California AHMCT Program
University of California at Davis
California Department of Transportation

A PRECURSOR SYSTEM ANALYSIS OF AUTOMATED CONSTRUCTION, MAINTENANCE, AND OPERATIONAL REQUIREMENTS FOR AUTOMATED HIGHWAY SYSTEMS (AHS)*

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METRIC CONVERSION CHART
(Replace w. FHWA SI (Modern Metric) Conversion Factors Chart

Class	Multiply	By:	To Get:
Area	acre	4047.0	m^2
	acre	0.4047	ha (10,000 m^2)
	ft^2	0.0929	m^2
	yd^2	0.8361	m^2
	mi^2	2.590	km^2
Length	ft	0.3048	m
	in	25.4	mm
	mi	1.6093	km
	yd	0.9144	m
Volume	ft^3	0.0283	m^3
	gal	3.785	L
	fl oz	29.574	mL
	yd^3	0.7646	m^3
	acre ft	1233.49	m^3
Mass	oz	28.35	g
	lb	0.4536	kg
	ton (2000 lb)	907.2	kg
Density	lb/yd^3	0.5933	kg/m^3
	lb/ft^3	16.0185	kg/m^3
Pressure	psi	9894.7	Pa (N/mm^2)
	lb/ft^2	46.88	Pa
Velocity	ft/s	0.3048	m/s
	mi/h	0.4470	m/s
	mi/h	1.6093	km/h
Light	footcandle (lumen/ft^2)	10.764	lux (lx) (lumen/m^2)
Temperature	°F	$t_c = (t_f - 32)/1.8$	°C

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CHAPTER 1: INTRODUCTION

The University of California-Davis and the California Department of Transportation (Caltrans) have participated in a Precursor System Analysis (PSA) of automated construction, maintenance, and operation requirements for Automated Highway Systems (AHS). Based on initial discussions during a kick-off meeting with the Federal Highway Administration (FHWA) and the contract monitors from the MITRE Corporation, research for this PSA has been focused on a specific AHS subsystem: the discrete magnetic marker system that has been developed by researchers in the Partners for Advanced Transit and Highways (PATH) research program.[1] This report documents the preliminary design of a prototype system for the automated installation of discrete magnetic markers for use as a reference system for an AHS. By focusing on a specific technology that has shown significant promise for application in AHS, the current PSA study was able to provide more concrete results and conclusions. The procedures presented here can be similarly applied in the design and analysis of automated systems for the installation and maintenance of other forms of AHS infrastructure in the future.

The initial step in this study was a comprehensive literature survey of AHS research and technology. This study resulted in a technical report,[2] and provided the necessary background material to facilitate the remainder of this study. A brief summary of the survey paper is provided in appendix A of this report..

Based on the literature survey, it was realized that there is a need for tools to assist in the organization of AHS technology. A functional architecture was developed for an AHS facility, along with a classification system that can quickly identify different representative system configurations as well as different physical devices used as subcomponents of an AHS. This classification system, documented in a technical report,[3] provides the basis for the development of a knowledge-based deployment analysis tool for AHS configurations. Such a system would greatly facilitate quantitative analysis of various configurations during the design and down-select process envisioned by the FHWA. In the current research, the reference architecture and classification system were used as a means of organization. Appendix B provides a summary of this AHS reference architecture and classification.

As noted previously, the main focus of this PSA study was the investigation of automated robotic installation of an AHS lateral reference system consisting of discrete magnetic markers embedded in the roadway. These markers will be used as both a guidance reference and an information database for lateral control in an AHS. This report contains the preliminary design information for a discrete magnetic marker installation system. It includes a detailed set of functional specifications, subsystem strawman concepts, operational specifications, and an example prototype design. In addition, the report provides guidelines for feasibility studies, prototype system testing, field testing, and development of a production model. These steps are premature at this stage of AHS research; they are provided here as a framework for future research efforts.

The design presentation is augmented by further studies. Once the prototype design presented in chapter 6 was developed, the design was illustrated and investigated using a computer simulation and animation. This simulation is discussed in appendix C.

Motivation for Development of a System for Automated Installation of Discrete Magnetic Markers

Researchers at PATH are currently developing a lateral control system[4] to be used as a part of their full Intelligent Vehicle/Highway System (IVHS) architecture. PATH's system uses an Intelligent Roadway Reference Systems (IRRS);[1] magnetic markers are installed in the roadway to provide lateral position and road preview information to vehicles for lateral control.

PATH's lateral control system is now ready for large-scale testing. Before such large-scale tests can be conducted, a system must be developed to install the magnetic markers quickly and reliably. This report documents the initial design of a robotic type system to perform automated installation of the magnetic markers for lateral control.

PATH's system uses permanent magnets for reference markers. The magnets facilitate lateral control in two ways. First, they provide a lateral position reference. The magnets, which are positioned at regular intervals along the center of the AHS lane, define a path for the vehicle to follow. Sensors on the vehicle are spaced on either side of the path, as shown in figure 1, to determine the vehicle's displacement from the lane centerline. The vehicle lateral controller can then modify the vehicle's steering angle to move it back toward the middle of the lane. The marker separation is small enough to ensure that the vehicle sensors will not "miss" a marker's magnetic field (M-field) and lose the reference path.

Second, the magnetic markers provide road preview information. The polarity of the magnets is used to code binary information about the roadway. The vehicle magnetometers distinguish between positive and negative charge, and the onboard computer system treats this information as ones and zeros. By treating this information as a digital 'word' of information, the system can obtain a preview of the upcoming roadway geometry, including curvature, which can be used by the lateral controller to provide a feedforward term in the control law, thus reducing the burden on the feedback controller. The interested reader is referred to the PATH publications for further information regarding the IRRS and its use for vehicle lateral control.[1,4]

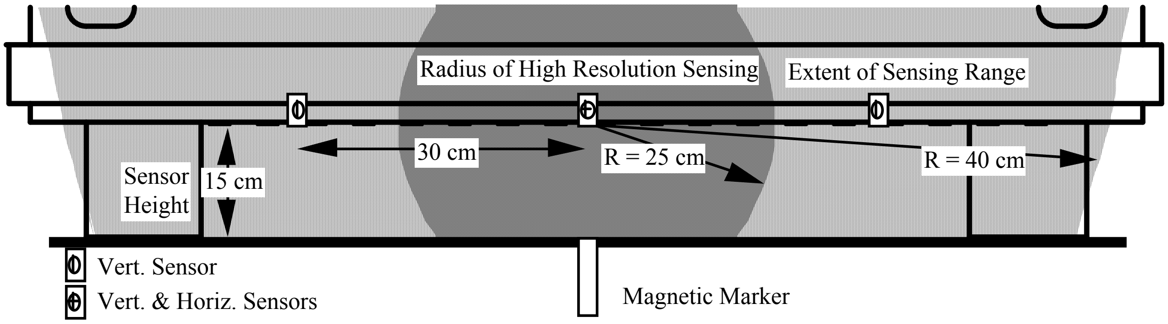

Figure 1. Range of sensors.

The Hall-effect magnetometer configuration currently used in the PATH test vehicle has a sensing range of 400 mm from the marker (i.e. a total sensor range of 800 mm), with high resolution sensing within 250 mm of the marker.[4] The sensors are mounted approximately 150 mm above the road surface. The sensing range is illustrated in figure 1.

Design Process and Report Structure

This report is organized to correspond to the AHMCT design process. The structure of this process is diagrammed in figure 2.

The first step in this design process is to develop functional specifications, which identify the desired/necessary output of the automated system. Chapter 2 provides the functional specifications for a discrete magnetic marker system. A vehicle dynamic simulation is used to determine placement tolerances of the markers. Specifications are also provided for the marker casing, marker-to-pavement bonding, polarity coding, allowable degradation of markers/pavement during installation, and acceptable marker costs.

Chapter 3 identifies the subsystem operations, and presents strawman concepts for each of the subsystems. Identifying subsystems involves breaking down the concept of an automated marker placement system into specific tasks that will be needed for the complete task. These subsystems can be developed concurrently, then put together to form a working machine. The first stage in this development is the introduction of strawman concepts. Strawman concepts are initial ideas which are developed after preliminary research. Six subsystems were identified for the discrete magnetic marker placement system. At least four concepts are presented for each subsystem; fourteen are presented for the positioning system. Error sources for each positioning system concept are identified, but not quantified.

Chapter 4 discusses tactics for feasibility studies. Note that no feasibility studies have been done for this report; this chapter and the following chapters merely establish an architecture and provide a framework for future work for designing a discrete magnetic marker placement system. Feasibility studies are generally done at this stage of the design process to determine whether or not strawman concepts will work. From the results of the studies, the best concepts can be selected for the prototype.

Chapter 5 provides general operational specifications for the system. Operational specifications are separate from functional specifications; functional specifications define the output of the machine, while operational specifications define the machine itself. In addition to the general specifications listed in this chapter, system and subsystem specifications must be developed after the individual subsystems have been tested and selected.

Chapter 6 gives an example prototype design. Prototyping involves combining all of the subsystems into a complete working system, i.e. the machine is actually built. At the end of this step, the machine should work well enough to install markers under laboratory (semi-ideal) conditions. The prototype design presented in this chapter could be used as the basis for the development of this initial machine.

Chapter 7 discusses the final design steps of field testing and development of a production model. In field testing, the machine created in the prototyping phase is tested in the working environment on the road. The machine is adjusted to deal with problems that may arise in actual use. Field testing ends with a fully functional machine. Finally, after a last analysis on the manufacturability and maintainability of the machine; small adjustments are made, resulting in the production model.

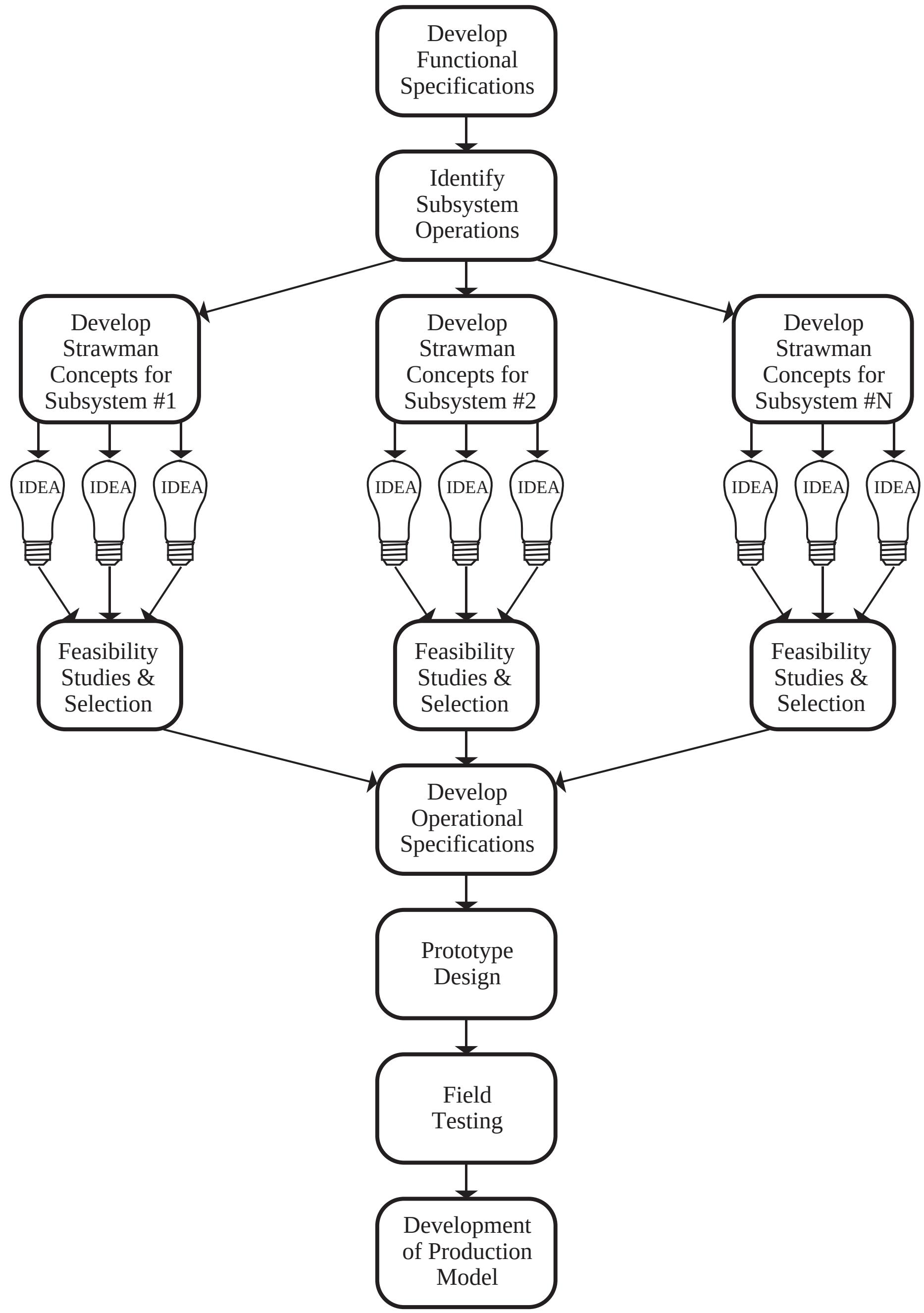

Figure 2. Overview of design process.

In addition to the system design presented in chapters 2 through 7, manpower and economic analyses were performed for the automated installation of discrete magnetic markers. Chapter 8 discusses the application of an analytical approach for the assessment of manpower requirements for the construction and maintenance of an AHS to estimate the manpower requirements for the automated installation of discrete magnetic markers.[5] Additionally, a model was developed to examine the cost-benefits of robotic construction and maintenance for AHS.[6] Chapter 9 presents the application of this model to the automated installation of discrete magnetic markers.

Chapter 10 provides overall conclusions for this Precursor Systems Analysis, as well as recommendations for future research. Appendices A through C provide summaries of research that supported the development of this design concept. These summaries include a literature survey of research related to AHS, a reference architecture and classification of AHS, and a computer simulation illustrating the example prototype design concept.

CHAPTER 2: FUNCTIONAL SPECIFICATIONS

The first step in the design process is the development of functional specifications which define the required output of the automated system. The functional specifications for the installation of the discrete magnetic marker system are presented in this chapter.

Marker Placement and Placement Tolerancing

Definition of Placement Dimensions
The positioning of the markers must be fully described in order to define the requirements for the placement system. Dimensions define the nominal placement requirements for the markers, while tolerances define acceptable error ranges. The placement dimensions are broken down into three groups:

- **Longitudinal Dimensions** - Dimensioning w.r.t. the direction of travel of the lane.
- **Lateral Dimensions** - Dimensioning w.r.t. a perpendicular to the direction of travel, on the pavement surface.
- **Vertical Dimensions** - Dimensioning w.r.t. a perpendicular to the pavement surface.

The dimensions that fall under these subheadings depend on several factors. Table 1 summarizes the necessary dimensions and the factors which influence them. Figure 3 illustrates these dimensions.

Table 1. Dimensions & tolerances and their determining factors.

Dimension	Determining Factors
Longitudinal	
Spacing	Vehicle Dynamics, Control Following Ability, Speed Measurement, Compactness of Marker Coding, Passenger Comfort.
Spacing Tolerance	Vehicle Dynamics, Control Following Ability, Speed Measurement, Compactness of Marker Coding.
Cumulative Tolerance	Marker Coding
Lateral	
Centering Tolerance	Lane Width, Limit of Control Width, Vehicle Width
Amplitude Tolerance	Lane Width, Control Program, Limit of Control Width
Alignment Tolerance	Control Program, Passenger Comfort
Vertical	
Depth Dim. & Tol.	Marker Style, Magnetic Field, Vehicle's Sensors
Tilt Tolerance	Magnetic Field, Vehicle's Sensors

Longitudinal Dimensions

• **Spacing** - Spacing is the distance between two markers in the longitudinal direction. For spacing, the major concern is to ensure that the markers are sufficiently close to prevent the vehicle from losing the path by missing a marker. This dimension is determined by the vehicle's dynamic characteristics, velocity, and yaw angle, as well as the ability of the geometry preview control to maintain proper vehicle heading.

Maximum spacing should also be based on the comfort level of the driver and passengers. The vehicle dynamic model-based approach predicts the spacing using the sharpest turn that the vehicle can safely execute, without considering the comfort level of the

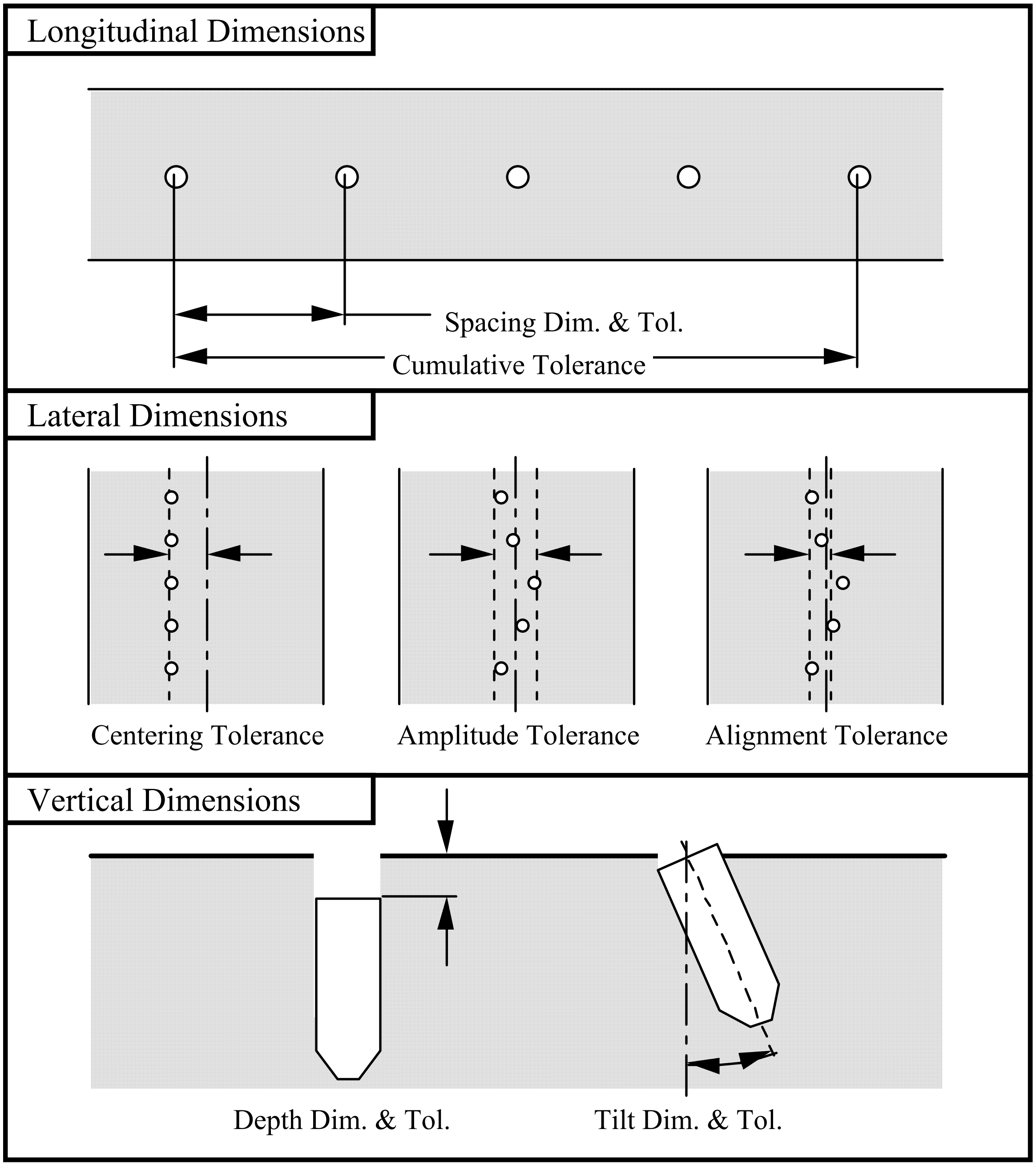

Figure 3. Illustration of dimensions & tolerances.

passengers, to determine the spacing. The passenger comfort model determines maximum spacing using the sharpest turn that maintains the vehicle lateral acceleration below the comfort level, defined as 0.3 g. The passenger comfort model-based spacing yields a larger spacing for the markers; this implies a lower cost system, as fewer markers are required. The vehicle dynamics model-based spacing provides more of a safety factor, as the markers will be more closely spaced, facilitating more extreme emergency maneuvers.

The efficiency of the code used for preview information also influences the maximum tolerable spacing. Some feasible roadway geometries, such as a compound turn on a grade, will require a significant amount of information to be coded into a small length of road. In such areas, the standard spacing distance may need to be reduced, which may sacrifice the accuracy of the longitudinal speed measurement, if the magnetic markers are also used to estimate vehicle speed.

The speed measurement factor requires the markers to be spaced evenly to allow conversion from time of travel between markers into a measure of vehicle speed. An evenly spaced system is a convenience, but is not necessary for the control of the vehicle, as vehicle speed can be obtained by other means.

The minimum marker spacing distance is also affected by the marker's magnetic field characteristics and the sensitivity of the vehicle magnetometers. The marker spacing must be large enough to obtain a discrete signal from each marker. Since it is cost-effective to maximize the spacing rather than minimize it, this factor is not used for normal spacing requirements. However, it may be used in tolerancing for certain configurations, such as dedicated entry and exit lane markers.

• **Spacing Tolerance** - The longitudinal direction tolerance specifies acceptable error between individual markers. This value must be chosen in conjunction with the spacing dimension. Tolerance that shortens the marker spacing between markers is not very critical; it would only effect the speed measurement capability of the system. Tolerance that lengthens the spacing would cause failure if the spacing dimension was already maximized. Therefore, any tolerance that increases spacing should be investigated.

• **Cumulative Tolerance** - The cumulative error is the sum of the spacing errors after a number of marker installations. Cumulative error could cause preview information on geometric features to be coded too soon or too late for vehicle reaction. It should not, however, be a problem for continuous straight roadway information or non-geometric information, such as route number. To minimize the effects of cumulative error, marker positioning references should be updated at the end of preview information segments, and markers should be installed from that point in the opposite direction of traffic flow.

Lateral Dimensions

• **Centering Tolerance -** The centering tolerance specifies the acceptable displacement of the marker reference line, or average position, from the lane centerline, as illustrated in figure 4. This tolerance is limited by how close the widest vehicle can come to the edge of the road or lane. It is affected by the lane width, the maximum vehicle width, the required vehicle clearance ,“C”, and the expected error bound of the lateral control system.

The expected error bound, or limit of control width, is the lateral distance which the vehicle is controlled within w.r.t. the marker reference line . Stated another way, the limit of control width is the lateral 'play' of the vehicle while following the markers. For example, the PATH lateral control tests specified a maximum deviation of 250 mm from the desired path.[4] The limit of control width in this case is 500 mm.

• **Alignment Tolerance** - The alignment tolerance is the allowable lateral displacement between two consecutive markers. A vehicle following the markers exactly would zig-zag when following markers installed with an appreciable alignment error. With a significant error, this zig-zagging motion would become noticeable to the passengers and be considered unacceptable. However, the control program may not follow the markers exactly. Sophisticated algorithms using approaches such as fuzzy logic might ignore certain amounts of deviation to provide a smoother ride. Thus, the dynamic behavior control algorithm itself should be considered in determining the alignment tolerance.

• **Amplitude Tolerance** - The amplitude tolerance specifies how far the markers can be located from their reference line. It essentially defines an acceptable error band around the marker reference line. The amplitude tolerance will add to the vehicle's lateral error, based again on the dynamic behavior control system.

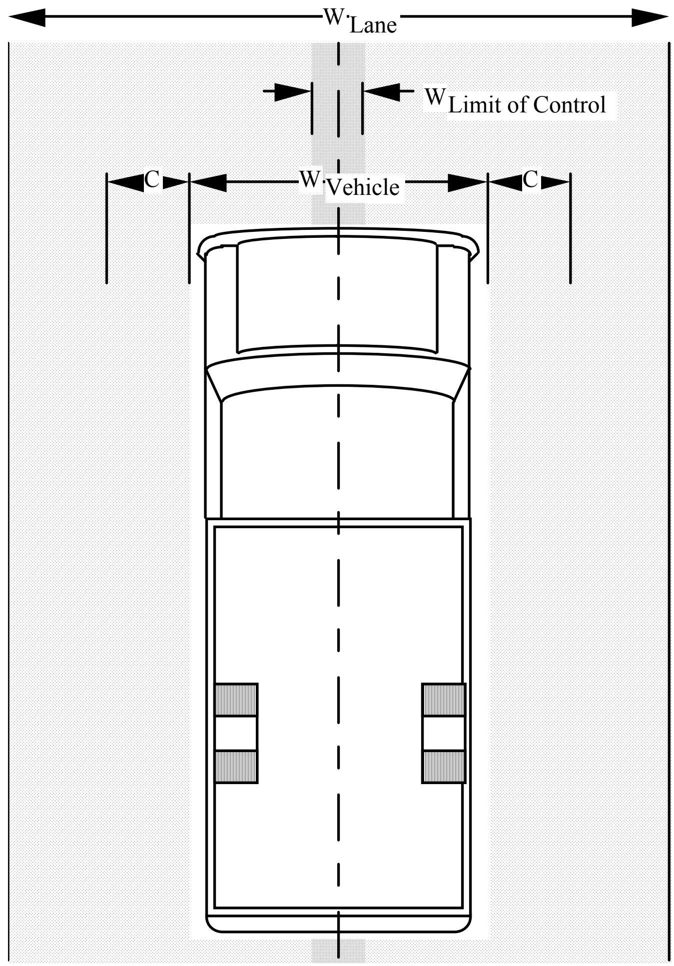

Figure 4. Limit of control width & other centering factors.

Vertical Dimensions

- **Depth Dimension and Tolerance -** This specifies marker installation depth. It may be established by investigating the effects of varying the distance between the magnetic field generator (the marker) and the sensors. This dimension is also be governed by the type of marker selected. Obviously, surface-mounted markers will sit on top of the pavement surface. Markers installed directly into the pavement should not be so deep that the magnetic signal is lost, or protrude outside the pavement enough to risk damaging either vehicle tires or the markers. The depth dimension should be set based on these factors. The tolerance value is less critical here, as the sensing algorithm developed by PATH is fairly insensitive to vertical height, as long as the preceding conditions are not violated.

- **Angular (or Tilt) Dimension and Tolerance** - Nominally, the markers should be installed perpendicular to the road surface. The angular tolerance specifies acceptable roll & pitch of the marker, w.r.t. the road's surface. The values for the angular tolerance should be given in degrees. The angular tolerance can be determined by analysis of the effects of a tilted magnetic field on the sensor measurement.

PATH Experimentally Tested Dimensions [4]

The marker placement dimensions and tolerances shown in table 2 have worked well in field tests done by PATH.[4]

Table 2. Dimensions & tolerances field tested by PATH.

Dimension	Values From Initial Testing
Longitudinal	
Spacing	1 meter
Spacing Tolerance	± 0.0125 meters
Cumulative Tolerance	Not Available
Lateral	
Centering Tolerance	Not Available
Amplitude Tolerance	± 0.0125 meters
Alignment Tolerance	± 0.0125 meters
Vertical	
Depth Dim. & Tol.	Not Available
Tilt Tolerance	Not Available

For this experiment, markers were placed manually, subject to very tight tolerances. While it is encouraging to see the control system work under these conditions, such stringent tolerances are unacceptable for roadway construction. With any dimension, tighter tolerance implies slower and more expensive fabrication. For a cost-effective the system, positioning tolerances and longitudinal spacing must be maximized. The following analysis provides the maximum allowable spacing and tolerancing.

Dimensional Requirements for the General Case

Longitudinal Dimensions

- **Spacing** - A vehicle dynamic model was used to determine the maximum allowable longitudinal spacing of the markers.[7] Two cases were considered in the analysis:
  1) The vehicle turns with a large steering angle, $\delta = 4°$.
  2) The vehicle turns with a steering angle, δ, which ensures that lateral acceleration remains below the passenger comfort level of 0.3 g.

In order to determine the marker spacing that works in the first case, the vehicle was modeled to travel with a constant steering angle for a given time period. The longitudinal spacing required for the vehicle to follow the marker path was determined by interpolating the longitudinal distance traveled for a given lateral distance. This is illustrated in figure 5. This 'lateral distance traveled' corresponds to the amount of lateral correction the vehicle may need to make, defined previously as the lateral alignment tolerance. Note that longitudinal spacing and sensor range are coupled. A larger sensor range implies a larger acceptable marker spacing. To maximize spacing, the maximum possible sensor range should be used.

