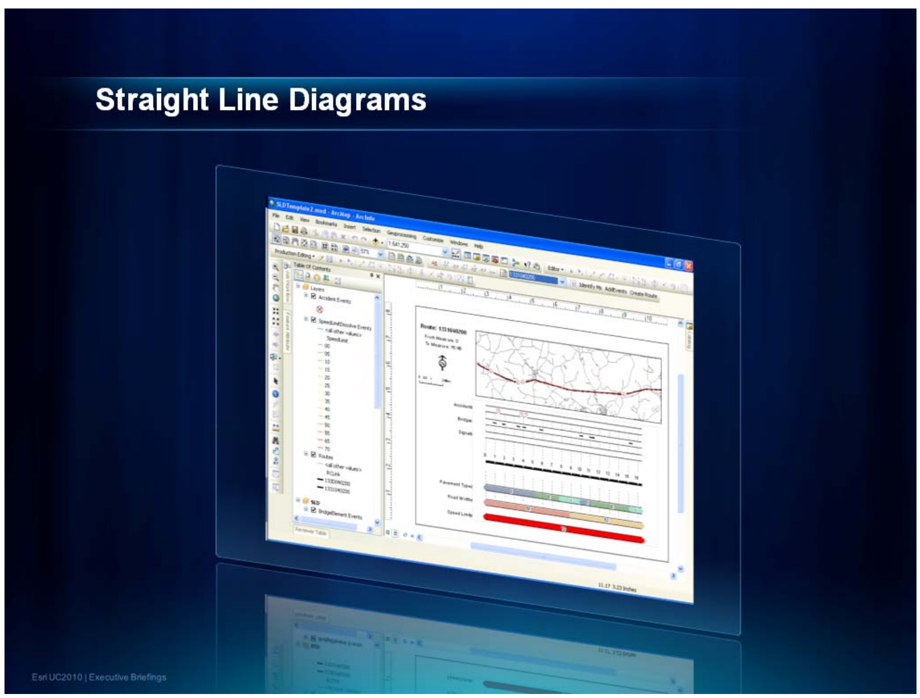
Mobile applications are part of the future vision of Esri's highway data management solution. Although there are no specific applications being developed for the initial release, the mobile element of data management has not been left out. The solution supports the incorporation of data collected in the field through GPS or mobile devices. When a mobile device is synchronized with the desktop, the data collection activity is reinitialized and a notification is sent to the field supervisor.

Analysis and Reporting

Esri's highway data management solution offers a broad spectrum of standard and custom reports as well as the creation and printing of simple maps. Road inventory and pavement reports can be generated with a single click of a button from the Web interface. Custom reports and queries can be created by accessing asset data from multiple external systems using a variety of location referencing methods. An example of a custom query might be, "Show me all the crashes since 2005 that have occurred within 1,000 meters of an exit, on pavement type of asphalt, in moderate condition, where the speed limit is less than 65 mph." You simply add the layers you need to your map, turn them on, and select Create Ad Hoc Point Report from the reporting menu.

Visualization of event data on a map has always been challenging since it requires complex symbolization of linear events to differentiate one event from another. Highway departments typically use a straight line diagram view of the highway, which shows a schematic representation of the events in a stacked fashion. The highway data management solution provides the ability to quickly create and publish straight line diagrams as map services that can be accessed through the Web application.

Figure 19
Straight Line Diagram



Esri Solutions for Transportation

Esri's highway data management solution is only the beginning of ArcGIS solutions to support the transportation industry. Esri also has solutions for cartographic production, data validation and review, network analysis, fleet management, and more. In addition to its COTS product offering, Esri's extensive partner network offers a wide variety of solutions to the transportation industry. See the Solutions Guide for Transportation for more info.

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The Road Ahead

Linear referencing plays a large role in the transportation industry for managing asset inventories, tracking maintenance activities, planning future development, and analyzing incident reports. The highway data management solution is expected to be released in early 2011. At that time, Esri will immediately begin work on the next release. Below are some things being considered for future releases:

- Robust mobile applications such as asset editing in the straight line diagram on a mobile device
- Advanced query functionality to streamline common queries
- A transit solution including support assets along bus and train routes
- A freight rail solution
- More robust integration with ArcGIS Network Analyst to support mobile assets and movable routes

About Esri

Since 1969, Esri has been helping organizations map and model our world. Esri's GIS software tools and methodologies enable these organizations to effectively analyze and manage their geographic information and make better decisions. They are supported by our experienced and knowledgeable staff and extensive network of business partners and international distributors.

A full-service GIS company, Esri supports the implementation of GIS technology on desktops, servers, online services, and mobile devices. These GIS solutions are flexible, customizable, and easy to use.

Our Focus

Esri software is used by hundreds of thousands of organizations that apply GIS to solve problems and make our world a better place to live. We pay close attention to our users to ensure they have the best tools possible to accomplish their missions. A comprehensive suite of training options offered worldwide helps our users fully leverage their GIS applications.

Esri is a socially conscious business, actively supporting organizations involved in education, conservation, sustainable development, and humanitarian affairs.

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