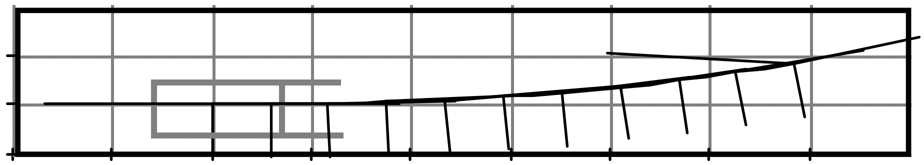

Figure 5. Sample data plot for dynamic modeling.

Several vehicles were modeled in this way, using vehicle parameters from Garrott, et al.[8] As a simplification, tire cornering stiffness was taken to be -9000 lb/rad for all cases. The vehicles were modeled at three different speeds: 48 km/h (30 mi/h), 81 km/h (55 mi/h), and 117 km/h (80 mi/h). The results from the first case ($\delta = 4°$) with the lateral distance to be traveled set at 250 mm is given in table 3. The lateral distance is based on the high resolution region of the sensing configuration used in the PATH experiments.[4]
Note that vehicles with lower mass and moment of inertia require the smallest longitudinal spacing. For this case, a longitudinal mark spacing of 6.5 meters seems to be appropriate for highway speeds of 81 km/h (55 mi/h).

The second case considers the passenger comfort level for lateral acceleration, by limiting lateral acceleration to 0.3 g. From table 3, it can be seen that lighter vehicles require the closest marker spacing. The 1987 Pontiac LeMans was modeled for a range of steering angles and lateral travel (sensor range) values. Analysis was performed for vehicle speeds of 81 km/h (55 mi/h) and 117 km/h (80 mi/h). Table 4 provides the lateral acceleration and longitudinal spacing required based on these simulations. Highlighted areas on the tables indicate lateral accelerations below 0.3 g. All highlighted values for longitudinal spacing would be considered 'comfortable' spacing values. For systems being designed with a target value for spacing, table 5 shows longitudinal travel vs. steering angle.

Table 3. Required longitudinal spacing for several vehicles, with 4° steering and 250 mm sensing range.

Constants:	
Cornering Stiffness (N/rad)	-40000
Applied Steering (rad)	0.07
Desired Lateral Travel (m)	0.25

Vehicle	1987 Lemans	1983 Jeep CJ-7	1985 Fiero
A: Dist. from Front Axle to CG (m)	1.00	1.22	1.39
B: Dist. from Rear Axle to CG (m)	1.52	1.16	0.98
M: Mass (kg)	940	1390	1260
Iz: Yaw Moment of Inertia (kg m^2)	1418	1994	1625
Min Spacing at 30MPH (feet)	16.26	18.75	18.65
Min Spacing at 55MPH (feet)	24.153	27.89	26.62
Min Spacing at 80MPH (feet)	32.392	37.52	35.48
Min Spacing at 30MPH (m)	4.96	5.72	5.68
Min Spacing at 55MPH (m)	7.36	8.50	8.11
Min Spacing at 80MPH (m)	9.87	11.44	10.81

Vehicle	1980 Olds 98	1987 Toyota LE	Ford F250 4x4
A: Dist. from Front Axle to CG (m)	1.32	0.94	1.45
B: Dist. from Rear Axle to CG (m)	1.70	1.30	1.94
M: Mass (kg)	1890	1510	2610
Iz: Yaw Moment of Inertia (kg m^2)	5006	2202	7944
Min Spacing at 30MPH (feet)	21.16	18.66	23.79
Min Spacing at 55MPH (feet)	33.08	31.63	38.10
Min Spacing at 80MPH (feet)	45.47	39.79	52.94
Min Spacing at 30MPH (m)	6.45	5.69	7.25
Min Spacing at 55MPH (m)	10.08	9.64	11.61
Min Spacing at 80MPH (m)	13.86	12.13	16.14

Table 4. Required longitudinal spacing for the 1987 Pontiac LeMans, steering angles vs. sensor range.

Lateral Acceleration (g) for a 1987 LeMans at 55 MPH (24.58 m/s)								
Lateral	Steering Angle							
Travel (m)	0.50°	1.00°	1.50°	2.00°	2.50°	3.00°	3.50°	4.00°
0.05				0.34	0.42	0.49	0.56	0.63
0.10				0.34	0.43	0.52	0.60	0.68
0.25				0.34	0.42	0.51	0.60	0.69
0.40				0.34	0.42	0.51	0.59	0.68
0.80				0.33	0.42	0.50	0.59	0.67

Longitudinal Travel (m) for a 1987 LeMans at 55 MPH (24.58 m/s)								
Lateral	Steering Angle							
Travel (m)	0.50°	1.00°	1.50°	2.00°	2.50°	3.00°	3.50°	4.00°
0.05				4.70	4.24	3.85	3.56	3.33
0.10				6.61	5.96	5.43	5.03	4.70
0.25				10.29	9.26	8.47	7.86	7.37
0.40				12.89	11.59	10.61	9.86	9.24
0.80				17.97	16.15	14.78	13.73	12.87

Lateral Acceleration for a 1987 LeMans at 80 MPH (35.76 m/s)								
Lateral	Steering Angle							
Travel (m)	0.50°	1.00°	1.50°	2.00°	2.50°	3.00°	3.50°	4.00°
0.05			0.44	0.57	0.70	0.82	0.94	1.05
0.10			0.43	0.58	0.73	0.87	1.01	1.15
0.25			0.39	0.54	0.69	0.84	0.99	1.15
0.40			0.38	0.51	0.65	0.80	0.95	1.10
0.80			0.37	0.50	0.62	0.75	0.88	1.02

Longitudinal Travel for a 1987 LeMans at 80 MPH (35.76 m/s)								
Lateral	Steering Angle							
Travel (m)	0.50°	1.00°	1.50°	2.00°	2.50°	3.00°	3.50°	4.00°
0.05			7.44	6.52	5.85	5.36	5.00	4.66
0.10			10.24	8.96	8.11	7.44	6.92	6.52
0.25			15.42	13.56	12.28	11.31	10.55	9.94
0.40			19.05	16.73	15.15	13.96	13.05	12.28
0.80			26.06	22.86	20.67	19.02	17.77	16.73

Table 5. Required lateral alignment tolerances for the 1987 Pontiac LeMans, steering angles vs. longitudinal spacing.

Lateral Acceleration (g) for a 1987 Lemans at 55 MPH (24.58 m/s)								
Long.	Steering Angle							
Travel(m)	0.50°	1.00°	1.50°	2.00°	2.50°	3.00°	3.50°	4.00°
1								0.317
2					0.315	0.378	0.441	0.504
5				0.341	0.427	0.512	0.597	0.682
10				0.339	0.423	0.508	0.593	0.677
20				0.334	0.418	0.502	0.585	0.669

Lateral Travel (m) for a 1987 Lemans at 55 MPH (24.58 m/s)								
Long.	Steering Angle							
Travel(m)	0.50°	1.00°	1.50°	2.00°	2.50°	3.00°	3.50°	4.00°
1								0.005
2					0.011	0.014	0.016	0.018
5				0.056	0.071	0.085	0.099	0.113
10				0.235	0.294	0.353	0.412	0.472
20				0.999	1.251	1.504	1.758	2.014

Lateral Acceleration (g) for a 1987 Lemans at 80 MPH (35.76 m/s)								
Long.	Steering Angle							
Travel(m)	0.50°	1.00°	1.50°	2.00°	2.50°	3.00°	3.50°	4.00°
1							0.308	0.352
2				0.315	0.394	0.472	0.551	0.630
10			0.429	0.572	0.715	0.859	1.002	1.145
20			0.374	0.498	0.623	0.747	0.872	0.996
30			0.372	0.496	0.620	0.744	0.868	0.992

Lateral Travel (m) for a 1987 Lemans at 80 MPH (35.76 m/s)								
Long.	Steering Angle							
Travel(m)	0.50°	1.00°	1.50°	2.00°	2.50°	3.00°	3.50°	4.00°
1							0.002	0.003
2				0.005	0.006	0.007	0.008	0.009
10			0.095	0.127	0.158	0.190	0.222	0.253
20			0.446	0.595	0.744	0.893	1.043	1.193
30			1.086	1.450	1.815	2.182	2.551	2.923

If the lateral control program can maintain lateral acceleration within the comfort range, then the data in table 4 is valid. Given a lateral sensing range of 250 mm, longitudinal spacing of 11 meters seems appropriate for highway speeds of 81 km/h (55 mi/h).

• **Spacing Tolerance** - As noted in the definition, spacing tolerance becomes critical when it either causes the spacing to exceed the maximum safe distance, or the range is so large that the marker spacing becomes significantly less cost-efficient. A recommendation for a good spacing tolerance would then be:

Upper Bound: +0
Lower Bound: -1 percent of the spacing dimension

From the spacing dimension based on passenger comfort, the spacing tolerance would be +0/-110 mm.

• **Cumulative Tolerance** - Based on the solution given in the definition of cumulative tolerance, it can be seen that this dimension is not significant.

Lateral Dimensions

• **Centering Tolerance -** Referring to figure 4, the ideal centering dimension would be 1/2 of W_{Lane}, i.e. directly in the center of the lane. The centering tolerance is found by calculating the 'unused' portion of the road. This is done by subtracting the maximum amount of the lane width required for vehicle travel. The remaining amount is the 'unused' portion, which can be used for the centering tolerance. This amount must also account for the effects of the other lateral tolerances, which would increase the limit of control width to $W_{LC'}$. Mathematically, the centering tolerance is given by:

$$T_{Centering} = \pm\frac{1}{2}\left(W_{Lane} - 2C - W_{Vehicle} - W_{Limit\ of\ Control} - \left(W_{LC}' - W_{Limit\ of\ Control}\right)\right) \tag{1}$$

$$T_{Centering} = \pm\frac{1}{2}\left(W_{Lane} - 2C - W_{Vehicle} - W_{LC}'\right) \tag{2}$$

• **Amplitude Tolerance** - The amplitude tolerance will increase the limit of control width in the following manner:

$$W_{LC}' = W_{LC} + 2\left(T_{Tilt}\right) + T_{Amplitude} \tag{3}$$

where W_{LC} = Original limit of control width
$W_{LC'}$ = Limit of control width for toleranced system
T_{Tilt} = Additional error caused by marker tilt
$T_{Amplitude}$ = Amplitude Tolerance

The amplitude tolerance has the largest effect on W_{LC}'; the error due to tilt tolerance is small and relatively difficult to adjust. Since centering tolerance is dependent on W_{LC}', centering and amplitude tolerances compete for roadway space.

Both the amplitude tolerance and the centering tolerance should be minimized. Of the two, it is more critical to minimize the amplitude tolerance, since the centering tolerance has little or no bearing on ride quality. A car following a set of markers with a large centering tolerance and a small amplitude tolerance follows a smooth, continuous path, but may come closer to the edge of the lane. A car following a set of markers with a small centering tolerance and a large amplitude tolerance will stay in the center of the lane, but tend to weave uncomfortably.

• **Alignment Tolerance** - Since the comfort level of lateral acceleration was used to determine the longitudinal spacing, and the amplitude tolerance, which is the limiting factor for alignment tolerance, is minimized and is much less than the longitudinal spacing dimension, the alignment tolerance can be set equal to the amplitude tolerance.

Vertical Dimensions

• **Depth Dimension and Tolerance** - Small differences in the installation depth will have no effect on vehicle control. Figure 6 gives the Hall-effect sensor readings, assuming that the marker is a magnetic dipole. The solid line represents readings for a dipole with its top flush with the pavement surface. Subsequent dotted lines represent readings if the dipole is installed further down into the pavement, in 2 mm increments.

Although the magnitudes of the horizontal and vertical components change with different installation heights, the relationship between the two components can still be used to determine the lateral displacement the marker at each height. This determination is already part of the lateral sensing system anyway, since the distance between the vehicle's sensors and the top of the markers will be variable.[1,4] Factors such as bouncing suspensions, varying tire radius, rutted pavements, etc., require the sensing system to deal with height differences of at least a few centimeters.

Therefore, it is estimated that an installation depth requirement with the top of the marker installed flush with the pavement surface, and a depth tolerance of ± 5 mm, is reasonable.

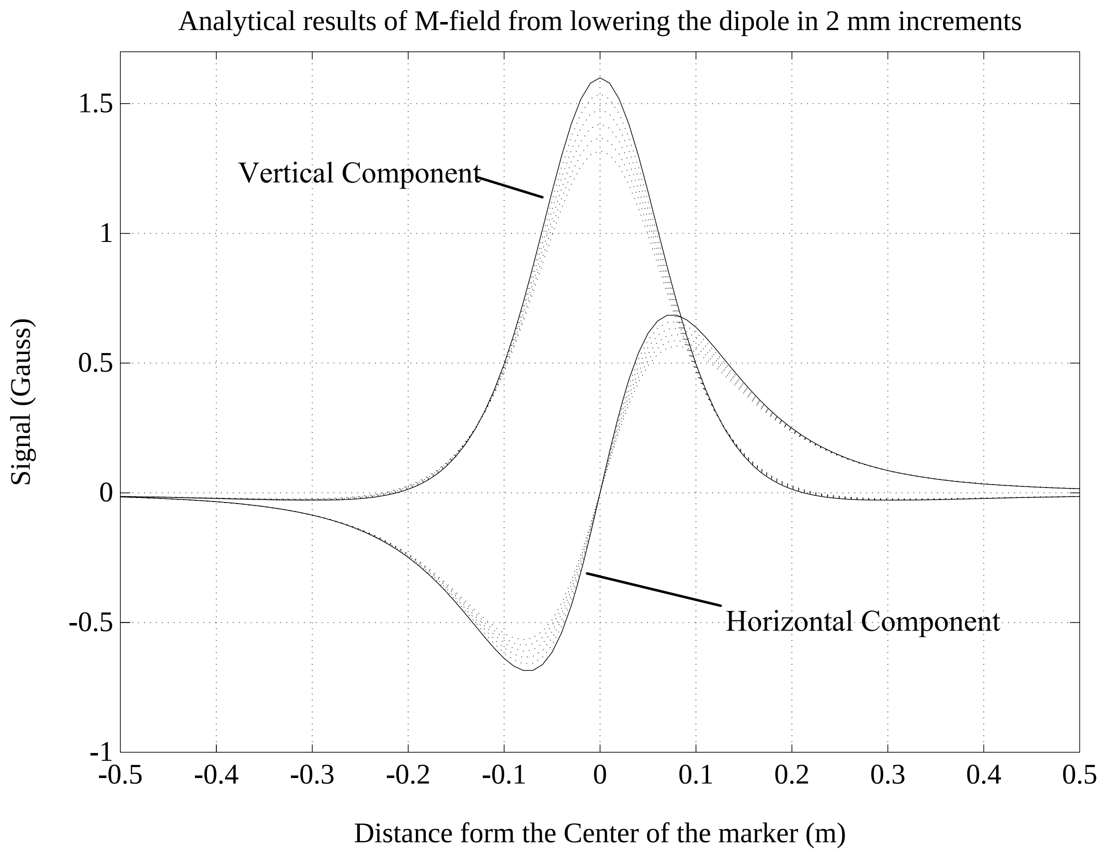

Figure 6. Sensed signal for dipole at different installation depths.

• **Angular Dimension and Tolerance -** Markers should be installed so that the magnetic field is normal to the road surface. The effects of tilting the dipole in 1° and 5° increments can be seen in figures 7 and 8. The solid line represents the vertical dipole; the dashed lines represent the dipole tilted in the indicated increments. Comparison of figures 7 & 8 to figure 6 indicates how the sensors will read a tilted dipole field. The detected results of a tilted dipole will resemble the results of a dipole that is weaker in signal, or further away from the sensors. The reading will also include a lateral error due to the tilt. Table 6 contains approximate error values for small degrees of tilting.

The acceptable tilt tolerance for a marker installation depends on the acceptable sensor error for the control system. Tradeoffs must be made between tilt accuracy, amplitude tolerance, and centering tolerance.

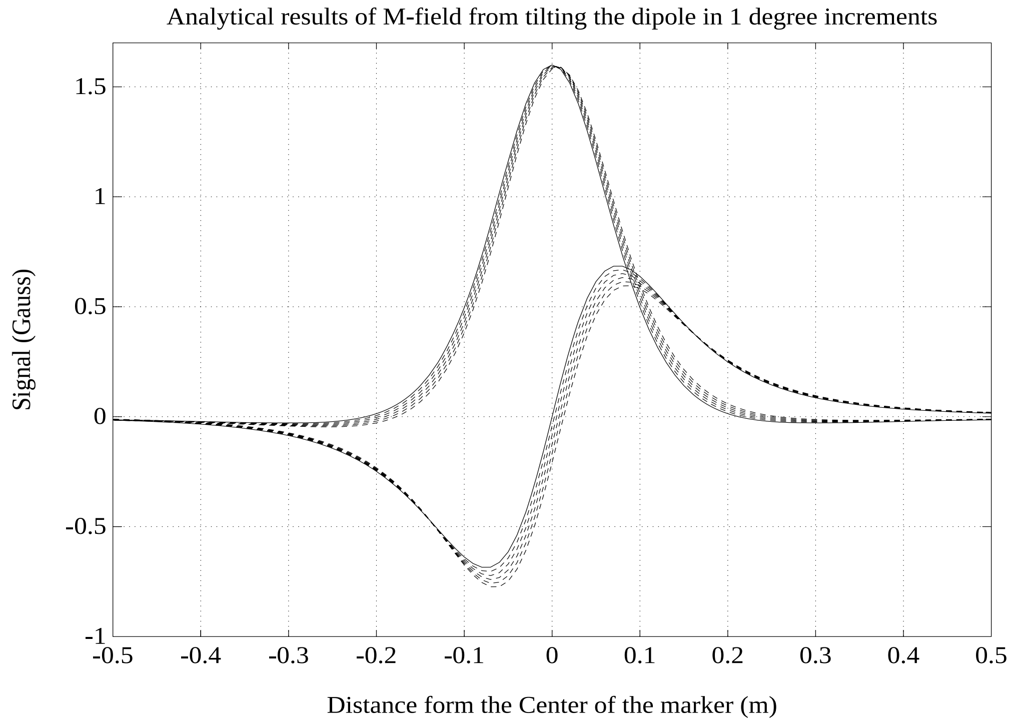

Figure 7. Sensed signal for dipole tilted in 1° increments.

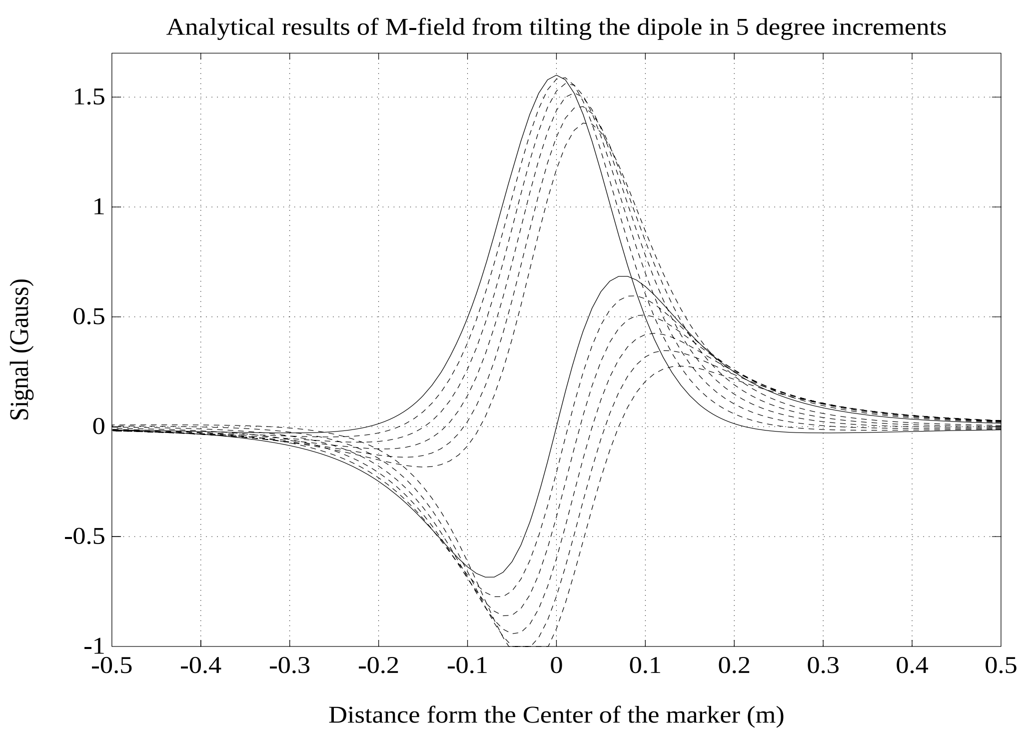

Figure 8. Sensed signal for dipole tilted in 5° increments.

Table 6. Effect of tilt on marker detection.

Tilt Angle Of Dipole	Distance between actual and perceived location of marker
0°	0.0 mm
1°	13 mm
2°	26 mm
3°	39 mm
4°	52 mm
5°	67 mm

Procedure for Employing Dimensional Requirements

The following example demonstrates how to apply these dimensional requirements to determine tolerances for a specific system. The example used is for the PATH system mentioned in the previous section.

Step 1: Identify System Constraints

Identify the following parameters for the system (refer to figure 4):

Parameter	Example
Lane Width	3.658 m (12 ft)
Max. Vehicle Width	2.438 m (8 ft)
Clearance	0.254 m (10 in)
"Ideal" Limit of Control Width †	0.5 m (19.69 in)
Acceptable Limit of Control Width	0.6 m (23.62 in)
Vehicle Target Speed	88.5 km/h (55 mi/h)

† The ideal limit of control width refers to the expected error bound of the lateral control system when the markers are installed in 'perfect' locations. This value must be either estimated with a control simulation, or tested by installing markers under laboratory conditions, as done by PATH.[4]

The type of marker used will also constrain the system, in terms of installation depth. For this example, a nail-type marker is used, giving a depth tolerance of ±5 mm.

Step 2: Allot Tolerances for Lateral Errors

First, determine the available lane width which is left for tolerancing.

$$Available\ Width = W_{Lane} - 2C - W_{Vehicle} - W_{Limit\ of\ Control} \quad (4)$$

$$= 3.658 - 2(0.254) - 2.438 - 0.5$$
$$= 0.212 \textit{ meters}$$

Next, subtract out the difference between the acceptable and ideal control error bounds to obtain the *centering tolerance.*

$$\textit{Centering Tolerance} = \textit{Avail. Width} - (\textit{Acceptable L.C.} - \textit{Ideal L.C}) \tag{5}$$
$$= 0.212 - (0.6 - 0.5)$$
$$= 0.112 \text{ meters}$$

Next, the 0.1 m difference between the ideal and acceptable control error bounds is allocated between the amplitude tolerance and the error caused by angular tolerance.

$$\textit{Acceptable L.C.} - \textit{Ideal L.C} \geq \textit{Amplitude Tolerance} + 2(\textit{Error from Angular Tolerance}) \tag{6}$$

Here, 2° is used as the maximum angular tolerance, since that is the angular drilling precision of a standard industrial pavement drill. Referring to table 6 shows this value to be 26 mm, leaving:

$$\textit{Angular Tolerance} = 2°$$
$$\textit{Amplitude Tolerance} \leq 48 \text{ mm}$$

or, ± 0.024 meters from the centerline. The alignment tolerance would also be equal to ± 0.024 meters from the centerline.

Step 3: Identify Longitudinal Tolerances

Assume that the ideal limit of control width, or error bound, is 0.5 meters. Referring to table 4 and interpolating for a lateral travel of 0.5 meters gives a required longitudinal spacing of 16.26 meters between markers when the turning angle is 1.50°. Note that the actual limit of control width will be larger, due to the lateral tolerances derived in the last step. The required spacing for the actual limit of control width, best determined experimentally. will be longer than for the ideal case. Therefore, using the ideal case provides a safety factor.

The upper bound of spacing is +0, and the lower bound -0.16 meters, which is -1 percent of the spacing dimension.

These results for this example are summarized in table 7.

Table 7. Dimensions & tolerances from example.

Dimension	Values From Initial Testing
Longitudinal	
Spacing	16.26 meters Apart
Spacing Tolerance	+ 0, -0.16 meters
Cumulative Tolerance	Not Necessary
Lateral	
Centering Tolerance	0.112 meters
Amplitude Tolerance	± 0.024 meters from Centerline
Alignment Tolerance	± 0.024 meters from Centerline
Vertical	
Depth Dim. & Tol.	± .005 meters from Surface
Tilt Tolerance	2°

Magnetic Marker Casing

To protect the ceramic magnets from damage due to installation, weather, traffic, etc., a protective casing may be necessary. The casing can also be used to facilitate the installation procedure by providing a geometry that is easily installed and anchored. Any casing must fulfill the following requirements:

- **Field Strength Weakening** - The magnetic field should be observable 400 mm from the marker, with high resolution sensing 250 mm from the marker, as described in the introduction. Any casing should not weaken the signal past this point.
- **Internal Bonding Stability** - The magnets must be permanently attached to the casing in a way that will not allow the magnets to slip or rattle.
- **Internal Bonding Tolerance** - Ceramic magnets should be positioned consistently inside the casing, with a tolerance of 0.5 mm.
- **Environmental Concerns** - Any casing material or bonding adhesive used should comply with all California environmental codes.
- **Casing Cost** - Casings should be as inexpensive as possible, without loss of functionality. Marker and casing assemblies should be produced in large quantities to limit costs.

Bonding to Pavement

- **Bonding Stability** - Markers should be rigidly attached to the pavement. Movement of the marker over time constitutes an additional positioning error source.
- **Sealant Characteristics** - The following characteristics for sealants were taken directly from de Laski and Patsonson,[9] which describes the characteristics that manufacturers consider desirable in sealant for inductive loop detection systems:

- Hard enough to resist penetration by foreign materials and debris, such as nails, metal fragments, etc., that might damage the marker.
- Flexible enough to deform without cracking during thermal expansion and contraction. Sealant must not fracture in extreme cold, and must have good elongation properties.
- Able to wear down as the pavement surface wears down.
- Able to adhere aggressively to both concrete and asphalt road surfaces without a primer.
- Able to cure rapidly, minimizing the time a lane must be blocked. This requirement can be avoided by sanding the surface or purposely leaving the sealant about 1/8-inch (3.3 mm) lower than the pavement surface.
- Easy to use and mix, without heating.
- Usable in freezing weather.
- Insensitive to moisture so that it can be used on damp surfaces. Sealant should displace water, and not mix with it.

Coding Requirement

• **Marker Coding** - The markers will be installed with either a positive field or negative field orientation, in order to code roadway data. Markers must be packaged in a way that allows for selection of the correct polarity marker at the installation site.

Acceptable Degradation Standards

• **Marker Integrity** - Installation should not cause damage to marker which impedes functionality or accelerates degradation.

• **Pavement Integrity** - Installation should not cause damage to the roadway which reduces its service life.

• **Design Service Life** - Markers should be in place and operable for the life of the roadway.

Cost

• **Marker Cost** - The marker cost will be one of the larger expenses in this system. As such, the cost should be minimized wherever possible. However, the serviceability of the marker should not be compromised to save cost. Quality of signal strength, alignment and durability take precedence over cost.

CHAPTER 3: STRAWMAN CONCEPTS OF SUBSYSTEMS

Subsystem Identification

To facilitate the design process, the system is broken into subsystems, so that parts of the system can be designed concurrently. By identifying these subsystems, the skeletal frame of the system is put together.

A discrete magnetic marker placement system will require the following six subsystems:

• *Magnetic Marker Casing Subsystem* - Some form of bonding or housing will be needed to hold the individual magnets together. In addition, casing will probably be needed to protect the magnets from damage during installation and regular use. The casing can also be designed for easier installation.

• *Positioning Subsystem* - The markers must be positioned with the accuracy specified in the previous chapter. A detailed explanation of positioning systems is given at the beginning of the positioning subsystems section in this chapter.

• *Installation Subsystem* - The installation system is responsible for affixing the marker to the road. This system must also perform any required asphalt surface preparation, e.g. drilling, and ensure that the markers are installed within the depth and tilt requirements. Any systems presented in this section that involve making a hole in the pavement can control depth of installation by limiting the depth of the hole. Marker tilt can be controlled by having some part of the 'installer' contact the road surface as a reference.

• *Feeding and Storage Subsystem* - Handling of the magnetic markers may be difficult, since the markers will tend to attract or repel each other. A system is needed that can keep the markers neat and orderly during both storage and presentation to the installation unit.

• *Separation and Sorting Subsystem* - The separation and sorting system is responsible for taking the correct nail from the storage system, and delivering it to the installation system with the correct polarity. Information regarding the polarity marker needed at a given site can either be stored electronically, or preordered in a cartridge in the storage system.

• *Pre-Installation Inspection Subsystem* - Before the marker is installed in the pavement, a polarity checking inspection unit will verify that the correct polarity marker is in the installation unit.

Magnetic Marker Casing Subsystem Options

As mentioned in the functional specifications, the casing both to protects the ceramic magnets and eases installation. Three options for casings are presented here, as well as a brief analysis of the caseless system.

Magnetic Nail Markers
Subsystem: Magnetic Marker Casing

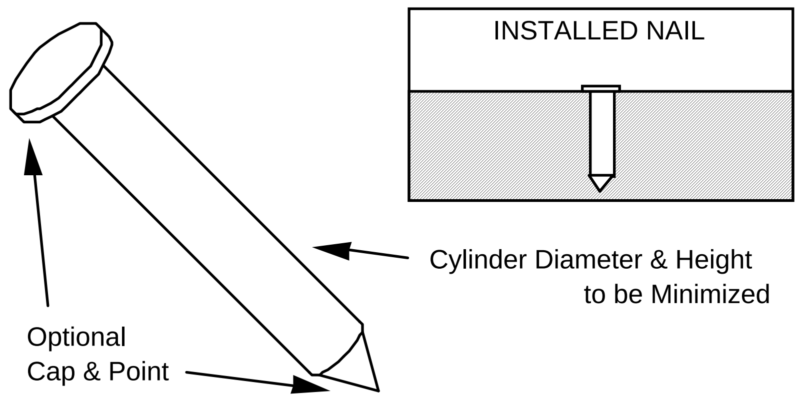

Figure 9. Magnetic nail marker.

Description:
The nail type marker would be essentially a cylindrical housing for the magnets. The diameter and the height of the nails would be minimized to ease installation. If gaps occur between the nail and pavement, filler material may be needed to hold the nail in place and seal the pavement.

As an option, a chamfer or point can be added on the lower end of the casing. The point will help guide the nail into a premade hole in the pavement. This guidance increases the allowable misalignment error, so a smaller diameter hole can be used. A smaller hole means less drilling time, and less filling material needed between the nail and the pavement. Countersinking the hole in the pavement to improve guidance in installation is not as viable, since the nail edge may cut into the soft asphalt, as shown in figure 10.

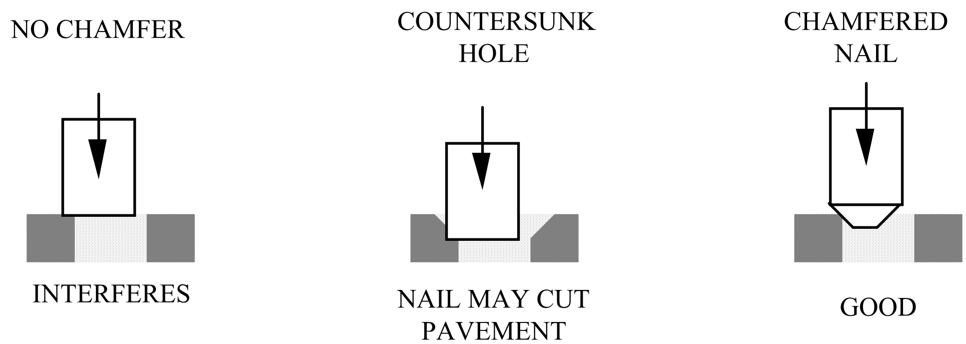

Figure 10. Effects of chamfering technique.

As another option, an oversized flat cap, or head, can be placed on the top end of the nail. This head would keep the top end of the nail aligned with the surface of the pavement. It can also be used to aid handling of new nails and removal of old nails, providing a convenient grasp geometry. An example nail with both the optional point and cap is shown in figure 9.

Advantages / Disadvantages:
+ Very resistant to damage.
+ Moderately inexpensive.
+ Chamfer/Point aids installation into hole.
- Of all presented casing concepts, the nail concept requires the largest pavement hole.

Magnetic Dot Markers
Subsystem: Magnetic Marker Casing

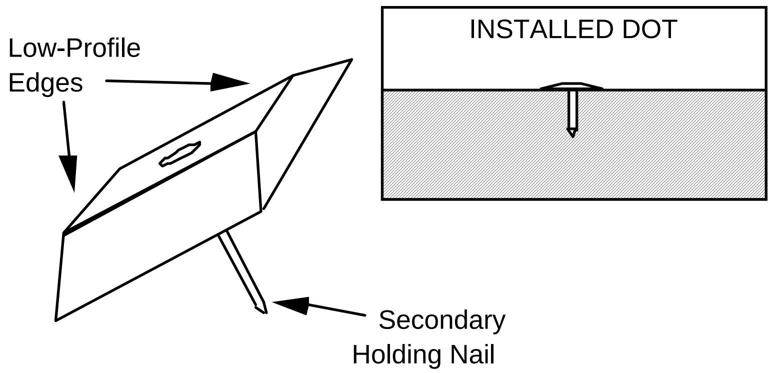

Figure 11. Magnetic dot marker.

Description:

The magnetic dot marker would be a marker that is attached to the surface of the roadway, rather than embedded in the asphalt. This marker casing is illustrated in figure 11. Rounded, low profile edges on the marker allow traffic to pass over the marker without dislodging it or damaging the casing.

The idea for a magnetic marker dot is based on existing Bott dot, which is a low profile raised pavement marker used to enhance lane edge visibility. One major difference between a magnetic dot and a Bott dot, aside from one containing magnets, is that the magnetic marker must be essentially a permanent fixture in the road. Because Bott dots are only for lane marking, a high percentage of the dots could be missing without affecting traffic. This is not the case for the magnetic markers, where a missing marker will have a significant impact on the performance and safety of the system.

The magnetic markers require a much stronger bond with the highway. While the dots are adhered the road with bitumen, as with Bott dots, they are also held down with a wire nail. Note that the nail may be redundant; since the magnetic markers will be placed in the center of the lane, rather than the edges, wear due to vehicle tires will be significantly less for the magnetic markers than for lane edge markers.

Advantages / Disadvantages:

+ Easiest concept to install.
+ A continuous installation system could be used, i.e. a system that does not stop while installing.
+ Of all concepts, damages the pavement the least.
+ Dots could be used for secondary optical scan, providing sensing redundancy.
+ Easiest to replace and/or update for new road configuration.
+ Installation depth is very easy to control.

+ Higher magnet location gives stronger signal to sensors.
- Most exposed system, since magnets are above the surface of the pavement.
- Dot markers may be expensive.

Bare Magnetic Markers (No Casing)
Subsystem: Magnetic Marker Casing

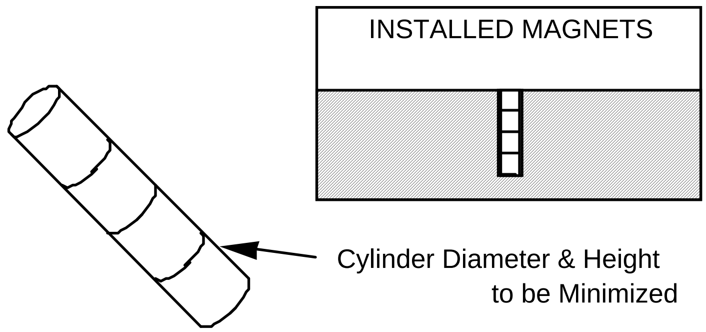

Figure 12. Bare magnetic markers.

Description:

This system features the four marker magnets glued together and installed in the pavement without any casing, as shown in figure 12. Some form of sealant would be needed between the magnets and the pavement. The advantage of this system would be the inexpensive markers. Also, if the marker needs to be removed, it can be easily drilled out. However, damage during handling, installation and use will be problems.

Advantages / Disadvantages:
+ Least expensive markers.
+ Magnets won't protrude past pavement surface; they will wear down to the surface level.
- Magnets can be easily damaged from handling/installation/traffic.
- System must be sealed in pavement.
- Installation depth will be difficult to control.

Receptacle Nail Marker
Subsystem: Magnetic Marker Casing

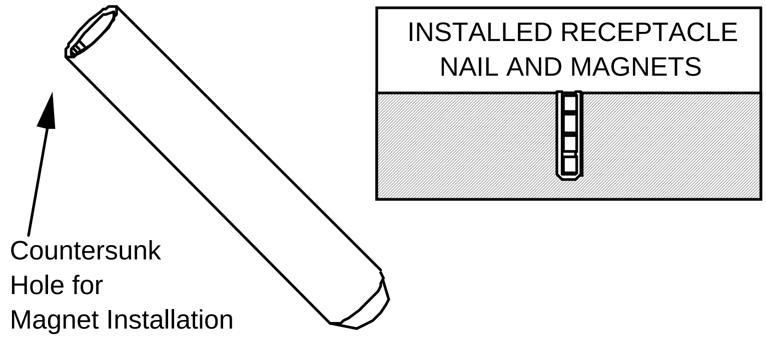

Figure 13. Receptacle nail.

Description:

The receptacle nail, shown in figure 13, is a variation of the nail presented in the “Definition of dimensions” section. The difference is that the nail is installed without the magnets. Magnets would be installed and sealed in the receptacles in a subsequent process. A significant advantage of this system is the ability to easily change magnetic coding after the full system is installed. This would be useful in situations where a new exit is added, or a lane is closed, for example.

Advantages / Disadvantages:

\+ Markers can be easily changed to cope with new road geometry.
\+ Once installed, magnets and casing are very resistant to damage.
\+ Moderately inexpensive.
\- Of all of the concepts presented for casing, the nail style would require the largest pavement hole.
\- Installation of casings and magnets requires two separate processes.
\- Magnets may be damaged easily when being installed into the casings.

Assessment of Magnetic Marker Casing Options

Each of the concepts presented for casings has distinct advantages and disadvantages. Table 8 shows a comparison of the systems for various performance criteria. Since some of the characteristics of the magnets to be used are currently unknown, the dimensions of the casings cannot be accurately estimated, so that the results shown in the table are somewhat speculative. An explanation of the criteria follows.

Table 8. Performance comparison of casing styles.

CASING STYLE	Speed of Installation	Least Damage To Road	Flexibility To Change	Endurance In Installation	Endurance In Road Use	Cost Per Marker
NAIL	🗐	🗐	🗐	🗐🗐🗐	🗐🗐🗐	🗐🗐
DOT	🗐🗐🗐	🗐🗐	🗐🗐🗐	🗐🗐	🗐🗐	🗐
BARE	🗐	🗐	🗐🗐	🗐	🗐	🗐🗐🗐
RECEPTACLE	🗐	🗐	🗐🗐🗐	🗐	🗐🗐🗐	🗐🗐

🗐🗐🗐 = Best Performance 🗐 = Worst Performance

• **Speed of Installation** - This refers to the number of successive steps needed to install the markers while the vehicle is stopped. Refer to the marker installation subsystems section for possible installation techniques. Casings requiring more than one sequential step while stopped were rated lowest. Casings that could be installed without stopping were rated highest. Speed of installation will be a critical factor in system design; as can be seen from the cycle time requirements in chapter 5.

• **Least Damage To Road** - This refers to the amount of cutting, drilling, or reshaping of the pavement required for installation. Casings that require the drilling of large holes or punching holes with heavy drivers were given the worst rating. The anchoring nail used in the dot design is considered a minor protrusion, and was given an average rating. The best rating would be given to a system that does not reshape the pavement at all, such as a dot without the anchoring nail. Preliminary analysis of the effects of drilling holes in the pavement was done to investigate the importance of this factor. Currently, no evidence has been found to show that drilling large holes in the lane centerline will significantly reduce pavement life. However, further testing is recommended.

• **Flexibility to Change** - If, for any reason, the coding of a road segment must be changed on either a temporary or permanent basis, the magnets will need to be replaced. The flexibility criterion refers to the relative ease of casing removal. The dot and cartridge magnets could be removed without significant pavement disturbance or complex operations, and were given the highest marks. The bare markers are given an average flexibility rating, since they can be drilled out, but the plain nail would probably need some complex procedure.

• **Endurance in Installation** - This rates the casing for protection of the magnets during installation. A heavy-duty casing, such as the nail, will protect the magnets best. The dot may be considered light-duty, since it would most likely be made of plastic or ceramic. Systems that don't provide protective casing at all when the magnets are installed will be the least protective. The rating given for the receptacle system assumes that the magnets will be added after the casing is installed.

• **Endurance in Road Use** - This is an assessment of how well the casings will protect the magnets from damage during their use in AHS guidance. Casings designed to shield magnets from both traffic loading and pavement shifting were given the best rating. The dot markers rely partially on their placement in a non-trafficked portion of the lane for protection, rather than the casing design itself, so they only get an average rating. Casings which lack protection from shifting pavement are given the lowest rating. The bare markers would only have the compliance of the bonding sealant for protection from pavement shifting. Since asphalt pavements are flexible, this is an important factor.

• **Cost Per Casing** - The cost per casing is a part of the cost per marker specification, which is to be minimized. The worst rating goes to the relatively expensive dots, based on the relative known expense of current lane marking dots. The nail and cartridge casings are estimated to be relatively cheap, due to simple geometry and inexpensive material. The bare markers don't have a casing, and receive the best score.

Positioning Subsystems

The strawman concepts for positioning systems are defined by the following three factors:

- <u>Type</u> of positioning performed (Lateral, Longitudinal, or Both).
- <u>Method</u> of measurement.
- <u>Landmark(s)</u> that measurements are taken with respect to.

Lateral and longitudinal positioning are, in most cases, treated as two different systems, since they are referenced to different classes of landmarks. Lateral positioning is referenced w.r.t. road geometry, while longitudinal positioning is referenced w.r.t. previous marker installation sites.

Both longitudinal and lateral positioning concepts are presented in this chapter. The description, basic operational procedure, and advantages & disadvantages of each system are also presented. Error sources for each system are identified, but not quantified.

Positioning Type

Lateral systems place the installation unit over the lane centerline. For each lateral system, the sources of centering and alignment error are listed . Centering error is a measure of how far the reference center, or average position, of the makers may be from the center of the road. The alignment error describes how far individual markers may be from the reference line .

Longitudinal systems ensure that markers are spaced the proper distance apart. For each longitudinal system the sources for spacing error, e_S, and cumulative error, ne_S are listed. Spacing error is the error in placement between two markers. Cumulative error is the error that builds up after installing several markers.

Positioning Method

Three types of positioning methods are considered. The methods are classified based on the approach used for landmark referencing and installation unit positioning.

Direct Comparison Methods - Direct comparison methods refer to operations where either the landmark referencing, or the installation unit positioning, or both, are done by a human operator. Direct comparison methods generally are the simplest; therefore, they are typically inexpensive and easy to maintain. However, the human operator may cause more error, .

Automatically Calibrated Methods - For these methods, all referencing and final positioning is automated. The references used with these systems will be on-site landmarks.

Database Methods - References for database methods are taken from previously recorded information, such as topographical highway maps, instead of relying solely on on-site landmarks.

Positioning Landmarks

The following outline indicates the landmark reference systems that are treated in this report:

Lateral Type

- Direct Comparison Method
    - Centerline Reference
    - One Edge of Pavement Reference
    - Two Edges of Pavement Reference
- Automatically Calibrated Method
    - Two Markers at Edge of Pavement Reference

Longitudinal Type

- Direct Comparison Method
    - Last Installation Site
- Automatically Calibrated Method
    - Last Installation Site

Lateral & Longitudinal Combined

- Database Method

- Differential Global Positioning System
- Dead Reckoning System
- Last Two Installation Sites

Lateral Type -- Straight Roadways Only

Automatically Calibrated Method

- Manufactured Group Positioning
- Laser Guidance

Painted Line Follower
Subsystem: Lateral Reference (Centerline) Location System - Direct Comparison Method

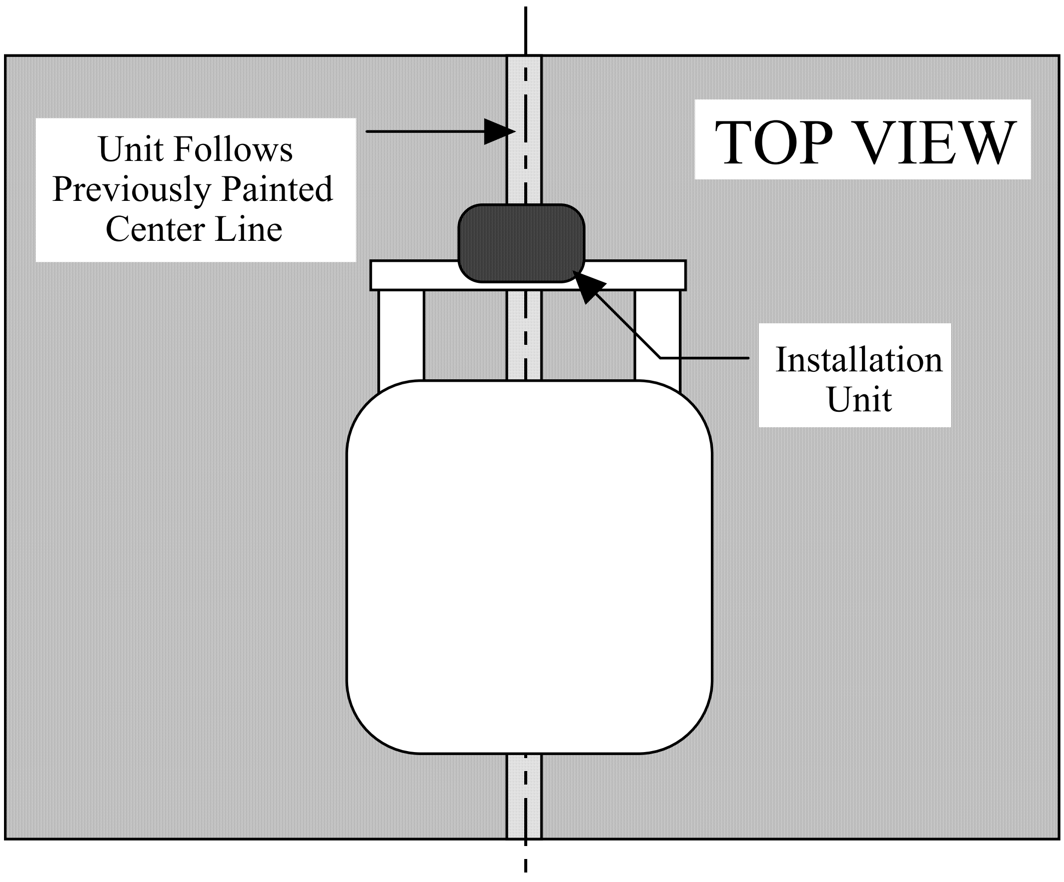

Figure 14. Painted line follower.

Description:

The Painted Line Follower, shown in figure 14, rides along a previously painted centerline. The magnetic markers are installed along the center of this line, with the operator locating the center of the line by eye. A linear slide may be needed to adjust the position of the installation device.

The painted line can be laid out using techniques based on conventional lane demarcation methods. A much narrower line than the lane marking lines can be used, since this line will only be used as an installation reference.

Operation:
1) Regular measurements are made to locate path of painted line.
2) Thin line is painted down center of lane.
3) Magnetic markers are installed by the operator along the center of the painted line.

Advantages / Disadvantages:
+ Markers are placed along a smooth, continuous line. Lateral variation is minimized.
+ Painted line may be used for other purposes.
- Surveying error could keep line off of true center.
- Line may not be exactly on lane center.
- System relies on human operator.
- Requires sequential measuring, line painting, and installation operations.

Referenced w.r.t.: Painted Centerline

Centering Error:

$$e_{\text{Edge of Pavement Survey}} + e_{\text{CenterlinePainting}} + e_{\text{Operator Placement}} \quad (7)$$

Alignment Error:

$$e_{\text{CenterlinePainting Smoothness}} + e_{\text{Operator Placement}} \quad (8)$$

Ruled Edge Locator
Subsystem: Lateral Reference (Centerline) Location System - Direct Comparison Method

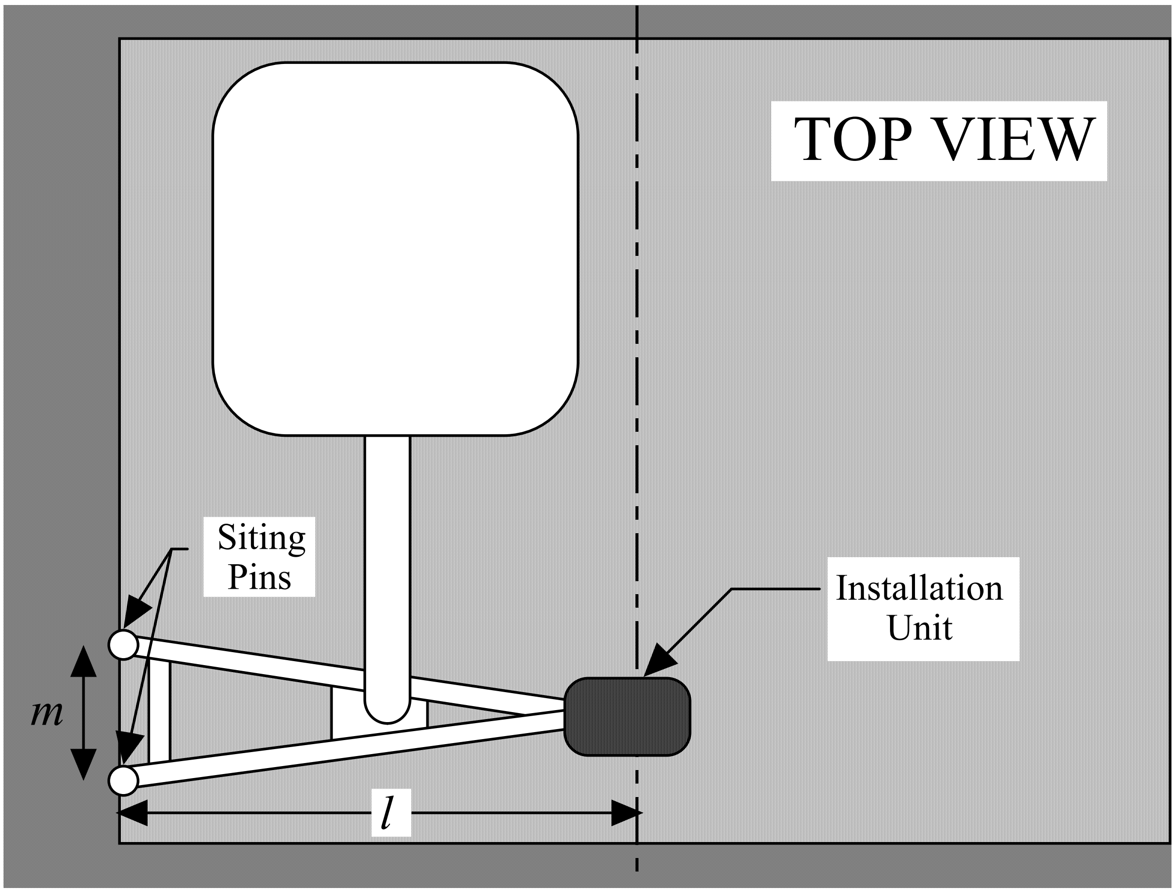

Figure 15. Ruled edge locator.

Description:

The Ruled Edge Locator uses one edge of the lane as a reference to find the center of the lane, as shown in figure 15. In this system, the lane width is assumed to be a constant, 2*l*. To place markers in the center, an arm of length *l* is aligned by positioning two siting pins over the Edge of Lane (EL) line. The EL line could either be a longitudinal joint between lanes, or a pre-painted line. When both pins are over the EL line, the installation unit is in the center of the lane, and installation begins. This design may need the ability to rotate the siting/installation assembly 180°, so that either edge of the lane could be used.

Operation:
1) Drive to approximate installation site.
2) Move both siting pins directly over Edge of Lane line.
3) Install marker.

Advantages / Disadvantages:
+ Simple operation
- System relies on human operator.
- System requires a smooth and discernible Edge of Lane line.
- System assumes that lanes are of constant width.

Referenced w.r.t.: One Edge of Pavement Line

Centering Error:

$$e_{\text{Edge of Pavement Survey}} + l - l \cos \sin^{-1}\left(\frac{e_{operator\ placement}}{m}\right) \tag{9}$$

Alignment Error:

$$e_{\text{Edge of Pavement Smoothness}} + l - l \cos \sin^{-1}\left(\frac{e_{operator\ placement}}{m}\right) \tag{10}$$

Note: This method may impart additional error in the longitudinal direction.

Averaged Edge Reference Locator
Subsystem: Lateral Reference (Centerline) Location System - Direct Comparison Method

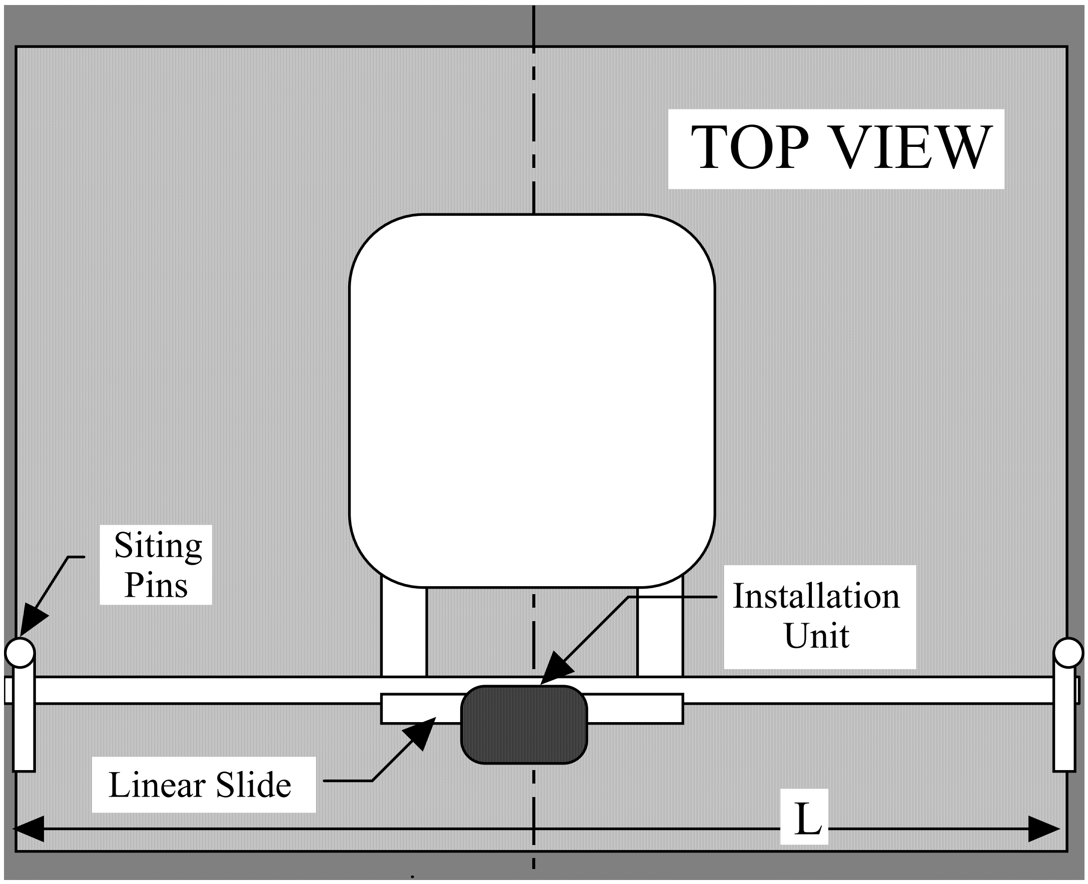

Figure 16. Averaged edge reference locator.

Description:

The Averaged Edge Reference system, illustrated in figure 16, uses both edges of the lane to find the center. As shown in the figure, there are siting pins on either side of the arm. The operator positions these pins over the EL lines, using a servo system. Once the pins are in place, the system automatically centers the installation unit on a linear slide, and the marker is placed.

Operation:
1) Drive to approximate installation site.
2) Operator moves siting pins directly over Edge of Lane lines.
3) Operator activates linear slide.
4) Linear slide moves installation unit to the center of the lane.
5) Marker is installed.

Advantages / Disadvantages:
+ Automated Centering
- May be slow to position.
- System assumes two smooth and discernible Edge of Lane lines.

Referenced w.r.t.: Two Edge of Pavement Lines

Centering Error:

$$2(e_{\text{Edge of Pavement Survey}}) + 2(e_{\text{Operator Placement}}) \tag{11}$$

Alignment Error:

$$2(e_{\text{Edge of Pavement Smoothness}}) + 2(e_{\text{Operator Placement}}) \tag{12}$$

Reflected Wave System
Subsystem: Lateral Reference (Centerline) Location System - Automatically Calibrated Method

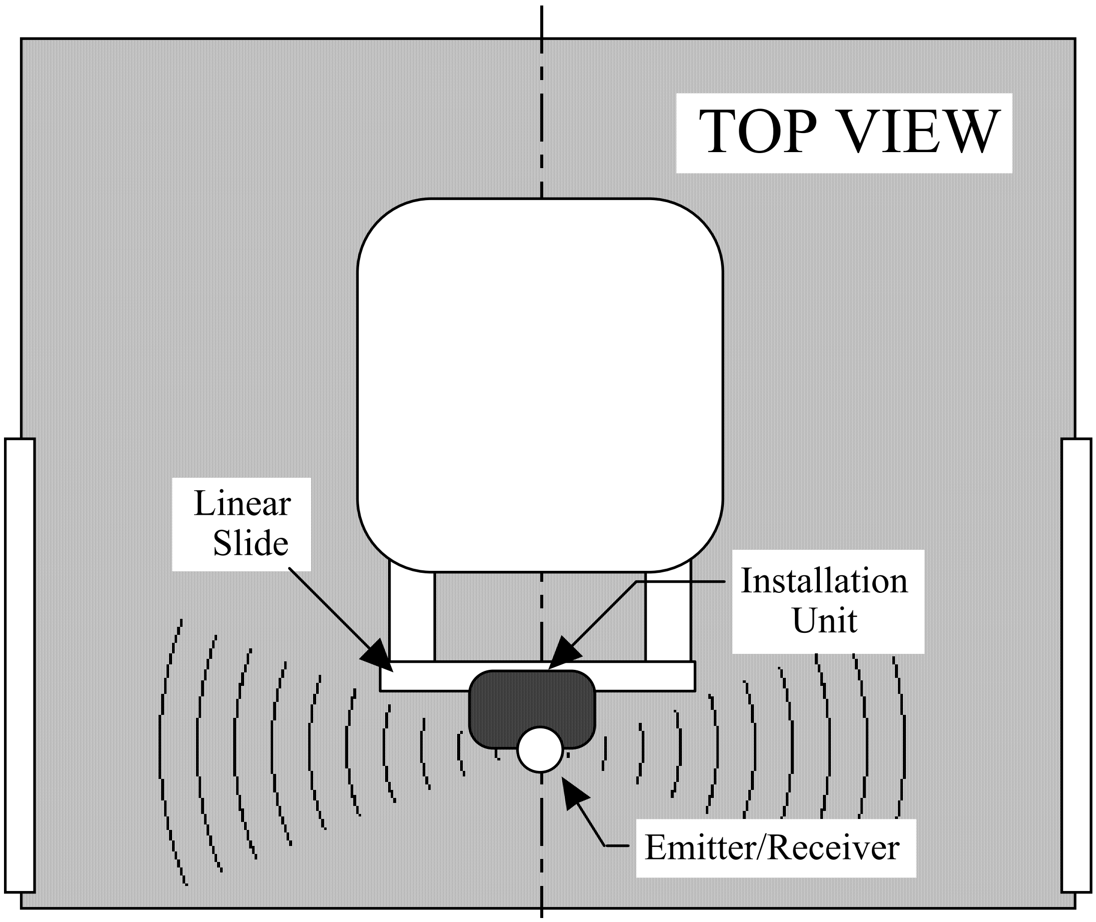

Figure 17. Reflected wave system.

Description:

This system, shown in figure 17, requires that there be some sort of reflective surface, such as a jersey barrier, located on both edges of the lane. When the system operates, pulsed sonic waves are sent out from a point on the installation unit in both lateral directions. These waves are reflected back off of the surfaces, then monitored by a receiver that is at or near the location of the emitter. If both reflections are not received within a specified time envelope, *t*, then the unit is not centered. A linear slide would then move the unit in the direction of the wave that had to transverse the longer distance and continue to emit and receive until both reflections are detected within time *t*. When both signals are received within the envelope, the unit is centered and the marker can be installed.

Operation:
1) Drive to approximate installation site.
2) Pulsed signal is emitted in both directions, then reflected back to receiver.
3) Installation unit slides towards the lagging signal side.
4) Pulsed signal continues during motion.
5) Slide stops when both signals are received within time envelope, *t*.
6) Marker is installed.

Advantages / Disadvantages:
+ Automated Centering
+ Quick to position.
- Desirable configurations on curves would require curved barriers.
- System requires barriers or other reflective surfaces.

Referenced w.r.t.: Two Edge of Pavement Reflective Markers

Centering Error:

$$2(e_{\text{Marker Placement}}) + e_{\text{Emitter/Receiver}} \tag{13}$$

Alignment Error:

$$2(e_{\text{Marker Smoothness}}) + e_{\text{Emitter/Receiver}} \tag{14}$$

Forward "Compass" Ruled Measure
Subsystem: Longitudinal Spacing System - Direct Comparison Method

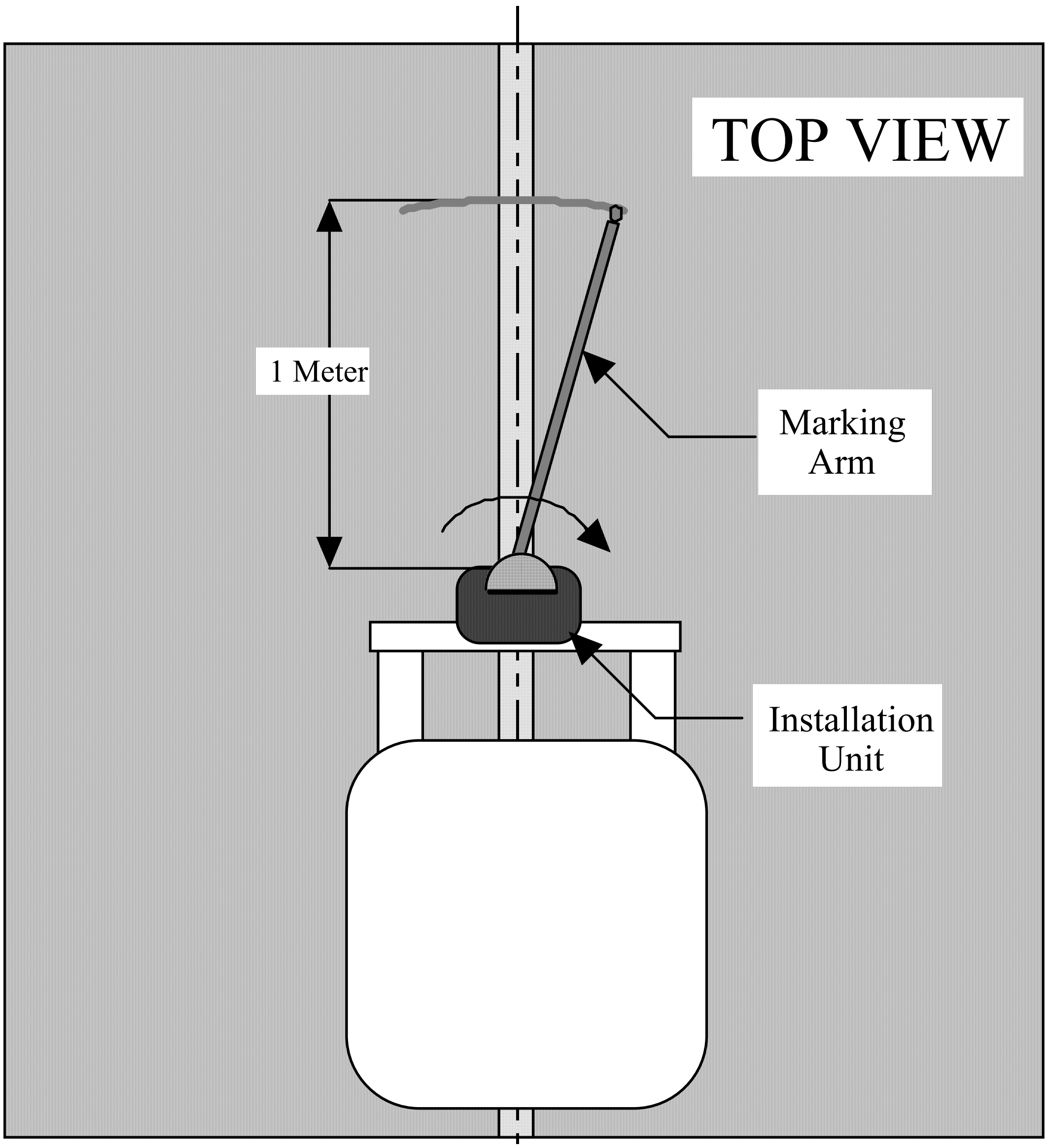

Figure 18. Forward "Compass" ruled measure.

Description:

The "Compass" system, illustrated in figure 18, uses direct ruled measurement to mark the installation locations for discrete markers. The system depends on the location of the previous installation site, measuring for the location of the second marker while the first is currently being installed. While the first discrete marker is being installed, a meter long arm with a sketching device draws an arc across a previously marked center line. The intersection point of the arc and the line indicates the next marker installation site. Note that for this system, the centerline must be detectable; a pre-painted centerline would be the easiest for the operator to see.

Note that this operation can occur while a marker is being installed at the last measured location.

Operation:
1) Marker is installed.
2) While marker is being installed, forward compass arm draws a small arc across a painted center line.
3) Operator positions installation unit over "X" created by the arc crossing the center line.
4) Operation is repeated.

Advantages / Disadvantages:
+ Simple system.
+ Quick, since two operations done simultaneously.
- Will not measure w.r.t. arc length.
- Requires previously painted center line.
- System relies on human operator.

Referenced w.r.t.: Last Installation Site

Spacing Error:

$$e_{\text{Measurement Technique}} + e_{\text{Operator Placement}} \tag{15}$$

Cumulative Error:

$$\sum_{Start}^{End} \left(e_{\text{Measurement Technique}} + e_{\text{Operator Placement}}\right) \tag{16}$$

Ruled Measure from Previous Mark
Subsystem: Longitudinal Spacing System - Automatically Calibrated Method

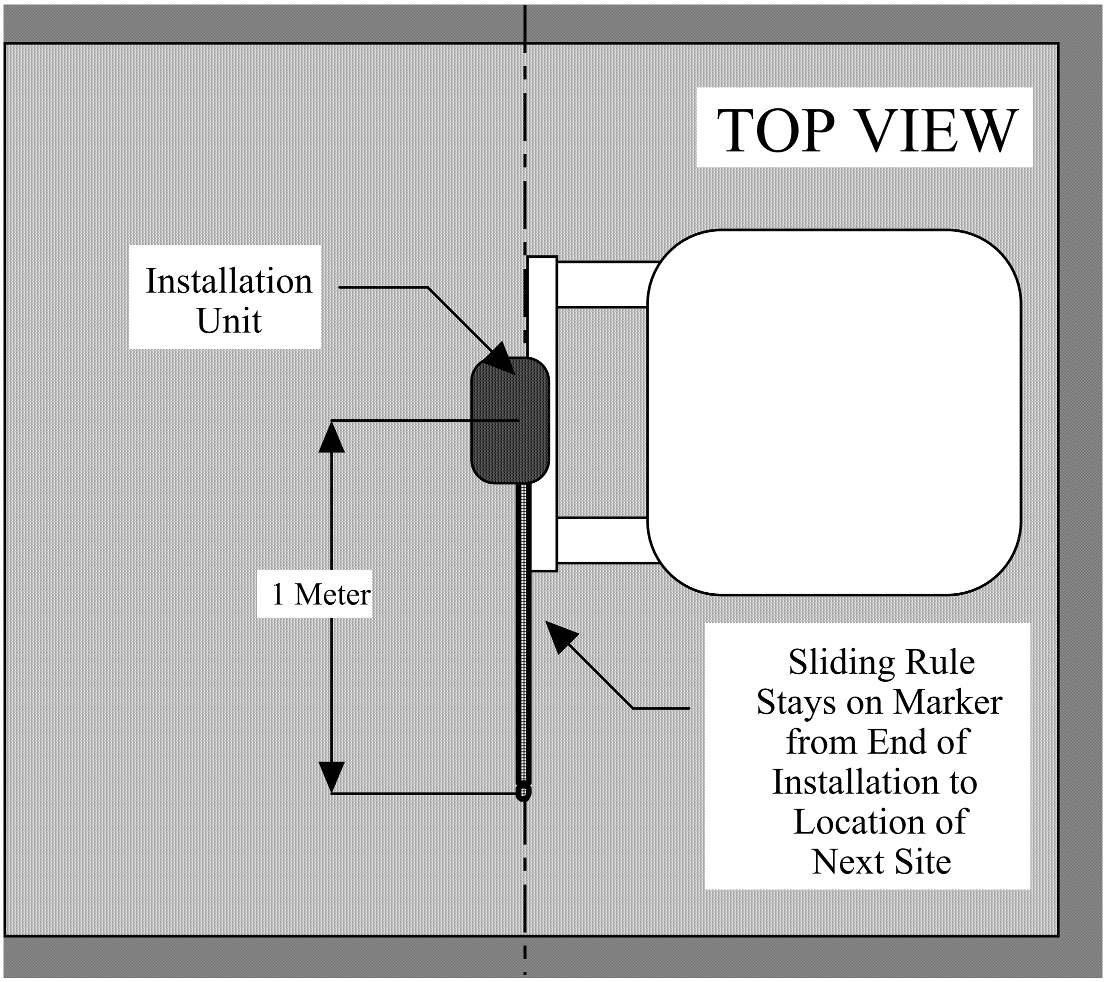

Figure 19. Ruled measure from previous mark.

Description:

This system uses direct ruled measurement from a previously installed marker to locate the next installation site, as shown in figure 19. After a marker is installed, a sliding rule is attached to its top, possibly magnetically. The rule extends as the installation truck travels towards the next site. When the rule is extended one meter, the truck stops, and the next marker is installed. The sliding rule is then detached from the first marker, and attached to the newly installed marker.

Operation:
1) Marker is installed.
2) End of sliding rule attaches to installed marker, possibly magnetically.
3) Truck moves to next site.
4) When rule is extended one meter, truck stops and installs marker.
5) Rule detaches from old marker, retracts, then attaches to new marker.

Advantages / Disadvantages:
+ Fairly quick.
+ Uses direct ruled measurement.
- Will not measure w.r.t. arc length.
- Complex system.
- Connection to marker will be a source of difficulty.

Referenced w.r.t.: Last Installation Site

Spacing Error:

$$e_{\text{Measurement Technique}} \tag{17}$$

Cumulative Error:

$$\sum_{Start}^{End} (e_{\text{Measurement Technique}}) \tag{18}$$

Encoder Wheel System
Subsystem: Longitudinal Spacing System - Automatically Calibrated Method

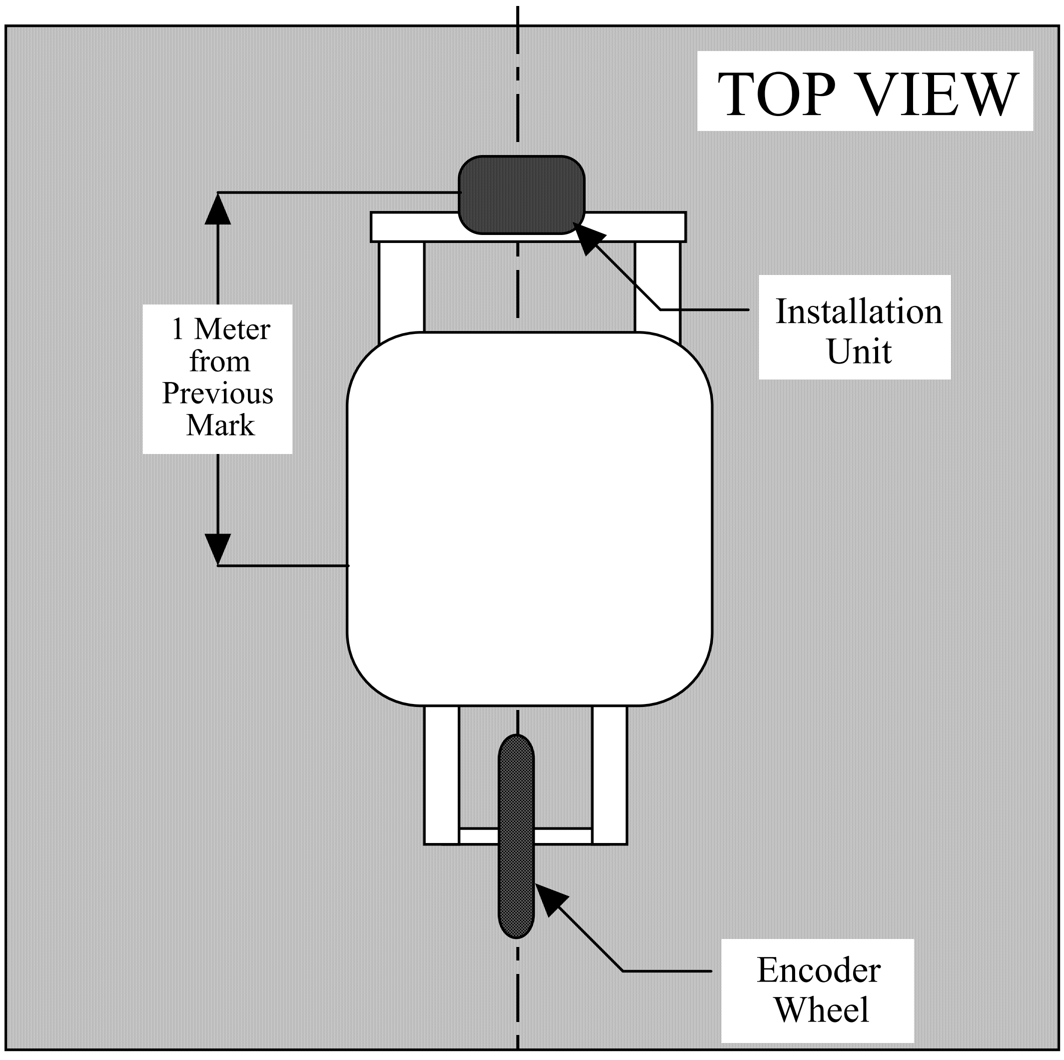

Figure 20. Encoder wheel system.

Description:

This system, shown in figure 20, uses an encoder wheel to find installation locations in one meter increments. For best accuracy, this wheel should operate on the centerline of the lane, or two wheels should be equally spaced on either side of the centerline, and the average of the two readings used

Operation:
1) Marker is installed.
2) Truck moves forward until encoder wheel signals a stop.
3) Repeat.

Advantages / Disadvantages:
+ Very simple system.
+ Quick.
+ Could be used with continuous marking systems.
+ Automatically makes corrections for arc length.
+ Controls cumulative error.

Referenced w.r.t.: First Installation Site

Spacing Error:

$$e_{\text{Measurement Technique}} \tag{19}$$

Cumulative Error:

$$e_{\text{Measurement Technique}} \tag{20}$$

Hall-Effect Distance Measuring System
Subsystem: Longitudinal Spacing System - Automatically Calibrated Method

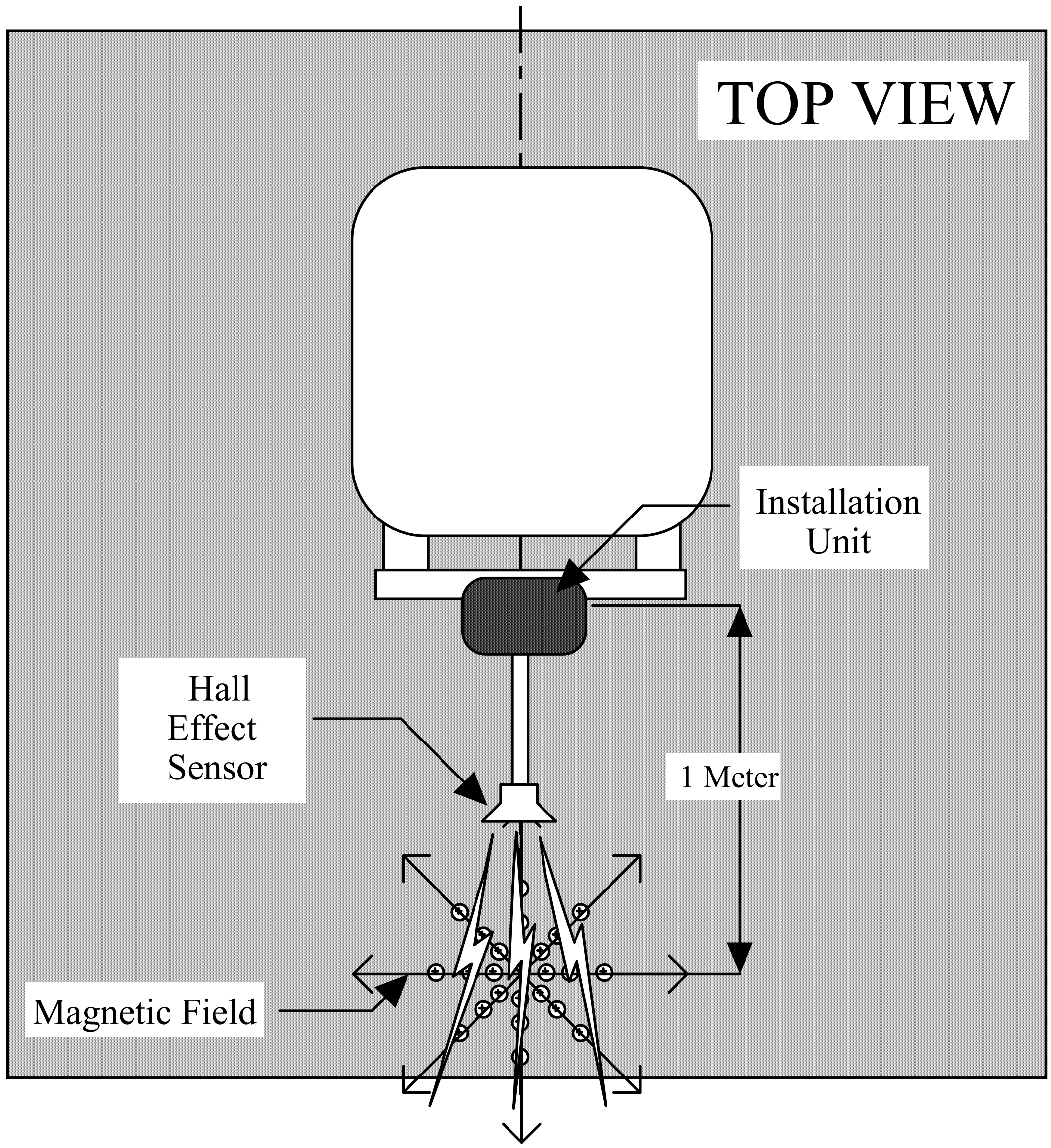

Figure 21. Hall-Effect system.

Description:

The Hall-Effect System, shown in figure 21, utilizes the magnetic field of the nail to measure distance. In operation, a Hall-effect magnetometer searches for a magnetic field strength, *B,* from the previously installed magnet. For measurement resolution of 1 percent, a Hall-Effect probe is adequate.[10] The strength *B* is an experimentally determined value which will be received when the distance from the marker to the sensor combined with distance from the sensor to the installation unit is exactly one meter.

Operation:
1) Marker is installed.
2) Truck moves forward until magnetometer reads correct signal. Truck stops.
3) Repeat.

Advantages / Disadvantages:
+ Markers are placed by a system that is similar to the vehicle lateral sensing system.
+ Quick.
+ Could be used with continuous marking systems.
- Will not measure w.r.t. arc length.
- Finding precision field strengths may be difficult.

Referenced w.r.t.: Last Installation Site

Spacing Error:

$$e_{\text{Measurement Technique}} \tag{21}$$

Cumulative Error:

$$\sum_{Start}^{End} \left(e_{\text{Measurement Technique}}\right) \tag{22}$$

Galvanometer Distance Measuring System
Subsystem: Longitudinal Spacing System - Automatically Calibrated Method

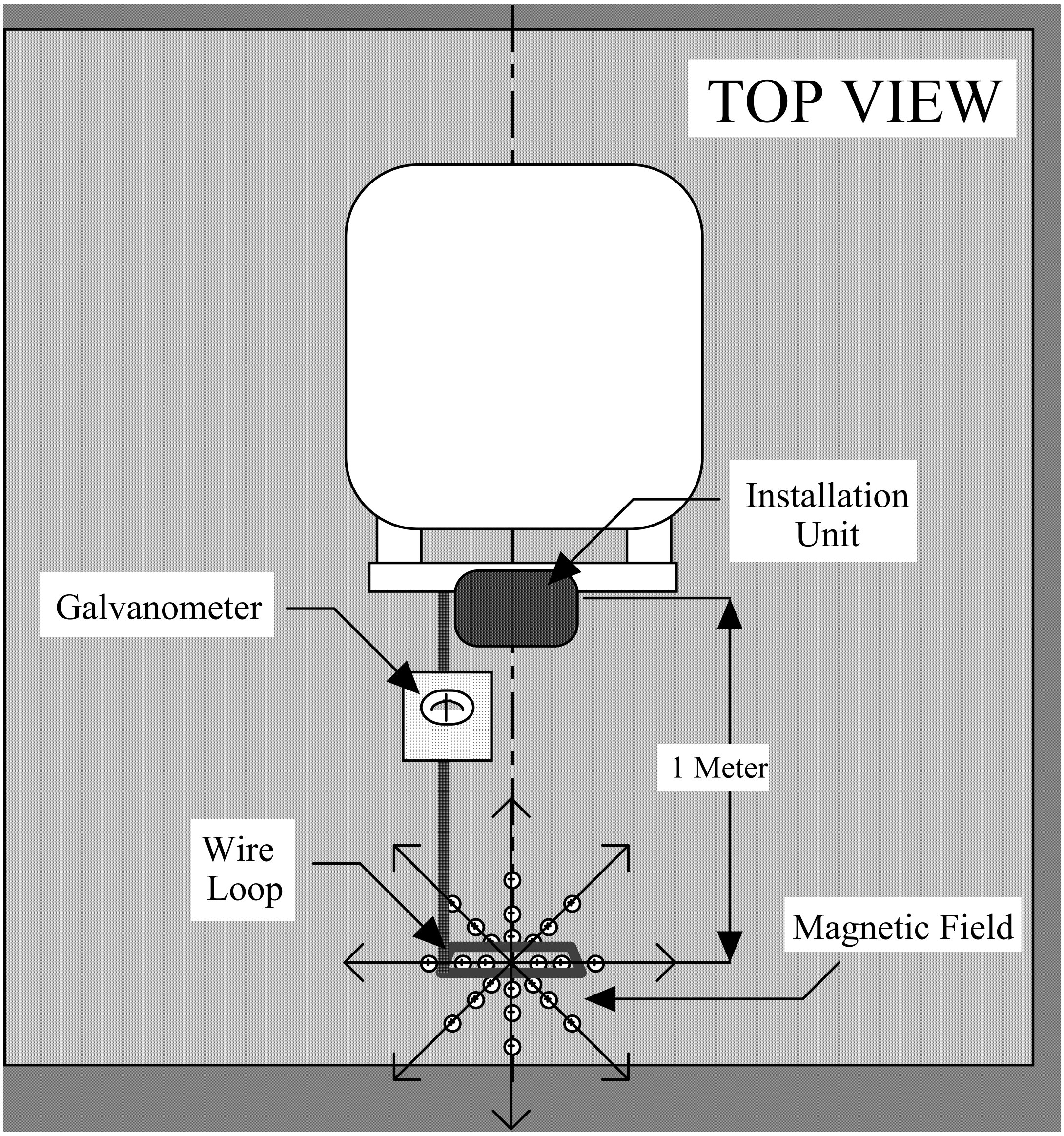

Figure 22. Galvanometer System.

Description:

The Galvanometer system, illustrated in figure 22, senses the magnetic field of the discrete marker by crossing part of the last magnet's field with a loop of wire to induce a current. The loop is oriented so that it is perpendicular to the road surface. When the loop is directly over the marker, it will be perpendicular to the magnetic field, and the reading will drop to zero, as shown in figure 23. The loop of wire will be spaced one meter from the installation unit.

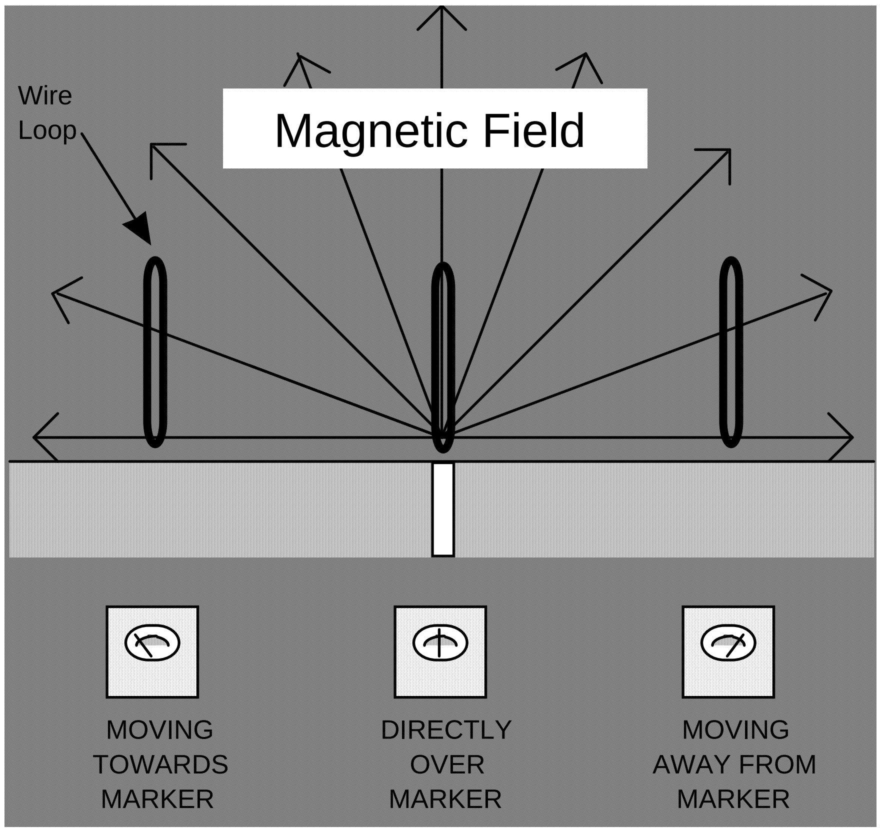

Figure 23. Galvanometer readings as wire loop moves through M-Field.

Operation:
1) Marker is installed.
2) Truck moves forward until galvanometer reads zero signal. Truck stops.
3) Repeat.

Advantages / Disadvantages:
+ Zero signal should be easily detectable.
+ Quick.
+ Could be used with continuous marking systems.
- Will not measure w.r.t. arc length.
- Wire loop must be in motion for system to work.
- Complex system.

Referenced w.r.t.: Last Installation Site

Spacing Error:

$$e_{\text{Measurement Technique}} \tag{23}$$

Cumulative Error:

$$\sum_{Start}^{End} (e_{\text{Measurement Technique}}) \tag{24}$$

Differential Global Positioning System (D-GPS) Method
Subsystem: Lateral & Longitudinal System - Database Method

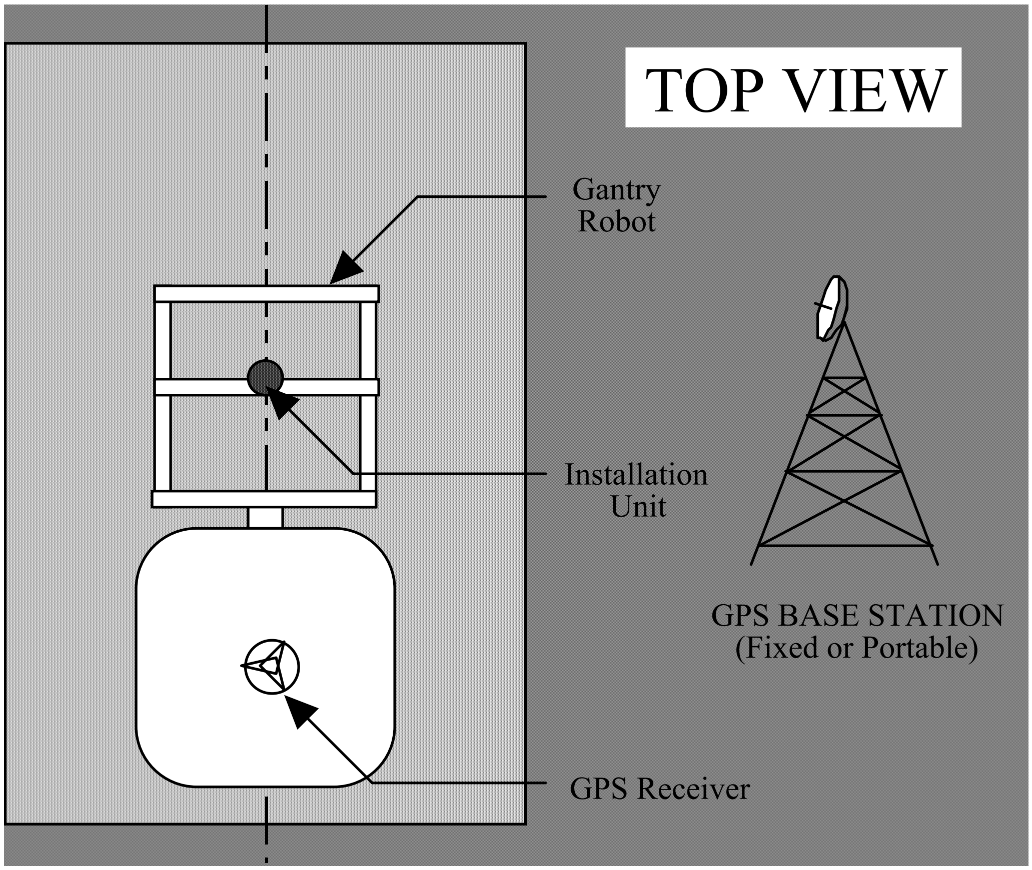

Figure 24. Installation using D-GPS.

Description:

A Global Positioning System (GPS), shown in figure 24, could be used to determine both longitudinal and lateral positioning, given preplanned coordinates for the installation locations. GPS is a triangulation system which uses the position of at least four orbiting satellites for reference points. To obtain acceptable working speed and accuracy, less than 10 mm, it is necessary to use Differential GPS and Carrier Phase Tracking. See [11] for details on GPS technology.

This type of system is not recommended for use on existing roads that are to be retrofitted with new markers. Refer to chapter 5 for detailed explanation.

The GPS receiver for the system would have to be placed the installation vehicle at a known or calibrated distance from the installation unit. The receiver in figure 24 is shown as being on the vehicle itself, where it would be protected from installation vibrations. Since D-GPS provides point locations, a method is needed to determine the orientation of the vehicle. One possibility is to use second GPS receiver. Another alternative would be to mount the receiver directly over the installation unit, and provide vibration damping.

Operation:

1) Vehicle drives to approximate installation location.
2) D-GPS system determines location of receiver(s).
3) Orientation of installation unit is determined.
4) Gantry robot moves installation unit to installation site.
5) Marker is installed.

Advantages / Disadvantages:

+ Highly accurate placement.
+ Both lateral and longitudinal positioning done in one step.
- Complex system.
- Areas exist where the four satellites are not accessible to the receiver, such as under foliage, in tunnels, and between tall buildings.
- Not recommended for retrofitting old roadways, as discussed in chapter 5.

Referenced w.r.t.: Differential Global Positioning System

Centering Error:

$$e_{Map} + e_{D\text{-}GPS} \tag{25}$$

Alignment Error:

$$e_{Map} + e_{D\text{-}GPS} \tag{26}$$

Spacing Error:

$$e_{Map} + e_{D\text{-}GPS} \tag{27}$$

Cumulative Error:

$$e_{Map} + e_{D\text{-}GPS} \tag{28}$$

Dead Reckoning Method
Subsystem: Lateral & Longitudinal System - Database Method

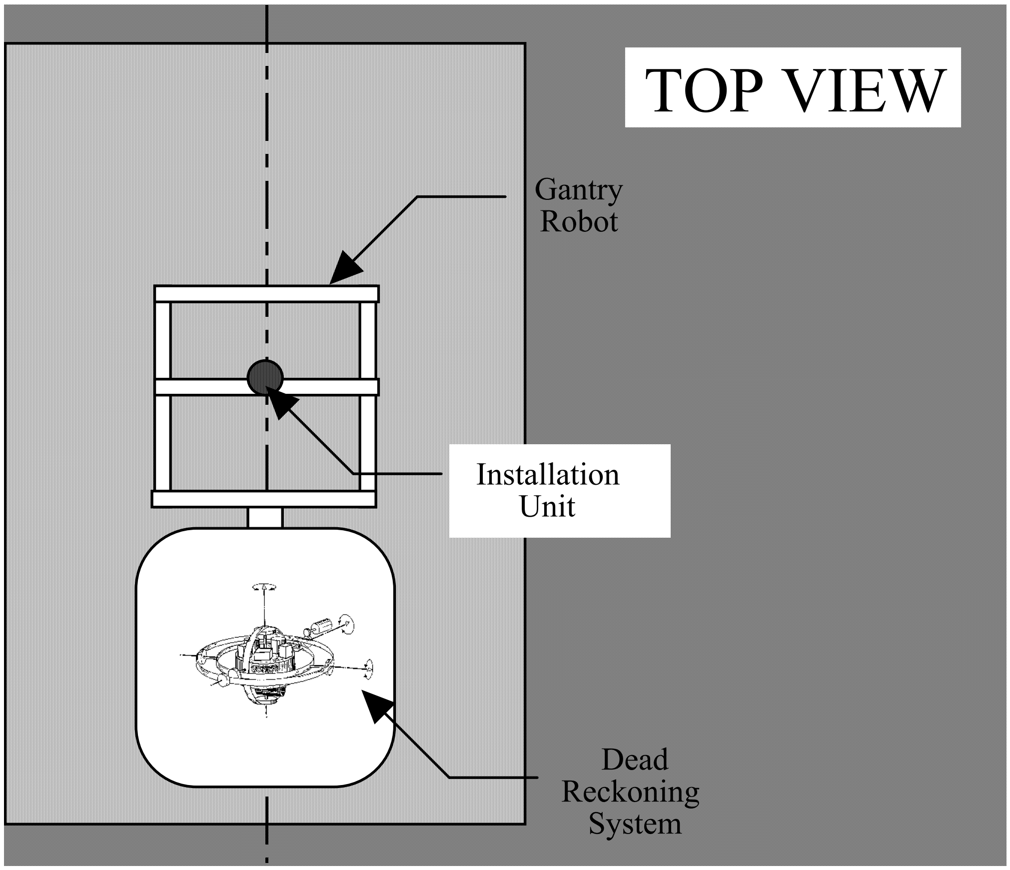

Figure 25. Dead reckoning positioning.

Description:

A dead reckoning system, such as an Inertial Sensing System (ISS), could be used with a map of marking locations to travel from site to site, as illustrated in figure 25. The vehicle starts from a known location, and is brought to an approximate installation location. The onboard dead reckoning system keeps track of the dynamics of the vehicle's movement, i.e. the speed, heading, time traveled, etc., and analyzes this information to derive the new location of the vehicle. The installation unit can then be positioned w.r.t the dead reckoning system using the gantry robot to the correct coordinates. The position of the vehicle would have to periodically be updated to keep cumulative errors within acceptable bounds. This system could be very powerful when combined with D-GPS.

Operation:
1) Location of vehicle is surveyed, as well as the orientation of the vehicle.
2) Operator moves the vehicle to approximate location of next installation.
3) Dead Reckoning System computes new location of the vehicle.
4) Gantry robot moves installation unit to installation site.
5) Marker is installed.
6) Steps 2 to 5 are repeated until error accumulates to a cutoff point.

Advantages / Disadvantages:
+ Highly accurate placement.
+ Both lateral and longitudinal positioning done in one step.
- Complex system.
- Not recommended for retrofitting old roadways, as discussed in chapter 5.

Referenced w.r.t.: Dead Reckoning

Centering Error:

$$e_{\text{Initial Positioning Survey}} + e_{\text{Map}} + \sum_{Start}^{End}\left(e_{positioning}\right) \tag{29}$$

Alignment Error:

$$e_{\text{Map}} + \sum_{Start}^{End}\left(e_{positioning}\right) \tag{30}$$

Spacing Error:

$$e_{\text{Positioning}} \tag{31}$$

Cumulative Error:

$$\sum_{Start}^{End}\left(e_{positioning}\right) \tag{32}$$

Two-point Reference System
Subsystem: Lateral & Longitudinal System - Database Method

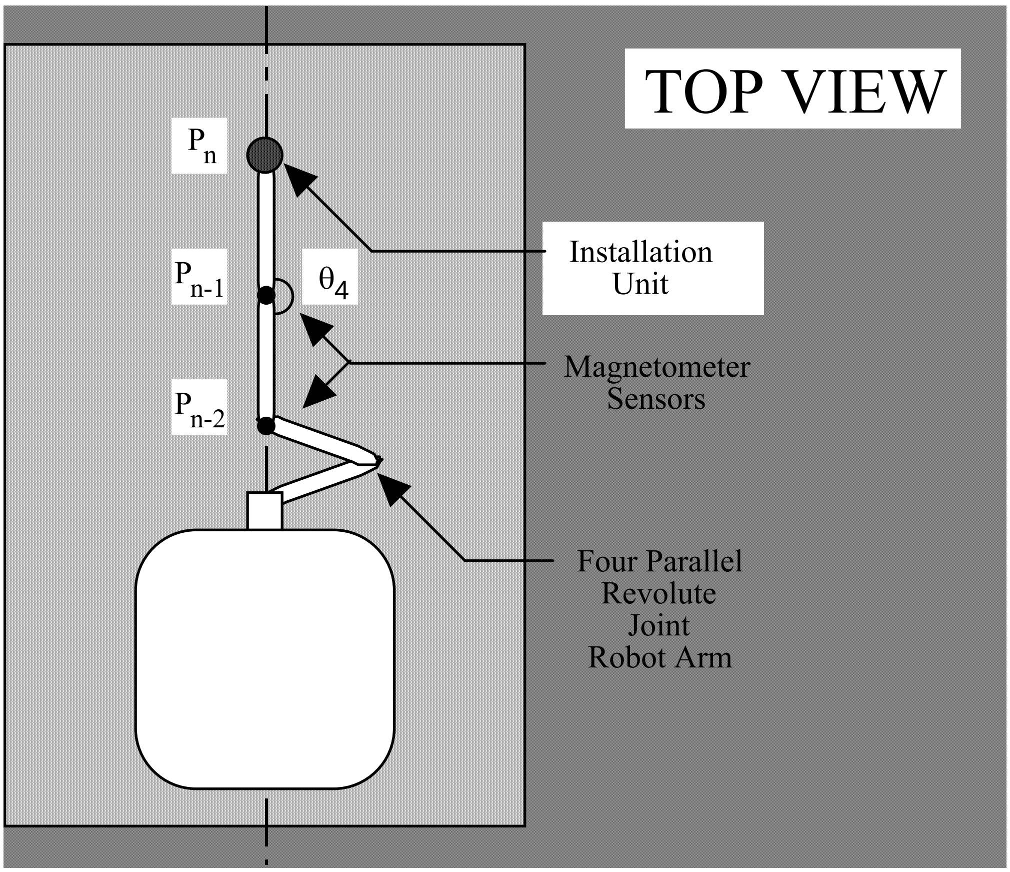

Figure 26. Installation w.r.t. the last two markers installed.

Description:

This system, illustrated in figure 26, calculates the position of the new installation site, given the locations P_{n-1} and P_{n-2}, and a database of desired marking locations. A 4R manipulator arm could position sensors over the two existing markers. The desired angle θ_4 between the lines P_nP_{n-1} and $P_{n-1}P_{n-2}$ would then be retrieved from the database, and the arm would be adjusted to this position The new marker would then be installed at P_n.

Operation:

1) Operator moves the sensor at P_{n-2} on the robot to approximate location of first previously installed marker.
2) Magnetometer at P_{n-2} is used to accurately position the joint over the marker.
3) Operator moves the sensor at P_{n-1} on the robot to approximate location of second previously installed marker.
4) Magnetometer at P_{n-1} is used to accurately position the joint over the marker.
5) System retrieves data on desired angle, q_4, and positions P_n. Note that this step can take place during steps 1 through 4.
6) Marker is installed.

Advantages / Disadvantages:

+ Accurate placement.
+ Both lateral and longitudinal positioning done in one step.
- Complex system.
- Requires having two markers previously installed.
- Could induce cumulative error.
- Not recommended for retrofitting old roadways, as discussed in chapter 5.

Referenced w.r.t.: Position of previous two markers & database.

Centering Error:

$$e_{\text{Position of Previous Two Markers}} + e_{\text{Locating of Previous Two Markers}} + e_{\text{Manipulator}} + e_{\text{Map}} \tag{34}$$

Alignment Error:

$$e_{\text{Locating of Previous Two Markers}} + e_{\text{Manipulator}} \tag{35}$$

Spacing Error:

$$e_{\text{Locating of Previous Two Markers}} + e_{\text{Manipulator}} \tag{36}$$

Cumulative Error:

$$\sum_{Start}^{End}\left(e_{Locating of Previous Two Markers} + e_{Manipulator}\right) \tag{37}$$

Gang Installation System
Subsystem: Special Systems for Straight Roadways - Automatically Calibrated Method

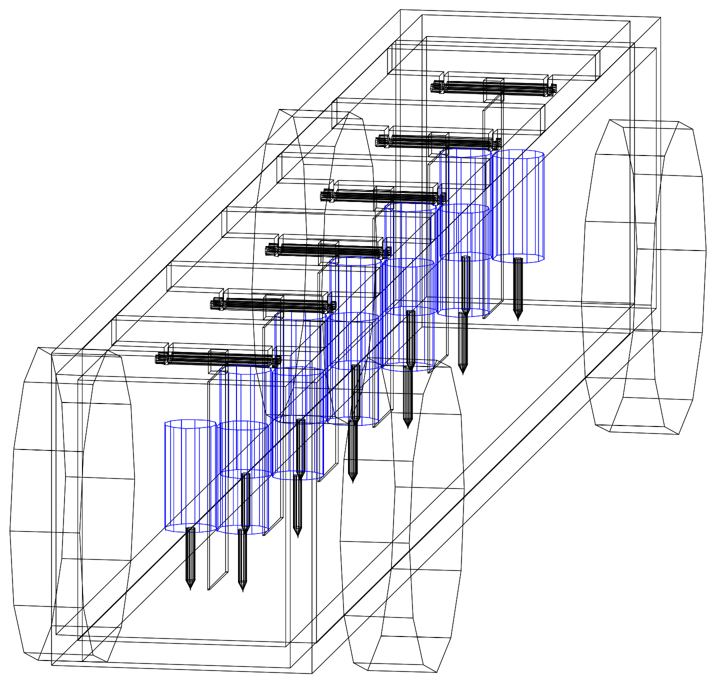

Figure 27. Six station gang installation.

Description:

The Gang Installation System, illustrated in figure 27, features several installation stations spaced one meter apart from each other. All stations work simultaneously, so the improvement of the cycle speed will be determined by the number of stations on the unit. Note that positioning times may take slightly longer with this system, since both ends of the unit must be located on the centerline of the lane. One extra dimension of positioning requirement has been added.

Operation:
1) The gang installation system is positioned to three degrees of freedom by the means of other positioning systems. The 3 d.o.f. must to specify lateral and longitudinal position of the first marker installation site and the rotation of the gang system from that point.
2) System is activated, and markers are installed.

Advantages / Disadvantages:
+ Extremely accurate positioning between installation units on gang.
+ Very fast system.
- Requires additional 3 d.o.f. positioning methods.
- Cannot be used for curved roadway.

Referenced w.r.t.: Gang Placement
Note: Repositioning the Gang Installation System would require the use of an additional positioning system.

Centering Error:

$$e_{\text{Manufacturing Error}} \tag{38}$$

Alignment Error:

$$e_{\text{Manufacturing Error}} \tag{39}$$

Laser-guided Centering System
Subsystem: Special Systems for Straight Roadways

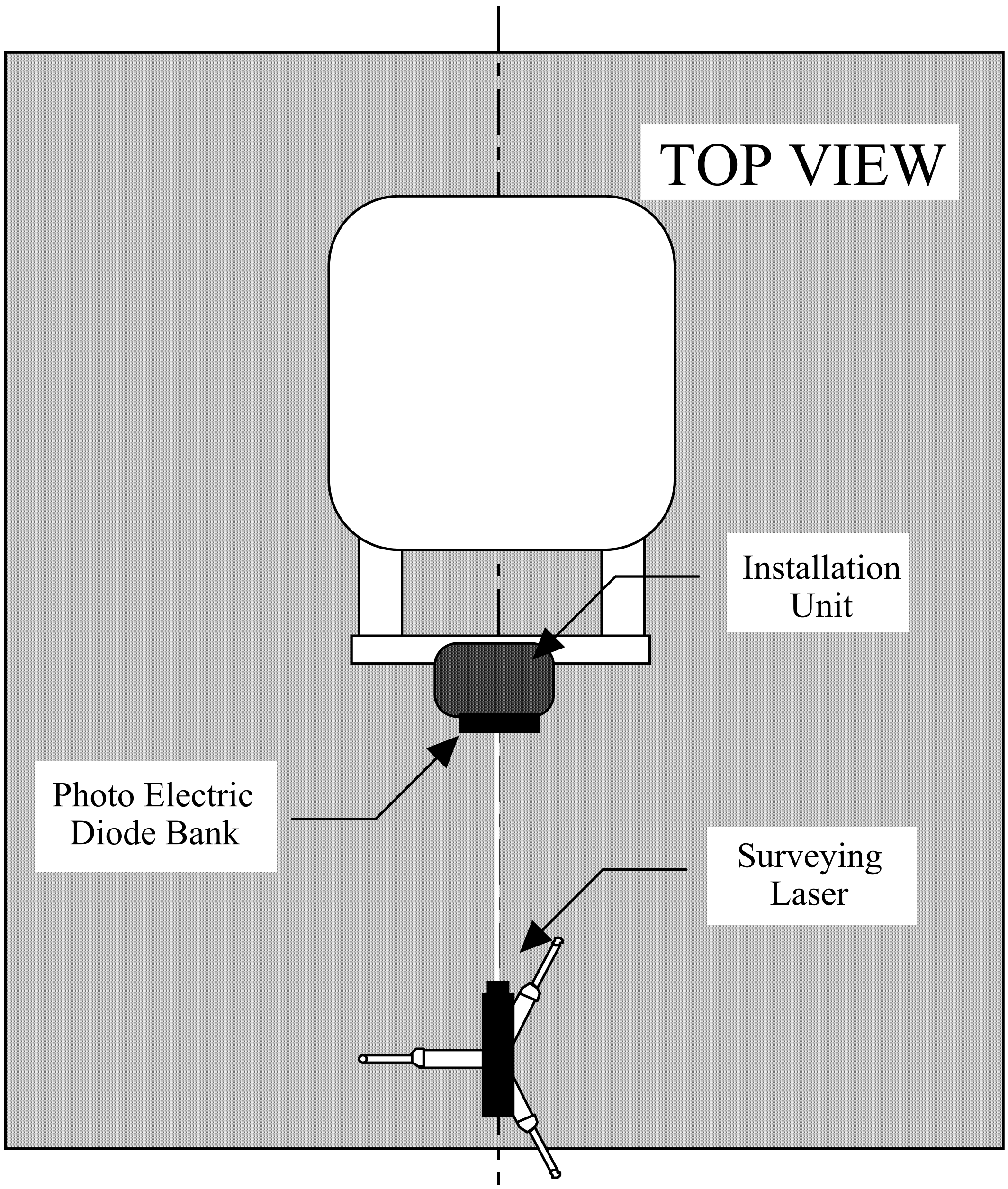

Figure 28. Laser-guided centering.

Description:

In the laser-guided system, shown in figure 28, a beam of visible red light from a He-Ne laser is fired up the centerline of the road. The beam is received by a bank of

photo electric diodes on the installation vehicle. The vehicle's position is corrected, either manually or automatically, to center the beam on the bank of diodes. The bank would be situated so that when the beam is centered, the installation unit is also centered. Under normal conditions, the red spot is visible up to 200m away.[12]
Note that the rotation of the application system will induce error in placement. This can be avoided by placing the beam sensing equipment on top of the installation unit.

Operation:
1) Laser is set in the center of the lane by surveyor.
2) Installation unit moves on linear slide until diodes sense that the unit is centered.
3) Marker is installed.

Advantages / Disadvantages:
+ Very high precision alignment of markers.
- Surveyor has to move laser every 175 to 200m.
- Lasers of class 3b or higher would be a safety concern.

Referenced w.r.t.: Laser Guidance

Centering Error:

$$e_{\text{Laser Placement}} + e_{\text{Diode Sensing}} \tag{40}$$

Alignment Error:

$$e_{\text{Diode Sensing}} \tag{41}$$

Marker Installation Subsystems

The installation system is responsible for affixing the marker to the road. This system must also perform any pavement surface preparation, such as drilling, and ensure that the markers are installed within the depth and tilt requirements. All systems presented in this section that involve making a hole in the pavement would control depth of installation by limiting the depth of the hole. Marker tilt could be controlled by having some part of the 'installer' come in contact with the road surface as a reference.

Drill-then-Press Installation Unit
Subsystem: Marker Installation System

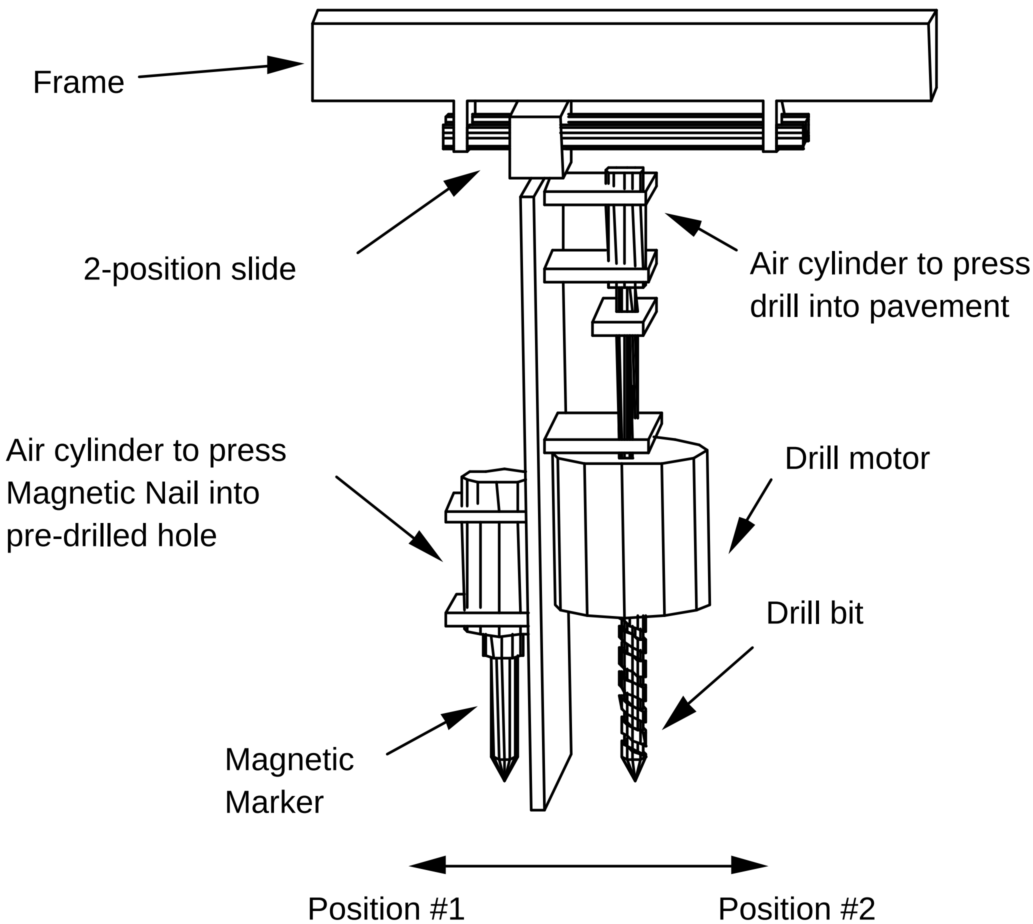

Figure 29. Drill-then-Press unit.

For use with the Casings:
Nail, Cartridge

Description:

The Drill-then-Press Unit, figure 29, prepares for installation by drilling a hole in the pavement large enough for a compression fitting of the magnetic marker. It then slides to allow an air cylinder to press the marker into the hole. Because the marker is pressed into the hole, no additional sealing should be needed to hold the marker in place. This system would require the magnetic marker to have a chamfer at the bottom to help fit into the hole. Positioning of the marker over the hole could also be done with a rotary actuator, if a more compact system is desired.

Operation:
1) Hole is drilled with drill and first air cylinder.
2) Unit positions marker over hole.
3) Unit presses marker into hole, making a compression fitting.

Advantages / Disadvantages:
+ No sealing necessary around marker.
- Operation is relatively slow.
- Force fitting operation may be complex.
- May exert large force on markers.

Drill-then-Place Installation Unit
Subsystem: Marker Installation System

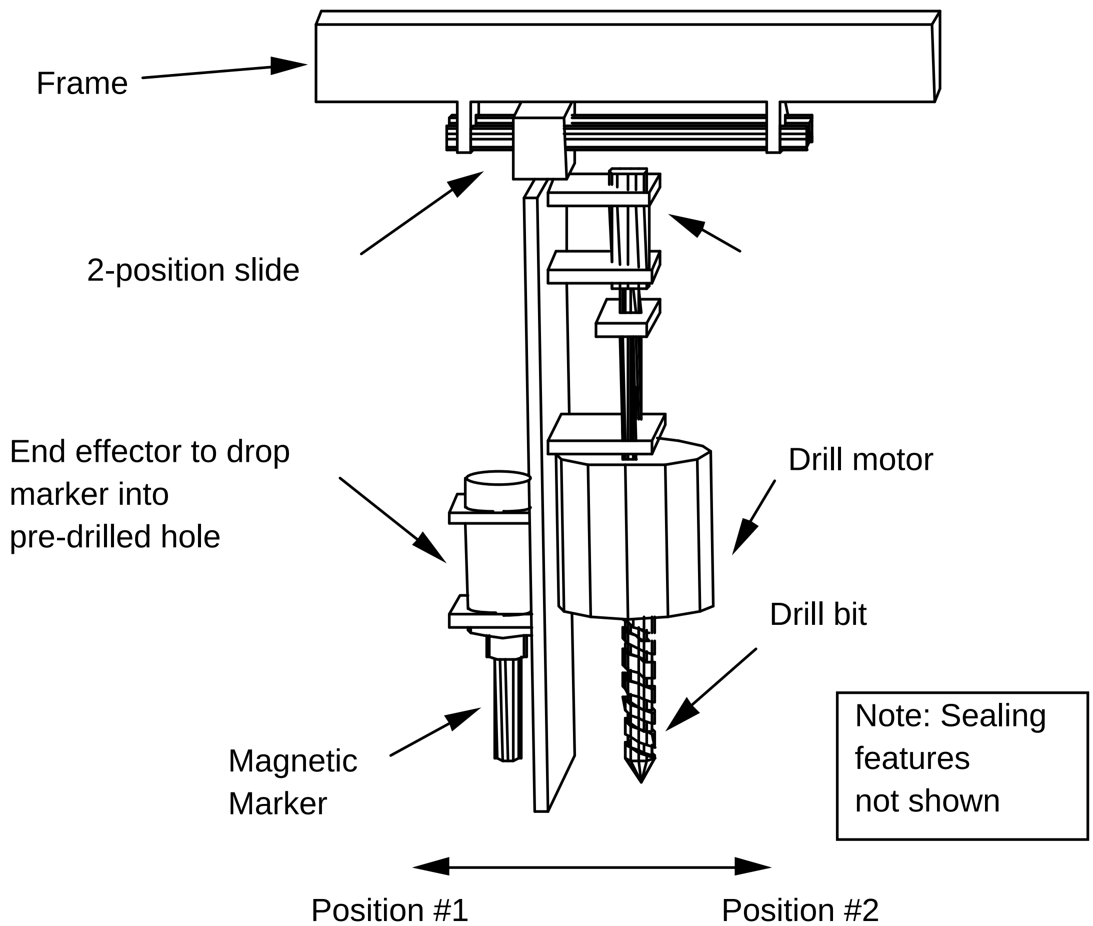

Figure 30. Drill-then-Place unit.

For use with the Casings:
Nail, Cartridge, Bare

Description:
The Drill-then-Place Unit, shown in figure 30, first prepares an installation hole by drilling a hole in the pavement large enough for a slip fitting of the magnetic marker. It then slides to allow an end-effector to drop the marker into the hole. After the marker is dropped in the hole, any gaps are sealed with a flexible sealant. The sealant must be pliant for the life of the marker. If the sealant is rigid, it can crack and break with pavement expansion and contraction. Positioning of the marker over the hole could also be done with a rotary actuator, if a more compact system is desired.

Operation:
1) Hole is drilled with drill and air cylinder.
2) Unit positions marker over hole.
3) Unit places marker into hole, making a slip fit.
4) Sealant system fills gaps between marker and pavement.

Advantages / Disadvantages:
+ No large forces are imposed on the markers.
- Operation is relatively slow.
- Requires sealing operation.

Continuous Dot Laying Machine
Subsystem: Marker Installation System

Figure 31. Continuous dot layer.

For use with the Casings:
    Dot

Description:

This unit will continuously install dot type markers, as illustrated in figure 31. As the vehicle travels down the road, dots are separated from a stack, then grabbed by a suction cup(s) on the end effector. Adhesive is quickly applied to the pavement, and a pick-and-place operation presses the dot onto the fresh adhesive. During the pressing, a nail gun shoots a nail through a clear hole on the dot for extra anchoring.

Operation:
1) Dot of correct polarity is separated from stack, and is grabbed by end effector.
2) End effector counters the speed of vehicle with the linear slide.
3) Bitumen is pumped onto the road by a nozzle on the end effector.
4) The dot is pressed onto the fresh bitumen.
5) A secondary holding nail is shot through a clear hole on the dot by a nail gun.

6) End effector resets.

Advantages / Disadvantages:
+ Continuous marking system.
+ Similar system has already been built and tested for application of Bott dots.
- Countering vehicle speed is difficult.
- May be difficult to integrate with reliable positioning systems.
- System may not have good curve-following abilities.

Pound-then-Press (Place)
Subsystem: Marker Installation System

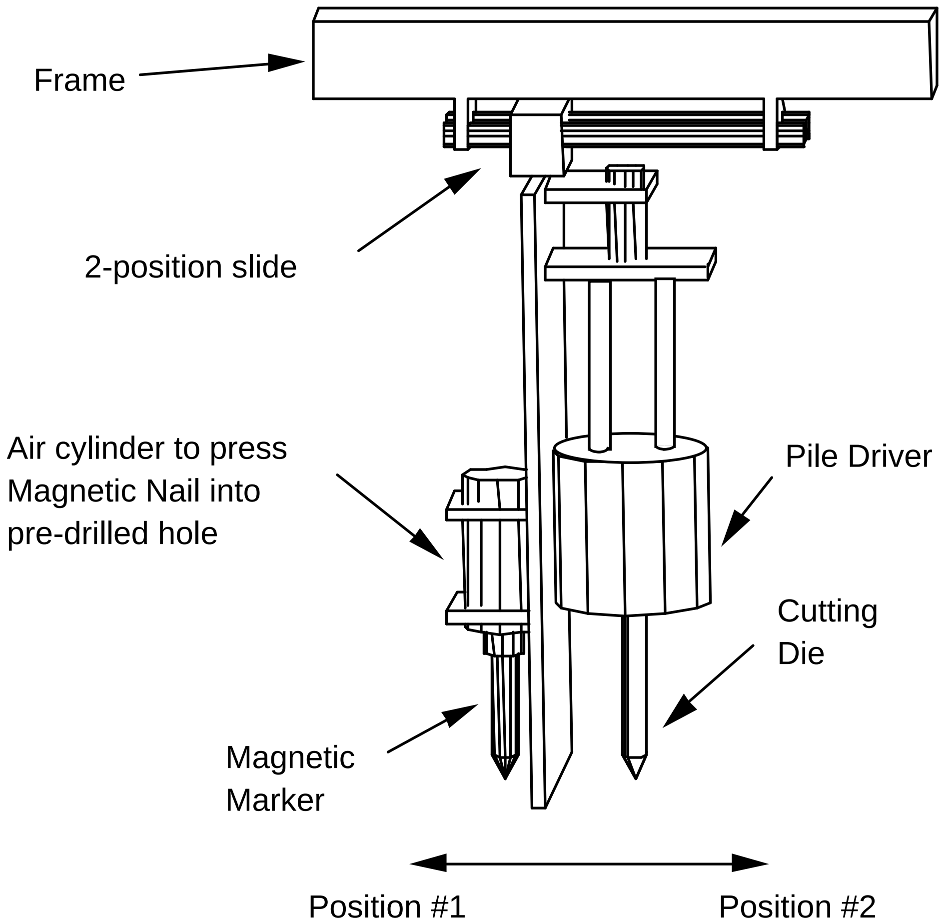

Figure 32. Translating pound-then-press unit.

For use with the Casings:
Nail, Cartridge, Bare(Place only)

Description:

The Pound-then-Press (Place) Unit, shown in figure 32, first prepares an installation hole by pounding a die into the pavement with a pile driver. This system is analogous to the drilling systems mentioned earlier; pound-then-press applications would use a compression fit, while pound-then-place applications would use a slip fit. This system would be much quicker than a drilling application, but could only be used to install small diameter markers. Pounding large holes in this manner would severely damage the pavement. The concept of pounding the markers directly into the pavement has been considered, and was found to be not particularly feasible. A poundable marker would have to have a very thick casing to absorb the shock, and still be of relatively small diameter. This does not leave much, if any, room for the magnets.

Operation:
1) Hole is punched with cutting die and first air cylinder.
2) Unit positions marker over hole.
3) Unit would either press or place marker into hole, depending on system. The hole would be sealed after placing operations.

Advantages / Disadvantages:
+ Pounding is much faster than drilling.
- Could easily damage the pavement.
- Only small diameter markers could be used.

Feeding and Storage Subsystems

Handling of the magnetic markers may be difficult, since the markers will attract or repel each other. A system is needed to keep the markers neat and orderly during storage, and can neat as they are presented to the installation unit.

Pressure Sensitive Adhesive Strips
Subsystem: Feeding and Storage System

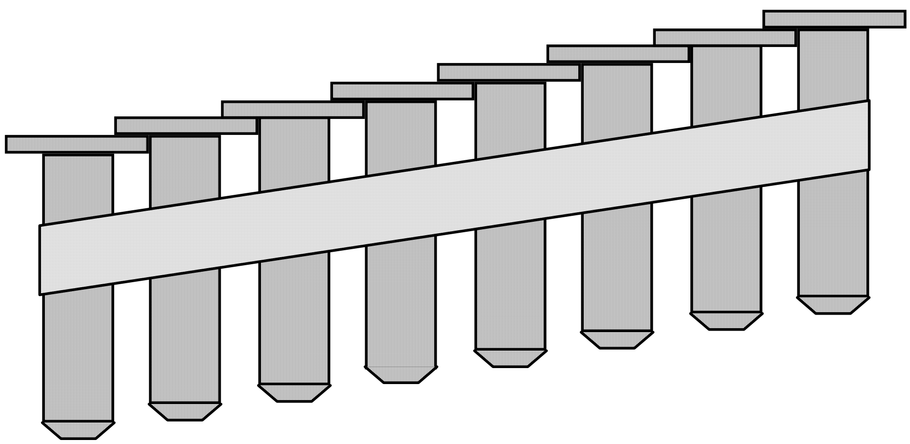

Figure 33. Markers joined with pressure sensitive adhesive.

For use with the Casings:
Nail, Bare, Cartridge
Description:
Strips of pressure sensitive adhesive would be applied to one or two sides of a row of markers, which have been laid out in an orderly fashion, as illustrated in figure 33. Spacing and orientation of the nails would be determined by the casing geometry and the separation system. A large number of markers could be stored by rolling the taped markers, or by folding the strips neatly.

Advantages / Disadvantages:
+ Inexpensive means of attachment.
+ Easy to apply.
- Adhesive may be heat sensitive.
- May have problems due to markers slipping or tearing free.

Thermal Adhesive Strips
Subsystem: Feeding and Storage System

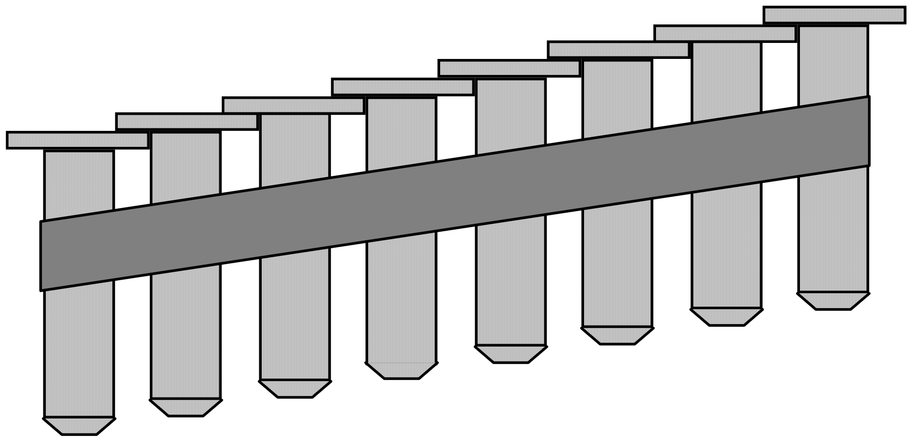

Figure 34. Markers joined with thermal adhesive.

For use with the Casings:
Nail, Bare, Cartridge
Description:
Strips of adhesive would be applied to one or two sides of a row of markers under high temperatures, as shown in figure 34. Spacing and orientation of the nails would be determined by the casing geometry and the separation system. A large number of markers could be stored by rolling the taped markers into rolls, or by folding the strips neatly.

Advantages / Disadvantages:
\+ Thermal strips are much more durable than pressure sensitive strips.
\+ Inexpensive means of attachment.
\- Application procedure more difficult than with pressure sensitive adhesive strips.
\- May have problems due to markers slipping or tearing free.

(Disposable) Plastic Chamber Strip
Subsystem: Feeding and Storage System

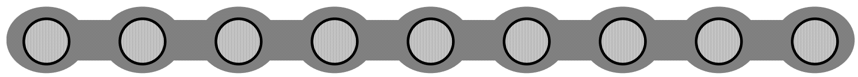

Figure 35. Markers joined with plastic chamber strip (end view).

For use with the Casings:
Nail, Bare, Cartridge

Description:

Markers would be joined with a disposable plastic strip attached approximately at the midsection of the marker, illustrated in figure 35. The marker may be pulled or torn out of the strip when it is needed for installation. The plastic strip would hold the nails in a manner similar to the way plastic retainer rings hold together a six-pack of beverages. Spacing and orientation of the nails would be determined by the casing geometry and the separation system. A large number of markers could be stored by rolling the taped markers, or by folding the strips neatly.

Advantages / Disadvantages:
+ Good grasping of the marker.
- Assembly may be expensive.

Wire Braised on Nail
Subsystem: Feeding and Storage System

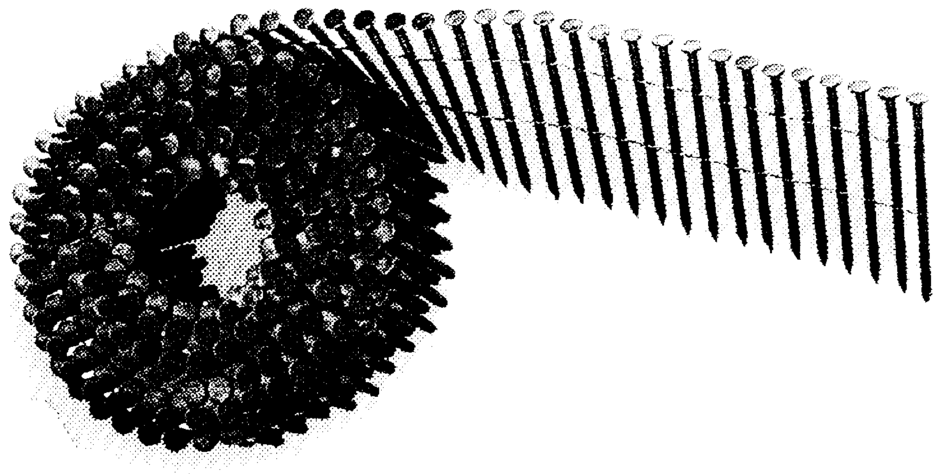

Figure 36. Markers joined by braised on wire.

For use with the Casings:
Nail, Cartridge

Description:
Nails are joined by one or more thin wires that are braised directly onto the marker's casing, as shown in figure 36. Spacing and orientation of the nails would be determined by the casing geometry and the separation system. A large number of markers could be stored by rolling the braised markers, or by folding the strips neatly.

Advantages / Disadvantages:
+ Wires are very flexible for bending.
+ Markers are very securely joined.
+ Inexpensive means of attachment.
- Wires need to be cut or melted off before installation.
- Burrs from braising may interfere with installation.

Gravity-fed Channels

Subsystem: Feeding and Storage System

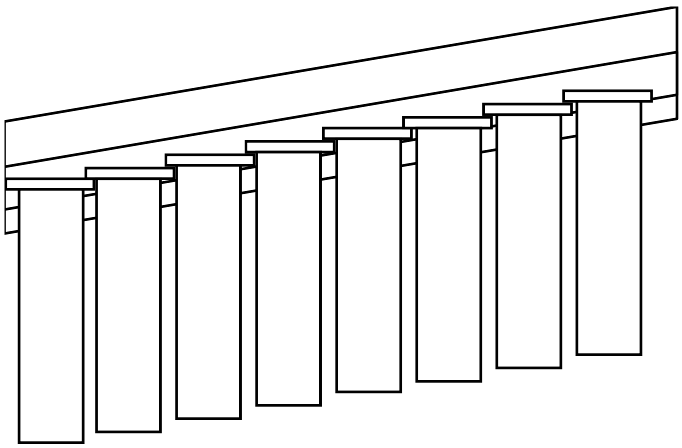

Figure 37. Nails in gravity-fed channels .

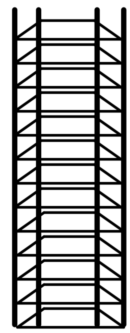

Figure 38. Column of dots.

For use with the Casings:

Nail, Cartridge, Dot

Description:

Markers are held in non-ferrous channels which hold the markers in order and allow the markers to slide down under their own weight. Figure 37 shows several nails that are held by their heads, while figure 38 illustrates a gravity-fed column for magnetic dots. Channels could be machined that would contain the nail in a variety of configurations, e.g. stacked end-to-end or side-to-side. In operation, the bottom marker would be removed, allowing the next marker slide in place.

Advantages / Disadvantages:

+ Reusable system.
- Storage capabilities may be low.
- Possibility of jamming.

Loaded Cartridge System
Subsystem: Feeding and Storage System

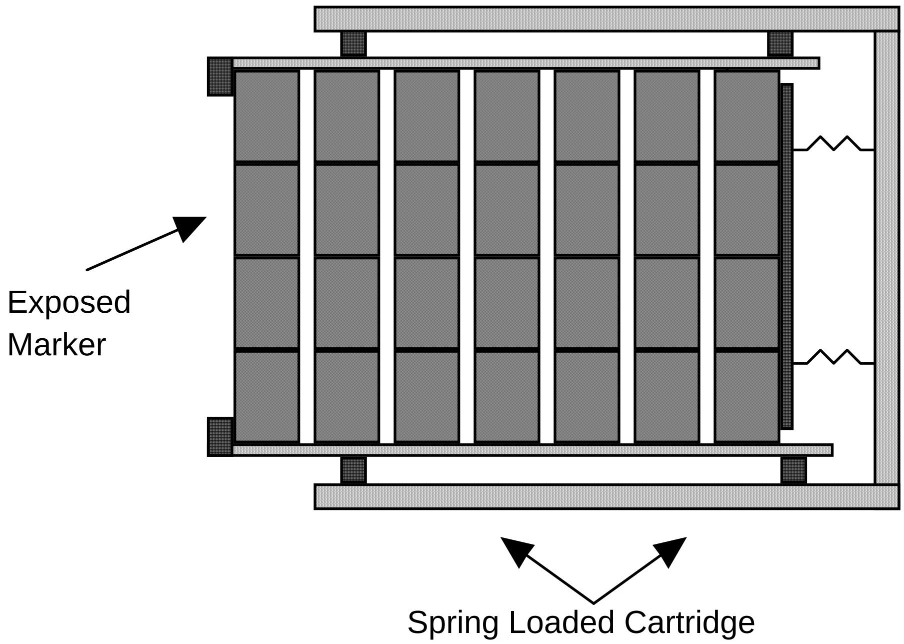

Figure 39. Loaded cartridge system powered with springs.

For use with the Casings:
Nail, Bare, Cartridge

Description:
Markers are stored in machined channels, and are presented by the application of some mechanical force. During operation, the exposed marker would be removed, and the mechanical force would push all of the other markers forward. An example, using spring loading, is shown in figure 39.

Advantages / Disadvantages:
+ Reusable system.
- Storage capabilities may be low.
- Possibility of jamming.

Reusable Chain Cartridge
Subsystem: Feeding and Storage System

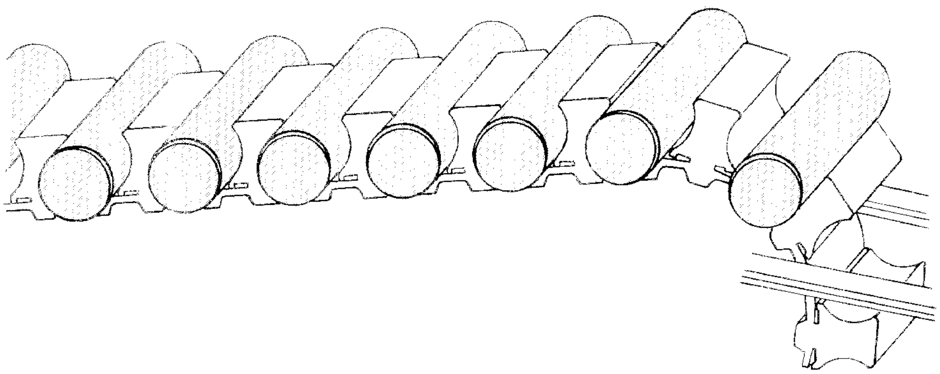

Figure 40. One style of reusable flexible chain.

For use with the Casings:
Nail, Bare, Cartridge

Description:
Markers are stored in a reusable, flexible cartridge chain. One approach is shown in figure 40, where markers are automatically released through bending in one direction. Another option would be to have a chain that could bend both ways; however, markers would have to be pulled out. This chain would hold markers in the same way ammunition is sometimes held by chains for automatic weapons.

Advantages / Disadvantages:
+ System is reusable
+ Markers are securely held.
+ Good bending flexibility.
- Manufacture & loading of the chains may be expensive.

Separation and Sorting Systems

The separation and storage system is responsible for taking the correct nail from the storage system, and delivering it to the installation system. Information regarding the polarity marker needed at a given site can either be stored electronically, or preordered in a cartridge in the storage system.

Polarity Rotator Device
Subsystem: Separation and Sorting System

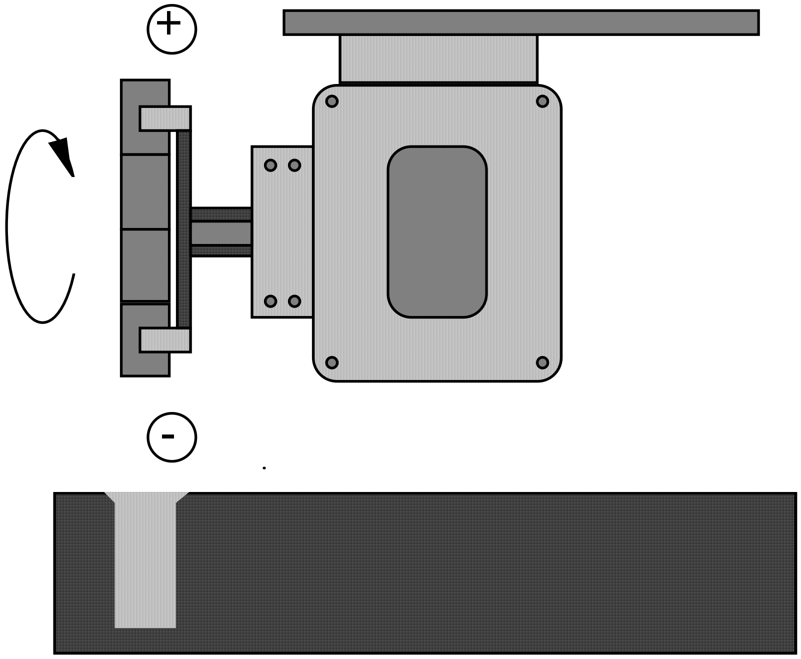

Figure 41. Polarity rotator with bare marker.

For use with the Casings:
Nail (Symmetric only), Bare

Description:
This system would prepare the correct polarity marker by flipping the marker so that either the positive or the negative side is facing up, as shown in figure 41. Markers fed into this system must all be oriented in the same direction, and symmetrical about the midsection.

Advantages /Disadvantages:
\+ Only one feed would be required for the system.
\- Pre-installation inspection may be difficult.

Feed Selector
Subsystem: Separation and Sorting System

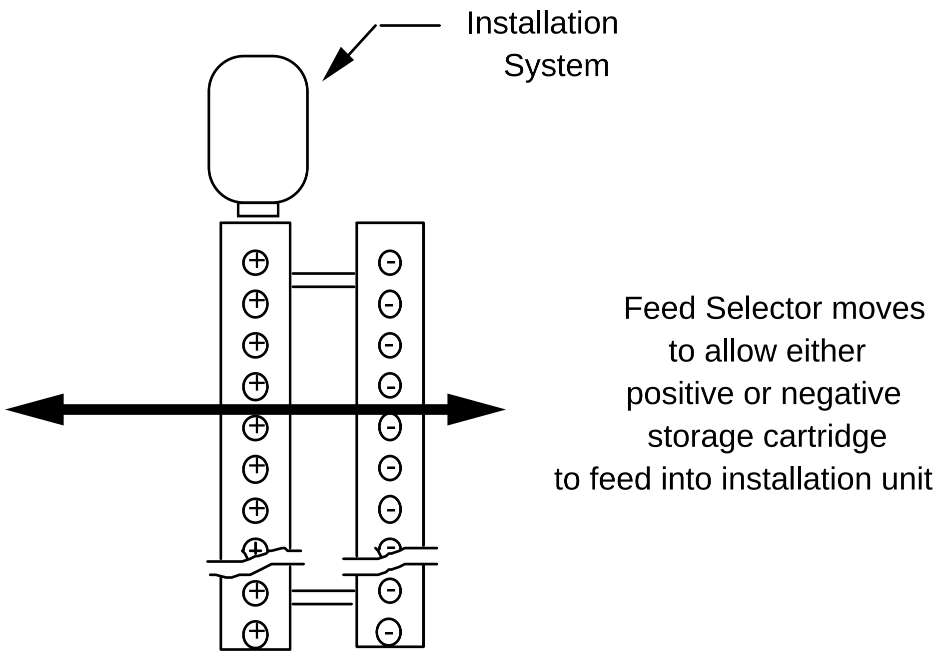

Figure 42. Feed selector system.

For use with the Casings:
Nail, Cartridge, Bare

Description:
This system would change between feeds of unipolar markers, as illustrated in figure 42. Each feed would require its own presentation system, such as sprockets to pull a chain feed. Mechanical switching between feeds would be determined by externally supplied data.

Advantages / Disadvantages:
\+ Easy to inspect marker polarity before installation.
\- Attachment and detachment may be difficult for some storage systems.

Gravity-loaded Dot Feeder [13]
Subsystem: Separation and Sorting System

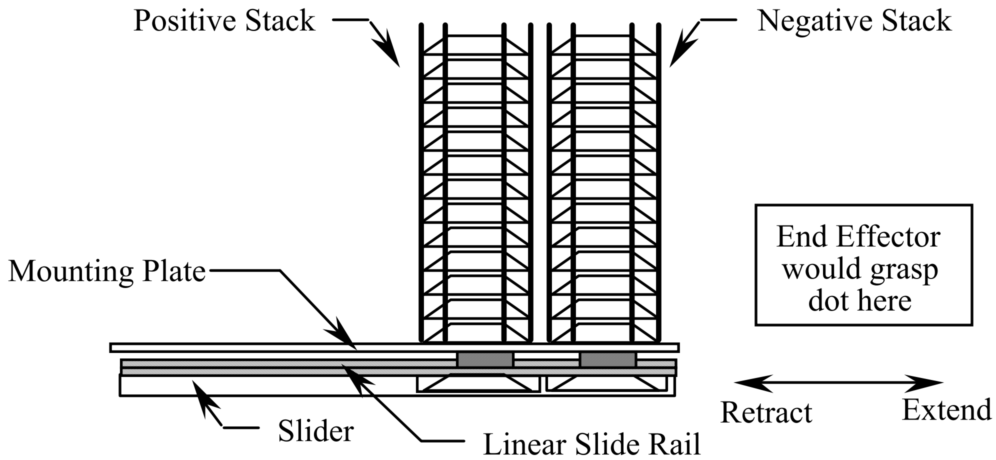

Figure 43. The gravity-loaded dot feeder.

For use with the Casings:
Dot

Description:
In this system, positive and negative dots drop from gravity feed systems into separate depressions in a slider. When a dot of a certain polarity is desired, the slider moves the depression containing that dot directly under the end effector. The end effector drops down, and takes the dot out of the depression. The slider then returns and reloads. The system is illustrated in figure 43.

Advantages /Disadvantages:
+ Previously tested working system.
+ Fast system.

Pre-Installation Inspection Subsystems

Before the marker is installed in the pavement, a polarity checking inspection unit will perform a “double check” to make sure that the correct polarity marker is grasped.

Hall-Effect Magnetometer
Description:
Polarity would be checked with a Hall-effect magnetometer. This magnetometer would look for a current induced in a voltage carrying conductor that would be brought near the magnet’s vicinity.

Flip Coil Magnetometer
Description:
A coil of wire is rotated near the end of the marker at a fixed speed. Either the integrated current or the induced AC voltage is read from the coil.

Repulsion Sensing Inspection
Description:
This system consists of an inspection magnet similar to the marker magnet mounted on a switch. The inspection magnet would be free to either rotate alongside the marker, or translate towards or away from the marker. Movement of the inspection magnet would trip the switch, indicating a positive or negative marker.

Flux Gate Magnetometer
Description:
A ferrous material is excited on one side of the marker. A field sensor monitors the changes in the ambient magnetic field on the other, and identifies the polarity of the marker.

CHAPTER 4: FEASIBILITY STUDIES AND SELECTION

Feasibility Studies

Feasibility studies are performed to determine if a particular concept will work, and, if it will work, whether it will work better than other concepts. Feasibility studies should answer the following questions:

What criteria do the subsystems need to meet?
How well do the concepts meet these criteria?

There are four types of studies that can be done:
1) Interviews with external vendors
2) Internal interviews with potential system users
3) Direct testing of methods
4) Analytical research on methods

The methods should be employed in a way that will get the most reliable data with the least expense of time and money. External interviews are the most economical 'first-cut' in a feasibility study. Vendors are usually happy to provide product information, and possibly do more testing, if the researcher expresses an intent to purchase the vendor's system. For example, a phone call to a GPS receiver company may teach the researcher which GPS methods are most promising for a particular application.

Internal interviews with personnel with experience in similar or related operations also provide valuable information that may qualify or disqualify concepts. For example, an interview with a land surveyor may show that the use of GPS to position the system w.r.t. existing survey information that more than a year old would not yield the needed accuracy, due to roadway shifting.

Internal interviews will also give valuable insight regarding problems that may be encountered when employing technologies and methods on the road. Vendors may be reluctant to give this type of information.

Direct testing of methods provides the best data, but is also the most expensive approach. Prototype subsystems must be built, and researcher time and facility space must be dedicated. In many cases, however, direct testing will be absolutely necessary to determine subsystem performance. Tests should not be performed solely under 'clean room' conditions. On-site tests should be performed as needed.

Analytical research may also provide valuable information on methods, but does not provide the intuitive or tactile feel that the other three methods can.

Selection

REQUIREMENTS FOR AUTOMATED APPLICATION OF MARKERS

With the results of the feasibility studies in hand, a research committee should be able to choose the best methods. The committee should rank the criteria for importance when making their decisions. At this time, there is insufficient information available on magnetic marker installation task to allow for a valid feasibility study and selection for the subsystems required.

CHAPTER 5: OPERATIONAL SPECIFICATIONS

Operational specifications define the operation of the individual subsystems and systems that are required to meet the functional specifications presented in chapter 2. The operational specifications presented here are not complete; system and subsystem specifications must be developed. These specifications can be made after feasibility studies are complete, and subsystems are selected.

Cycle Time

• **Operation Speed** - The cycle time has second priority; installation quality is the highest priority. The operating speed of the system must be minimized. To appreciate why this is critical, consider the following:

Assuming a one meter marker spacing, each second required to move from a previously installed marker, locate the site for the new marker, and install the new marker, adds 0.27 hours to the time to install 1 km of markers. Considering that in an eight hour shift, a work crew must travel between the dispatching area and the work area, perform preoperational inspection, setup, breakdown, etc., only about five hours of marker installation work may get done per day. The cycle speed needed to put down only one kilometer's worth of markers per shift is 18.7 seconds.

Onsite Packaging and Feeding

• **Marker Coding** - Markers will be installed with either a positive or negative field orientation, in order to code roadway data. Markers must be packaged to allow delivery of the correct polarity marker at the installation site.

• **Holding Capability** - Packaging should accommodate enough markers for at least one kilometer of roadway. For precoded storage, 1000 markers must be held in the correct order, again assuming a one meter marker spacing. For non-precoded storage, approximately 750 positive markers and 750 negative markers should be stored, or 1000 symmetric nails should be stored with the capability to orient them on-site.

Safety

• **Traffic Safety** - Installation procedures must comply with standard construction procedures [14] for issues such as traffic barrier placement, dust control, etc.

• **Worker Safety** - Automated workspaces should have appropriate safeguards such as fencing and trip devices.[15] Risk assessment techniques should be applied.[15]

Use of Positioning References

• **Use of Survey Information -** Positioning systems that rely on surveyed map information for guidance are not recommended for use on existing roads that are to be retrofitted with new markers.[16] Any operation that must conform to an existing roadway would either have to use landmarks on the roadway itself, or be resurveyed immediately before installation. Database systems are not recommended for positioning because of this requirement.

Although surveying information such as D-GPS can accurately locate an object on the Earth's surface to within 10 mm, the position of that object moves over time due to a variety of disturbances. For example, a point in California could move 10 mm/year due solely to tectonic shifting of the Pacific rim plate. Other random factors, such as erosion or pavement expansion-contraction, would prevent precision placement to be done from old survey information. New survey information, if taken, should be used in the same manner that survey information is used on new construction sites.

Reliability

- **Maintainability** - The system should be kept simple as possible in order to facilitate repairs. Parts should be purchased from commercial dealers whenever possible.
- **Robustness** - Care should be taken to ensure that any foreseeable possible failure would not be catastrophic. Emergency-stop capabilities should be provided where needed. Valves that dispense sealant should be rigged to shut off in the event of an air or power failure to their controls. Similar precautionary provisions should be made for other elements of subsystems.

Maintenance

- **Quality Control & Regular Inspection of Markers** - Immediately before installation, a safety-checking station should check the polarity of the markers. After markers are installed, follow-up vehicles should check for correct coding and sense marker deterioration. The follow-up inspection vehicle would be a separate system, and not a part of the installation system.
- **System Maintenance** - Pre-operational inspection and equipment logging procedures should be developed for the system for both maintenance and safety reasons. The system should be given routine maintenance inspections as well.
- **Service Life** - The service life of the installation system should be comparable to the life of other light- and medium-duty construction equipment. For accounting purposes, the system may be rated a life of 200,000 installations.

Cost

- **Fabrication Costs** - Speed and accuracy have priority over cost considerations. Fabrication costs can be considered negligible, within reason, compared to the amount of serviceability that will be derived from the system.
- **Operation Costs** - Operational costs are the costs that accrue during the system's normal use, such as power used, fuel used, and manpower. These costs are cumulative, and efforts should be made to keep these costs at a reasonable level. Since the greatest operational cost would most likely be manpower, the

most efficient way of controlling these costs is to minimize the cycle time. Note that a manpower assessment has been conducted for this operation.[5] This analysis is discussed in chapter 8. In addition, a preliminary cost-benefit analysis has been performed for automated installation of magnetic markers.[6] This analysis is presented in chapter 9.

Additional Requirements

- **Bridge / Unusual Roadway System** - Bridges and unusual road conditions may require a different system to be developed. This system would be considered a separate project, and would be covered under a separate set of requirements.
- **Alignment to Existing Marks** - The system may need to be able to orient itself to the end of an existing run of markers before it can install additional markers.
- **Replacement of Markers** - A system in addition to this one may be needed solely for the purpose of replacing old markers. This would be done to change roadway information or replace deteriorated markers.

CHAPTER 6: PROTOTYPE EXAMPLE OF AUTOMATED SYSTEM

This chapter describes a fully integrated, partially automated prototype system for the installation of magnetic markers into the pavement. This prototype system has been provided as an example to show how the subsystems can be integrated. Note that this prototype is not ready for fabrication; component feasibility studies must still be done.

The fully integrated example prototype consists of the following components:

Figure 44 shows a conceptual model for this prototype model. Some notes on this system follow: This system has also been illustrated using a computer simulation and animation, as summarized in appendix C.

System Support Vehicle

This system will require a custom base support vehicle, or at least a special modification of an unusual vehicle. The features that would make this vehicle unique are:

1) The operator's cab must be situated so that the operator may view the pavement immediately in front of him/her.
2) The installation rig must be situated immediately in front of the cab.
3) The vehicle should have an approximate two ton weight capacity.

The first two features are necessities of the positioning system. Since a part of the positioning system relies on the driver, a direct line-of-sight from the cab to the pavement in front of the vehicle is preferable. Indirect visual contact methods, such as mirrors or cameras, could be used, but would disorient new operators.

The weight capacity estimate is mainly due to the one or two thousand steel-sheathed ceramic magnetic markers that the truck would have to carry. The truck would also have to carry a generator, air compressor, installation unit, and other miscellaneous equipment.

The use of a trailer for this operation has also been considered. It was decided that truck-mounting is preferable, since a truck would be easier to position, and a trailer-mounted system would require a second operator.

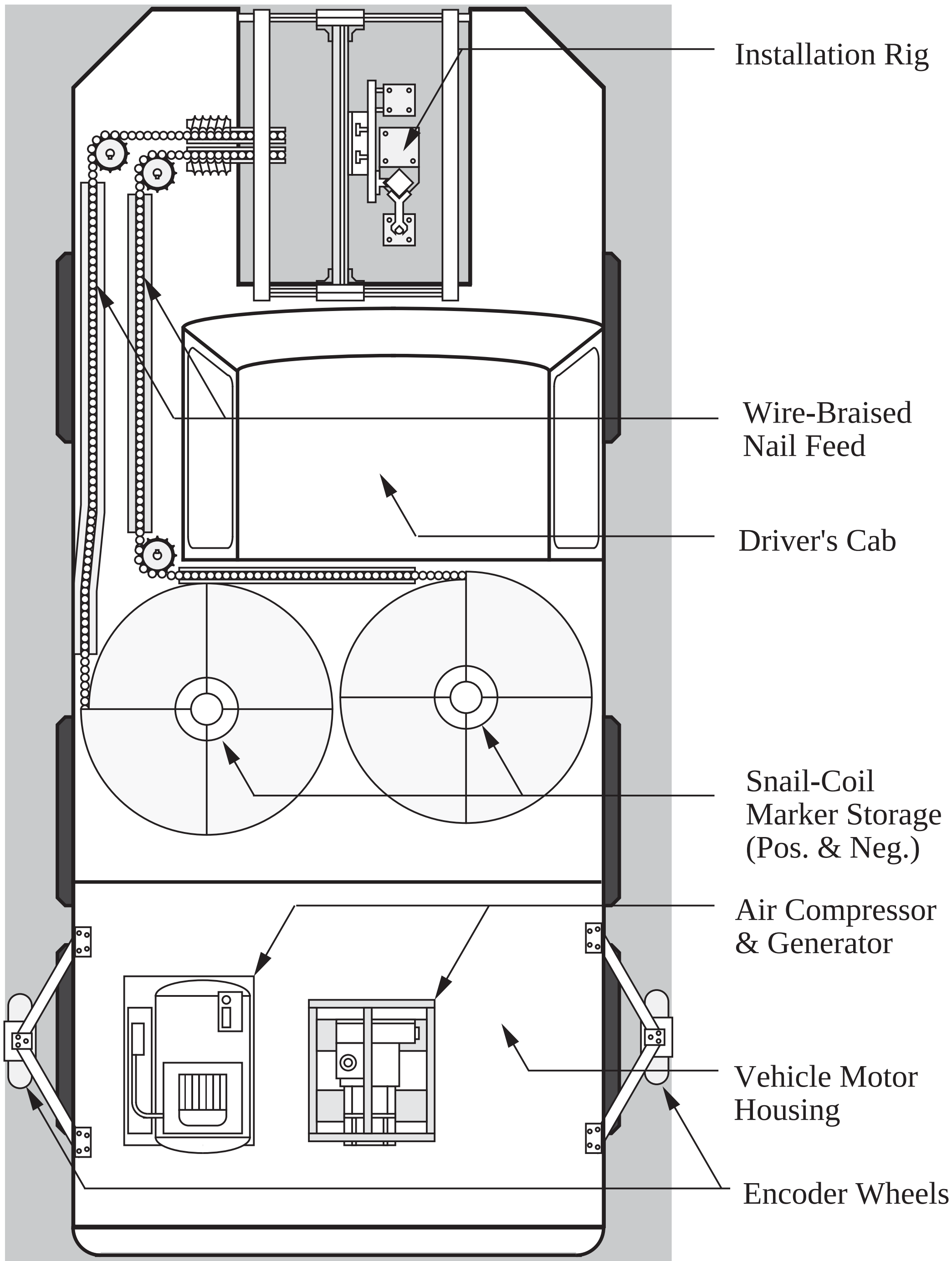

Figure 44. Prototype discrete magnetic marker placement truck.

Marker Casing

A prototype for the nail marker casing is shown in figure 45. The dashed rectangle indicates where the ceramic magnets would be seated. They would be held in place with some type of sealant, applied from the top, which is on the left in this figure. This part would most likely be made by cold forming a tube cut to length, with header molds used to form the top lip and bottom chamfer. Due to the nature of the end-use of this part, the casing could be designed so that the dimensional tolerances of the lip and chamfer are loose, making this a relatively inexpensive part.

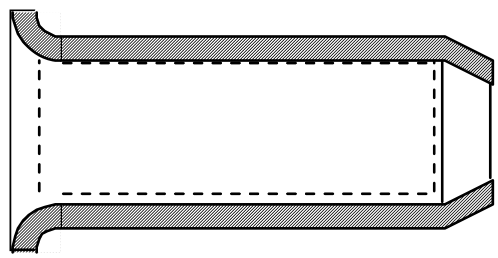

Figure 45. Prototype nail marker concept.

Positioning System

For lateral control, the Driver/Operator will steer the installation vehicle along a pre-painted centerline in the lane. When the operator stops at the installation site, s/he will make fine adjustments to the lateral position of the installation unit by controlling a lateral slide. This is illustrated in figure 46. Fine positioning will be done by siting the drill bit so that it is directly centered with the painted line. It is believed that if a sufficiently narrow (~ 20 mm) painted line is used, positioning with this method will be within a reasonable tolerance.

This design uses a human operator rather than an electronically controlled positioning system for the following reasons:

- It is assumed that both an electronic and a human guided system can laterally position the installation unit within 40 mm repeatably, and in roughly the same time.
- An electronic line-following system would be expensive, and subject to more down-time for maintenance.
- If the driver operates the system, there will be no additional manpower requirement.

For longitudinal control, distance will be measured by two encoder wheels located by the rear tires. The averaged signals from the encoders will either signal the driver to stop, or actually control the brakes to stop. Fine tuning of the longitudinal spacing will be done with a longitudinal slide, which will be electronically controlled.

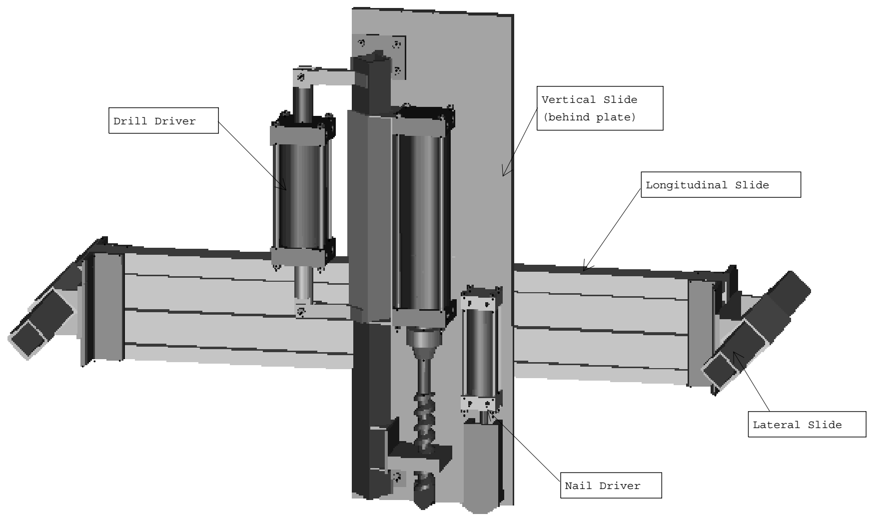

Figure 46. Conceptual draft of installation unit.

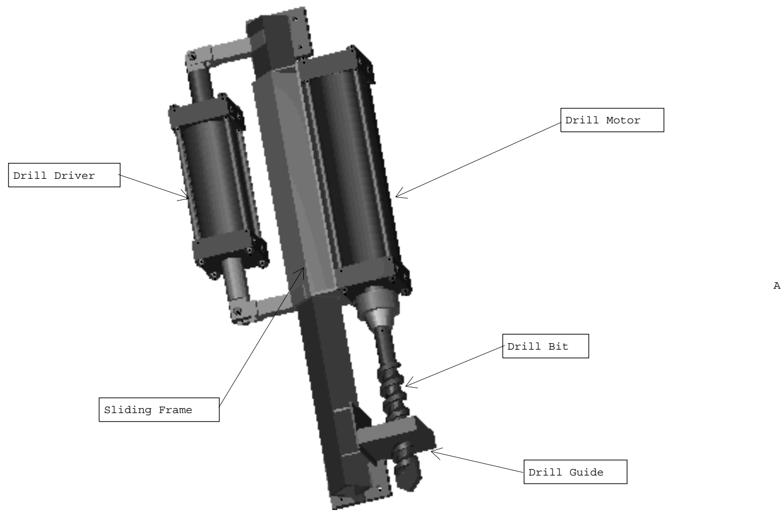

Figure 47. Conceptual design for installation drill.

Marker Installation System

The installation system would work in the following manner, as illustrated in figures 46 and 47:

1) Vertical slide drops the installation unit down to within a few centimeters of the pavement.
2) Longitudinal & lateral slide adjustments are made to position the drill bit over the installation site.
3) Drill motor turns on; drill spins.
4) Drill driver pushes the drill bit into the pavement
5) Drill driver comes to the end of its stroke length when the correct depth is drilled.
6) Drill driver lifts the drill bit from the new hole. The drill motor shuts off.
7) Lateral slide automatically positions the installation unit such that the nail driver is directly above the hole.
8) Nail driver presses the marker into the hole.
9) Nail driver retracts, and the vertical slide lifts the installation unit to the traveling height.

The truck is then be driven to the next position, and the process repeats.

Feeding and Storage System
The marker nails would be connected by wires that are either braised or soldered to the casing's surface. They would be stored in two drums, one full of positive oriented markers, and one full of negative oriented markers, as shown in figure 44. These markers would be wound in a 'snail-coil' inside the drums, and the markers would be pulled out in a way that is analogous to pulling out measuring tape from a coil. The snail-coils are shown with one coil wound clockwise, and the other counter clockwise. If the system is built such that one polarity of markers will only be wound CW, while the other is wound CCW, then there will be no chance of accidentally confusing the polarities of the snail-coils when reloading.

The snail-coils should be balanced on bearings that are slick enough to allow the markers to be drawn out with minimal pressure. Using motors to spin the coils would be tricky, since the radius of the roll of nails on the coil would change as more nails are rolled out. Instead, the nails should be pulled out and fed through channels by a system of driven sprockets and worm gears.

Separation and Sorting System
Marker sorting and separation would take place while the truck is moving from one installation site to the next. The procedure follows:

1) Marker is installed, and the vehicle starts for the next location.
2) Computer sends signal telling which polarity marker will be needed for the next site.
3) Longitudinal & lateral slides position the installation unit so that the nail driver is in front of the correct polarity feed, as illustrated in figure 48.

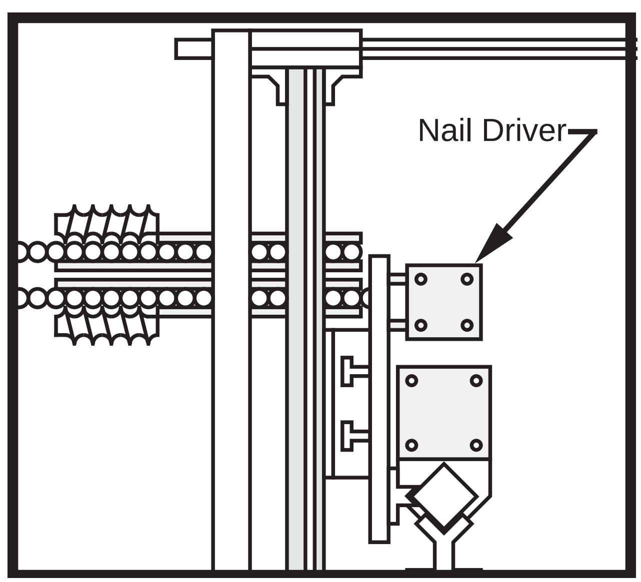

Figure 48. Marker being loaded into nail driver.

4) Sprockets and worm gears on the feed system advance one nail forward.
5) Nail driver head grasps the marker at the end of the feed.
6) Cutters separate the nail from the feed line. Nail is ready for installation.

Pre-Installation Inspection System

Inside the nail driver holding area will be a coil for a Hall-effect magnetometer. This is not shown in the illustration. This sensor will serve as a system check to ensure that the correct polarity marker is loaded. Before installation, the computer will check the output from the sensor, and verify that it matches the polarity of the marker that is scheduled to be installed.

Additional Hall-effect sensors will be mounted to the vehicle's front bumper. This set of sensors will be configured in the same way that the commuter vehicle's sensors are set up to follow the markers. These sensors will allow the truck to trace existing markers in the roadway, so that the marker installation vehicle can start working at the point where a previous installation ended. The computer would read the polarities of the existing nails, match the pattern with its database, and determine which nail is next in the installation sequence.

A third set of sensors could be placed on the rear bumper of the truck, in order to perform a last inspection on the nails that have just been installed. However, independent inspection may be preferable.

CHAPTER 7: FINAL DESIGN STAGES

Field Testing

Field testing follows the prototyping stage. The prototyping stage ends when the machine is built, and it will work repeatably under ideal conditions. Field testing continues testing of the prototype, introducing real-world conditions by taking the unit on the road.

When performing field tests, careful logs of machine performance should be kept. Problems with the system should be dealt with as they arise. The maintenance and operational procedures reports for the machine should also be written at this time.

Ideally, the machine should be tested in geographic areas that exhibit all of the conditions that the machine would be exposed to in normal operating conditions. If this type of testing is prohibitive due to time or other constraints, these tests should be performed through simulation.

Development of Production Model

Once a machine has been developed that performs to all specifications, thought should be given to the manufacture of the machine itself. The machine should be made so that it is easy to produce and maintain. These concerns should be present in previous design steps; but should be checked again as a final step. Chances are, there may be quick fixes in the prototype which have been added during troubleshooting stages. These components should be replaced using rigorous design.

CHAPTER 8: MANPOWER ANALYSIS

For any highway construction or maintenance operation, the manpower required is an important consideration. A particularly useful measure is the amount of manpower required for a standard unit of construction or maintenance work, i.e. the man-hours required to accomplish a given task. As part of this PSA study, a method was developed for assessing manpower requirements for manual and automated construction and maintenance operations for an AHS. The details of this method are documented in a technical report.[5] This chapter presents the results of applying this method to determine the manpower requirements for manual and automated installation of discrete magnetic markers for a lateral reference system in an AHS.

Manpower Background

The first step in determining on-site manpower requirements is to select the means of analysis for the construction or maintenance task. There are several standard methods for determining how long a task will take, in terms of time or man-hours.[17-19] Work measurement techniques include:

- Predetermined Motion-Time Studies (PMTS).
- Time Studies.
- Estimation Techniques.

Because of the lack of existing AHS facility operational experience, an analytical estimation technique was selected for the current study. Analytical estimation uses standard data times, work measurements, and practical experience to predict the requirements of future operations. The analytical estimation involves the following steps, illustrated in figure 49:

1. Develop and define the procedure for carrying out the job.
2. Break down the elements of the job into components, sub components, etc.
3. Apply standard data to the elements, where available.
4. Carry out PMTS and time studies where economically justified; for mechanical equipment, contact the manufacturer or calculate running speeds.
5. Estimate remaining operations and modifiers (set-up times, difficulties with terrain, etc.) by use of experience.
6. Assemble data to calculate time/unit and man-hours/unit.
7. Apply the procedure

For AHS construction and maintenance procedures, the best method for manpower analysis will depend on the particular job. Here, AHS construction and maintenance tasks can be broken down into two categories:

- jobs which are similar to current procedures, e.g. paving, crack sealing, landscaping, etc.

- jobs which are mostly unique, and have no logical precedent, e.g. installation of discrete markers, inspection of AHS, etc.

Comparative estimates should be attempted for jobs which can be based on previous procedures with readily available data. If the data is not available, it should be generated through a categorical study, and then analyzed in a categorical estimate. If the results of this categorical estimate will not yield the desired accuracy, then an analytical estimate can be prepared.

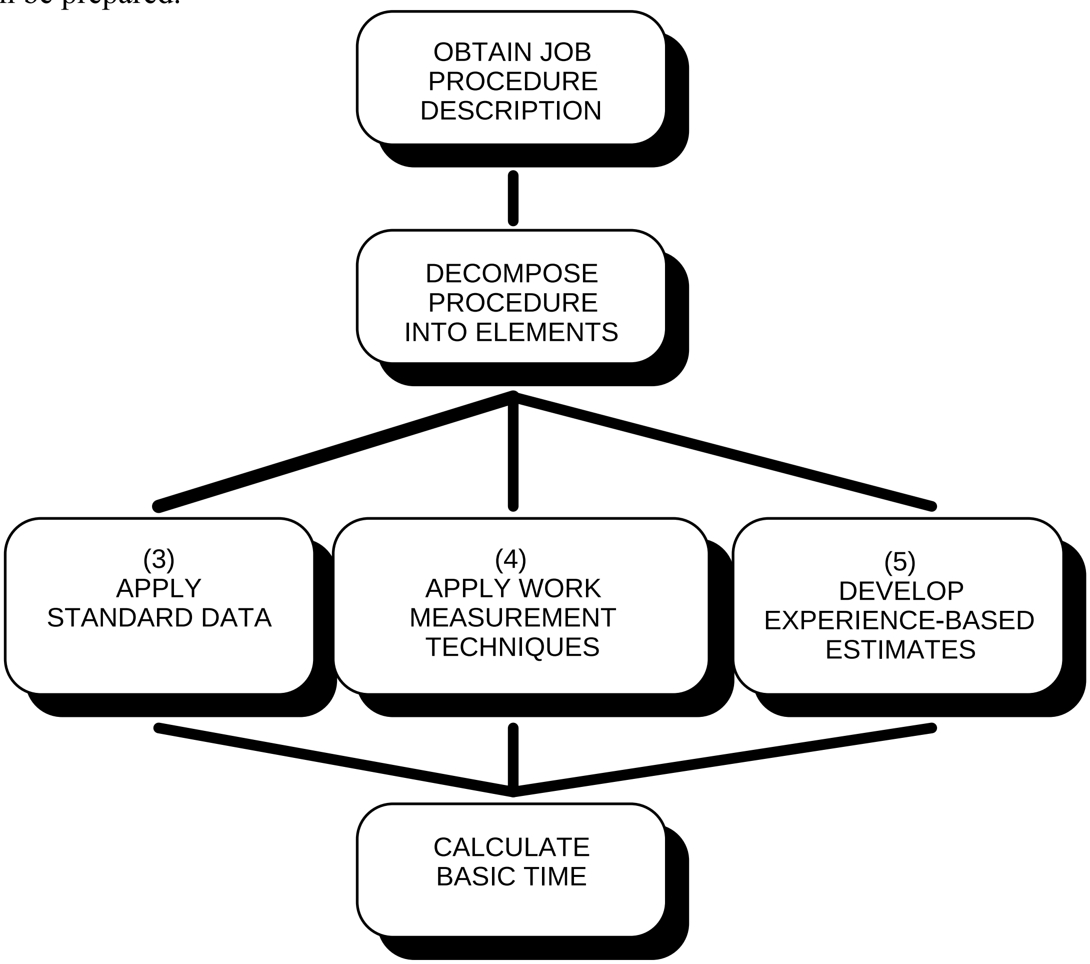

Figure 49. Analytical manpower estimation procedure.

New jobs should use analytical estimation. Ideally, this analysis should be incorporated into the design process.

The detailed steps of the manpower requirements analytical estimation technique are provided in a technical report.[5] The results of applying this estimation technique for manual and automated installation of discrete magnetic markers are discussed in the next section.

Manpower Requirements for Installation of Discrete Magnetic Markers

The manpower analysis technique was applied to the manual and automatic installation of discrete magnetic markers. A brief summary of these results is provided here. Further details can be found in the technical report.[5] The unit of work used here is the installation of one lane kilometer of discrete markers, assuming a four meter spacing between marker installation sites. The results of the analysis are shown in table 9.

The manual operation is performed using a grid survey and manual drilling. The grid survey uses a traverse surveying procedure to locate the installation sites for the discrete magnetic markers. Manual installation of the markers involves drilling at the previously surveyed locations, then gently hammering the markers into place. Manual operation will require two workers for the survey crew, and four operators for the installation crew, including the support and shadow vehicle drivers. The two procedures can be performed concurrently, so that the time estimate for this operation is taken from the longer of the two procedures.

The automated operation is based on the prototype system described in chapter 6. With this system, a single operator can drive the support vehicle, locate the installation sites, and install the markers. The estimated total cycle time for a single marker installation using this system is 30 seconds, with an additional 30 seconds required to move between installation sites.

Table 9. Manpower requirements for installation of discrete magnetic markers

Method	Op. Hr / Unit Work	Total Hr / Unit Work	Op. Man-Hr / Unit Work	Total Man-Hr / Unit Work
Manual Survey and Install		**20.8+ Setup**		**83.2 + Setup**
Survey	20.8 + Setup		41.6+ Setup	
Install	10.4		41.6	
Automated Installation	4.16	**4.16**	4.16	**4.16**

Based on the results of this manpower requirements analysis, it is clear that automated installation of discrete magnetic markers offers significant savings over manual installation. The numbers here must be considered rough estimates given current knowledge of the task. However, the analysis does provide a qualitative indication of need for and benefits of the application of automation for construction and maintenance of an AHS.

CHAPTER 9: ECONOMIC ANALYSIS

In addition to manpower analysis, it is important to investigate cost-benefits for automation of AHS construction and maintenance operations. The primary objective of AHS is to improve the performance of our highway system. Performance is expressed using terms such as: average speed, volume to capacity ratio (V/C), vehicle hours traveled (VHT), vehicle miles traveled (VMT), vehicle hours of delay (VHD), and safety. Each of these parameters can be adversely affected by highway maintenance and construction operations. As the demand and performance of the highway increases, the impact of maintenance and construction operations will in turn be more dramatic. Therefore, improved maintenance and construction techniques are vital to the success of the high capacity AHS. The development of such techniques and systems should include a cost-benefit analysis to justify the use of automated versus manual techniques.

A cost-benefit computer model was developed as part of this PSA study. The details of this model and its application to automated installation of discrete magnetic markers are provided in a technical report.[6] This chapter provides an overview of the cost-benefit model, and a summary of the results of the cost-benefit analysis of automated marker installation.

Overview of the Cost-Benefit Model

For this analysis the costs of AHS maintenance and construction have been categorized into two separate components: direct costs and user costs. The direct costs associated with a maintenance operation are those costs which will be directly incurred without considering costs associated with restricted traffic flow. These costs include labor, equipment, and material costs. The cost of maintaining the infrastructure of an AHS is dependent upon the degree to which automation functions are incorporated into the infrastructure. At a minimum, the direct cost of maintaining an AHS will be the same as for present highway systems. As more automation functions are shifted from the vehicle to the highway infrastructure, the cost of maintenance grows. Functions are associated with the maintenance of each AHS component, beginning with installation, then periodic inspection and preventative maintenance.

In addition to the direct operational costs of AHS, the total cost of AHS maintenance will include substantial user costs. When the capacity of an AHS lane(s) is reduced or eliminated due to maintenance operations, it is possible that the overflow traffic will be switched to manual mode through the work zone. The user costs associated with manual driving through work zones can be grouped into four general categories: delay or travel time costs, vehicle running costs, speed-change cycling costs, and accident costs. Delay costs result from reduced speed through the work zone, delay in slowing down from and returning to the approach speed, and delay in a queue if demand exceeds capacity. Changes in vehicle operating costs result from reduced speeds through the work zone and queue, if any. Speed change cycling costs are generated from slowing down to go through the work zone and stop-and-go conditions if a queue is present. Changes in user accident costs are difficult to quantify due to the lack of data related to changes in accident rates through a typical work zone.[20]

To determine the overall cost-benefits of robotic maintenance of an AHS, both direct and user costs must be considered. By comparing the costs of a manual method and a robotic method, the annual cost savings can be determined. Using the time value of money method, it is possible to determine the overall value of a proposed automation project or robot.

Considering the relatively early state of AHS research and the enormous uncertainty and variability in actual deployment approaches, it is difficult to estimate the construction and maintenance requirements of a future AHS. However as concepts evolve and maintenance requirements are defined, the current model will provide a framework for determining the overall cost savings of robotic AHS maintenance.[6] The model uses a computer program called Demos. Demos is designed for economic modeling applications, and incorporates a graphical interface, making its use simple. The framework of the model can accommodate a wide variety of possible maintenance scenarios and highway closure strategies. Model input data requires some detailed knowledge, including time estimates and labor requirements for the proposed automated method, as well as the manual method. For each maintenance function, the model will calculate the direct and user cost savings for both a manual method and an equivalent robotic method. As noted earlier, direct costs represent equipment, labor, and material costs. User costs represent the cost of traffic congestion resulting from highway maintenance activity. Further details of the cost-benefit model and its implementation with Demos, refer to the technical report.[6]

Cost-Benefit Analysis of Discrete Marker Installation

This analysis compares manual installation of magnetic markers with an equivalent automated process. The details of magnetic marker installation are presented in earlier chapters, including the example prototype automated installation system of chapter 6, which forms the basis for the results presented here. The corresponding data for this task has been entered into the cost model; the results are summarized here. Further detail is available in the technical report,[6] including the description of the manual and automated installation process and manpower requirements.

For the current study, the following installation scenario is considered. Magnetic markers are to be installed four meters apart on the automated lane of a three lane highway. The left lane of the highway is automated, with a capacity of 4000 vehicles per hour (vph). The other two lanes are conventional, with a capacity of 2000 vph. The maintenance operation is to take place seven hours a day, with one mile (1.6 km) sections of the lane closed at a time. There is enough work to sustain the manual operation for 250 days. Average hourly traffic volume and work zone capacity is specified. The value of time is $20.00 per hour for trucks and $10.00 per hour for cars. Traffic is eight percent trucks. The equipment operating cost of the manual method is assumed to be the same as the robot operating cost. The economic life of the robot is five years. The minimum attractive rate of return is 15 percent for the robot investment. Material costs are the same for the manual and robotic methods. Traffic volume and work zone capacity corresponding to a three lane highway with one AHS lane are specified in table 10.

For this scenario, the cost model indicates significant savings using automated installation. The annual operating cost savings of using the automated method of magnetic marker installation is $194,000, due to the decrease in the number of workers required and the increase in efficiency of the operation. The annual user cost savings is $49,000, which is most sensitive to the time and duration of the shutdown and the efficiency of the operation. The direct break even value of the robot is $552,000 and the total break even value of the robot, including user and direct cost savings, is $692,000. In this case it was found that the value of the robot is mostly a result of the direct cost savings. The value added to the robot from user cost savings is small, since work was performed only during off-peak hours, with little resulting effect on traffic flow.[6]

Table 10. Hourly traffic volume and capacity data for magnetic marker installation.

Hour	Traffic Volume	Capacity
1	1000	2900
2	1200	2900
3	1300	2900
4	900	2900
5	1000	2900
6	4000	8000
7	7500	8000
8	7000	8000
9	6500	8000
10	6000	8000
11	5700	8000
12	5500	8000
13	5700	8000
14	6200	8000
15	6700	8000
16	6900	8000
17	4200	8000
18	3200	8000
19	2300	8000
20	1500	8000
21	1200	8000
22	1100	8000
23	1000	2900
24	1000	2900

As with the manpower analysis results, the cost-benefit analysis summarized here should be considered rough, due to limited knowledge of the task. However, the analysis once again provides significant qualitative evidence of the significant savings when automated techniques are applied in the construction and maintenance of an AHS facility.

CHAPTER 10: CONCLUSIONS

An Automated Highway System will be a complex system, with associated complexity in both construction and maintenance. For cost-effective construction of a new AHS, or retrofitting of existing roadways with AHS technologies, automated robotic type construction techniques will be highly beneficial, if not indispensable. Similar techniques will be needed for maintenance, inspection, and operation of an AHS.

This report documents an initial investigation into some of the requirements for automated construction, maintenance, and operation of an AHS. A specific, infrastructure intensive AHS technology, discrete magnetic markers for use in vehicle lateral control, was selected to allow a realistic and focused design. An initial design for the subsystems required for automated installation of the magnetic markers has been presented, along with a complete example prototype system which would be capable of such an installation. In addition, preliminary manpower requirement and cost-benefit analyses have been done for manual and automated installation of the magnetic markers. These analyses dramatically illustrate the magnitude of the cost savings available by using automated construction and maintenance techniques for an AHS.

APPENDIX A: LITERATURE SURVEY

The initial phase in this PSA study included a comprehensive literature review of existing IVHS research, with a focus on areas relevant to AHS. The complete literature review is available as a technical report.[2] The review helped identify important research areas and results related to the design and deployment of an AHS. The review also identified certain gaps in the knowledge in the field. In particular, it was recognized that there has been very little work in the application of robotics and automation technologies in the construction, maintenance, and operations of an AHS.

The complete survey covers the following areas: general AHS research; longitudinal, lateral, and combined vehicle control; sensors and alternative AHS vehicles; communications requirements; system architecture; safety and fault tolerance; and human factors.[2] A summary of the significant findings in these areas is provided here.

General AHS Issues

The Strategic Plan for Intelligent Vehicle-Highway Systems in the United States[21] is a fundamental document for IVHS research in the United States. This plan includes: goals and objectives for a national IVHS program; challenges to deployment and ways to resolve them; suggested roles for public, private, and academic participants; a course of action with associated milestones and operational tests; cost estimates; and a very useful glossary of IVHS terms. This reference is seminal within the IVHS literature, and constitutes an excellent starting point for those initiating IVHS and AHS research.

There is a significant amount of foreign research in IVHS. Europe has strong IVHS research programs. McQueen and Catling[22] review the development of IVHS, referred to as Road Transport Informatics (RTI) or Advanced Transport Telematics (ATT), in Europe. It is interesting to note that in Europe a strong emphasis is placed on navigation, guidance, and information systems, while in the United States, more emphasis is placed on vehicle control and the eventual deployment of a full AHS. The Japanese approach to IVHS, relies more heavily on vehicle intelligence, rather than infrastructure.[23] In fact, the Japanese at the time of this report were studying Intelligent Vehicle Systems (IVS), rather than IVHS.

Until recently, AHS research in the U.S. has been somewhat sporadic, subject to whims of federal funding. However, since the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), commitment to the AHS concept and its eventual implementation at some level is fairly strong.. The ISTEA has had significant impact on the IVHS program.[24] As a result of this act, the U.S. Department of Transportation established a major AHS program. The program's foundation is a commitment to work closely in partnership with other public and private interests to achieve mutual program goals; the ISTEA provides support and funding for this partnership. A major element of the ISTEA is the Intelligent Vehicle Highway Systems Act of 1991. This act established an IVHS program with approximately $660 million authorized over a six year period.[24] It also mandates a 1997 demonstration of an AHS to serve as a prototype for future systems development.

Proponents of AHS agree that a proper combination of control, communication, and computing technologies in the highway and the vehicle can assist driver decisions in ways that will increase highway capacity and safety without building more roads. However, there is a wide range of opinion about the form of this ``intelligence'', due to variation in judgment about: the driving functions to be automated, and the degree of automation; the decomposition of functions into control tasks, and the assignment of tasks to subsystems; the division of intelligence between vehicle and infrastructure, and how technologies can be combined to implement this architecture; the timing of system development and deployment, and the extent to which the architecture can incorporate functions not originally planned for; and the effectiveness, costs, and benefits of various AHS proposals.[25]

Shladover discusses research needs in roadway automation technology within nine areas of an AHS.[26] He examines each area in terms of the data flow between system components of the system. Shladover views information flow as a method of focusing on the technical issues that must be resolved to implement the automation functions. The author notes that coordination of the individual automation functions into a full AHS requires a focused plan using good system engineering principles, identifies many important yet unsolved issues that are critical for the eventual success of an AHS, and provides significant guidance for the new IVHS researcher.

Harris and Bridges identify many areas of required research in AVCS, which will form a critical part of an AHS. Near-term areas include proximity sensing, lateral guidance sensing, and actuators and controllers. Long-term needs include study of vehicle dynamics, system dynamics, infrastructure support, safety criteria, standards and protocols, human factors, and other technologies.[27]

Vehicle Control

Achieving the goal of an AHS requires significant research in system modeling, lateral control, longitudinal control, and combined lateral and longitudinal control of vehicles. Generally, control systems in an AHS will rely on vehicle-to-vehicle communication, as information regarding velocity and acceleration of other vehicles, in particular lead vehicles in groups or platoons, will be utilized in individual vehicle controllers.[25,28] In addition, vehicle-to-roadside communication will be needed to establish nominal speed settings for the entire group of vehicles.

A significant lateral vehicle control experimental study for a full-scale automobile is presented by Peng, et al.[4] In this reference, the IRRS[1] is used to implement and compare two control algorithms: a frequency shaped linear quadratic (FSLQ) control law, and a simple PID controller. In both cases, a deterministic preview controller is added.

Test results, while good, indicate a need for additional development of the components and full-scale experiments under adverse conditions and at higher speeds.

One of the major concepts for lateral control is platooning, which is a formation of traveling vehicles which maintain close spacing at highway speeds. Platooning may double or triple highway capacity without the application of lateral control.[] The general concept of a platoon requires inter-vehicle communication links to provide velocity and possibly acceleration information for the lead vehicle to each of the follower vehicles, as well as velocity and acceleration of the immediately preceding vehicle in the platoon. Inter-vehicle communication aids the stability of the platoon formation. Longitudinal control also requires headway sensing to provide vehicle separation as an input to the control system; possible sensors here include radar and laser range finding systems. Longitudinal control of a platoon of vehicles has been experimentally demonstrated by Chang, et al.[28]

A significant amount of research has been done in the vehicle control, also known as Advanced Vehicle Control Systems, or AVCS. For further review of longitudinal, lateral, and combined vehicle control, refer to the technical report.[2]

Sensors and Vehicles

Sensor technology will have a critical role in AHS operation and safety. Some of the sensors will be needed for lateral and longitudinal control are reviewed here. In addition, alternative vehicle types and their impact on the AHS scenario are discussed

Technologies proposed for lateral control include wire guiding, discrete magnetic markers, and vehicle-based vision systems. Wire guiding has been demonstrated as technically feasible on test tracks[30], but in practice the approach requires significant additional capital investment in highway infrastructure. Vision-based sensing has shown significant promise in recent years, as shown for example in the CMU NavLab experiments, but may be prohibitively expensive. Because of these difficult issues, recent work has moved in the direction of some form of discrete marker system.[1]

Several systems have been proposed for headway sensing for use in either driver warning systems or longitudinal control. Chang, et al.[30] present experimental results for a longitudinal controller using front-mounted radar. The main drawback of this system is that it uses the Doppler effect, so that absolute distance information cannot be obtained when closing rates between vehicles are low. One alternative, microwave radar sensors perform very well in fog, heavy rain, and other low visibility conditions, but they are prohibitively expensive.[31] In this reference, the authors propose a laser diode radar system. This is a much cheaper system, although it does not handle low visibility conditions very well. The system has provisions to reduce the number of false alarms. The issue of false alarms is a significant consideration in AHS, as excess false alarms will lead to public rejection of the system, as well as failure of the driver to believe in the system when the alarms are not false.

In the area of alternative vehicles, the so-called "lean vehicle" is one concept which would have a major impact on AHS infrastructure.[32] Reduced vehicle weight and size is of great interest for AHS application. One block to transition of current commercial and private fleets to lean vehicles is the massive existing infrastructure that is designed for heavy vehicles. However, when considering a radical new system such as an AHS, the benefits of design for, or at least provisions for, lean vehicles should not be overlooked. As Garrison and Pitstick put it, "IVHS technologies might be used as building blocks for a lean vehicle system."[32]

Communications

AHS will require significant communications between individual vehicles, as well as between vehicles and the roadside. For a very brief review of AHS communications needs and research, refer to the technical report.[2]

System Architecture

The system architecture selected for deployment of an AHS is a very important issue. The architecture will have serious implications regarding performance, capacity, robustness, and safety.

Varaiya and Shladover present an overall system architecture combining ATMS, ATIS, and AVCS.[33] The architecture presented consists of a five layer hierarchy for ATMS and ATIS, and a separate five layer hierarchy for AVCS. The work presented here focuses on full automation, including platooning for high capacity improvements. The importance of an open systems architecture is emphasized here. The analogy to current computer networks illustrates the benefits of an open architecture: equipment conforming to standards will work with any other conforming equipment, although the equipment designs may be proprietary and different. With an open IVHS architecture, similar benefits may be achieved. Without one, equipment on different vehicles on different highways will be incompatible, more expensive, and less productive.[33] Development of such an open systems architecture will require the active participation of at least transportation agencies, automobile manufacturers, and control and communications equipment developers.

Safety and Fault Tolerance

Without question, the most important issues that must be resolved in IVHS relate to safety. Unless the safety of the overall system can be verified, the envisioned AHS will never be deployed. Safety and fault tolerance issues have been investigated by a number of IVHS researchers, but this appears to be an area where much additional work is needed. For a detailed review of safety and fault tolerance research and issues, refer to the technical report.[2]

Human Factors

In an advanced system such as an AHS, the driver will be confronted with significantly more information, and possibly more controls, than are currently used in vehicles. Other problems may arise that have no counterpart in current driving situations. For example, in a system that uses complete automation during some segments of a trip, safe transition from automated driving back to manual driving is a difficult issue. Concerns such as driver information overload and driver attention fall under human factors research. Human factors issues are intimately tied to the safety of an AHS. For a detailed review of human factors research and issues, refer to the technical report.[2]

APPENDIX B: REFERENCE ARCHITECTURE AND CLASSIFICATION OF AHS

Introduction

The field of Automated Highway Systems (AHS) is a diverse area of research. In the past, many system configurations and approaches have been proposed for an AHS. This diversity has increased due to the variety of studies currently being performed for the Federal Highway Administration (FHWA) Precursor Systems Analyses (PSA) of AHS. At this time, there does not seem to exist a unifying approach to the representation of an AHS that encompasses the currently proposed systems as well as foreseeable systems in an organized manner. The architecture presented here is an attempt to provide such a unified and organized reference architecture for AHS.

This architecture can be used in a variety of ways. It can be used to specify an AHS at the functional level, in terms of the general systems and approaches to be included, or it can be used to provide detail down to the specific physical components to be used. The nature of the architecture allows different users to focus on different aspects of the AHS. For example, a system designer with a DOT perspective could choose to focus specifically on areas that relate to the infrastructure, while a vehicle manufacturer could focus specifically on vehicle-related areas. In addition, the architecture, in its fullest sense, can be used as a detailed design specification for an AHS. With an AHS specified using the reference architecture, it would be possible to generate a bill of materials for the AHS, or for particular AHS subsystems. If additional information is added regarding properties of the individual components, e.g. component reliability statistics, it is possible to use the reference architecture to compute aggregate properties of subsystems, systems, and the complete AHS.

The architecture is expandable so that it can be customized to carry information required for a specific task. Here, we present a general overview of the reference architecture, followed by an application of the architecture to a classification of AHS, which at this time includes the functions of Driving, Structural Support, Traffic Separation, Vehicle/Road Interaction, and Power Source. This classification has been being coded into Nexpert Object, providing a basis for an expert system for AHS deployment analysis.

The information in this document is based on a broad search of the existing AHS literature. Detailed reference information is not provided here; however, much of the information included here can be cross-referenced using.[2] Information regarding structural support and traffic separation can be found in.[34,35] Additional information on structures has been obtained from.[36] Some of the details for various AHS sensors were found in.[37] Additional component information and cross-references into the literature and product information can be found in.[38] Finally, an overview of Group Technology Classification and Coding can be found in.[39]

Overview of the Reference Architecture

The AHS Reference Architecture is a hierarchical, modular architecture. A general overview of the architecture is shown in figure 50. At the top level, the architecture is divided into blocks based on function. AHS functions will include driving, for example. Functions can be added as needed, as the architecture is modular. Within the Function Level, there are sub-function layers as required. The next level down in the architecture is the Form Level, which indicates the general form of the technology that will provide the specified function. The Form Level can also have multiple internal layers. Below this is the Physical Level, which indicates the specific technology and equipment to be included in the system. At each level of the hierarchy, an additional property can be coded, indicating the location of the particular function or technology. This property is known as the Carrier. At this time, identified Carriers include the roadway, roadside, median, vehicle, and satellites. The Carrier is not included in the classification schematics in the appendices of the technical report, but has been incorporated as a property in the Nexpert model.[3]

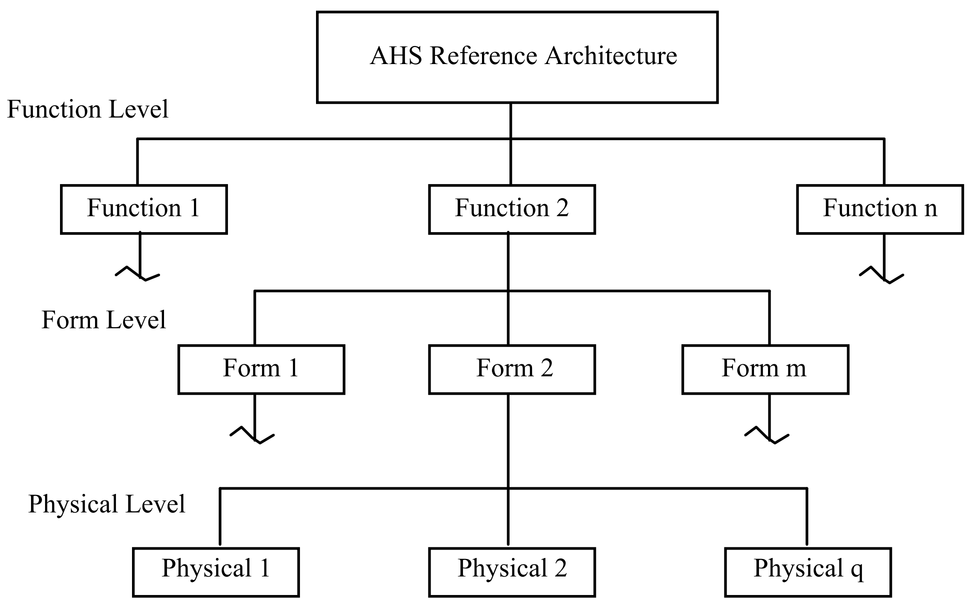

Figure 50. AHS reference architecture format.

With the above approach, the AHS Reference Architecture allows a broad range of detail in specifying an AHS. A researcher could designate a general functional level specification of an AHS, simply indicating the overall form for each of the functions, leaving the details of the physical implementation for later study. On the other hand, an AHS designer could use the same architecture to completely specify a system down to the level of the specific type of sensor to be used for headway sensing, for example. The architecture has been designed to be flexible, so that future technological and conceptual innovations in the area of AHS can be incorporated with minimal impact on the overall structure.

AHS Classification Based on the Reference Architecture

The architecture has been used to develop a classification system for AHS. The classification, like the architecture, is hierarchical. Choices made at the higher levels of the classification will constrain selections at the lower levels. However, every attempt has been made to minimize, and ideally eliminate, any dependencies across individual layers of the classification. This will allow easier enumeration of possible AHS configurations. With this feature, once codes are assigned at all layers of the classification, it is possible to enumerate all possible AHS Representative System Configurations (RSC's) to the required level of detail by simply cycling through all possible combinations of the codes. Note that this will yield an overwhelming number of RSC's if it is done for the entire classification. However, this feature can also be utilized at any level of the classification. For example, in a system that includes point follower control for longitudinal vehicle control, it would be possible to enumerate all available position sensing approaches. The hierarchical nature of the classification will be represented using a group technology hierarchical classification and coding scheme. The code digits will be grouped according to functional areas for easier identification.

To provide a better feel for how the AHS Classification System works, figure 51 shows a more detailed overview of the classification. In this figure, the actual functional areas are presented, along with some level of detail within each functional area. The amount of detail varies within each area based on two factors: the amount of information that appears needed at this time to specify an AHS, and the information that can be found in the relevant literature. For example, the function of Traffic Separation, here meaning separation of AHS and non-AHS traffic, lane delineation, and system entry and exit, requires significantly less detail than the area of automated driving. At the same time, there is far less discussion of this function in the literature when compared to the Driving function. Based on this, we have provided significantly more detail on the Driving function, and relatively less detail on the Traffic Separation function. As noted earlier, the detailed schematic diagrams for the AHS Classification are presented in the appendices of the technical report.[3]

AHS Classification Details

The complete code for the AHS Classification consists of a string of digits, providing a convenient and compact representation of the Automated Highway System and its components. The digits are grouped according to the hierarchy of figure 51, with the details of the hierarchy given in the appendices of the technical report.[3] The main groupings are by function, so that the code can be broken down into groups of digits for the Driving function, the Structural Support function, the Traffic Separation function, the Vehicle/Roadway Interaction function, and the Power Source function. Each of these groups can be subdivided based on the information in the schematics. The top-level code grouping is shown in figure 52. Each of the sub-groups in figure 52, e.g. Longitudinal Control, will consist of a set of digits describing that sub-function.

The details of various code groups are given in the subsequent figures. Most of the code groups contain significant detail and are well-suited to further breakdown, e.g. the Lateral and Longitudinal Control sub-functions. The details of the Longitudinal Control code group are shown in figure 53. The Lateral Control code group details are given in figure 54. Emergency Operation code group details are given in figure 55. The Structural Support function code group also bears further breakdown; details are shown in figure 56. Finally, the Traffic Separation code group breakdown is shown in figure 57. These figures present the breakdown of the code groups into blocks, but do not actually show the codes themselves, or the options within each of the blocks. Each of the groups of digits within the blocks will consist of one or more digits. For the details of the classification and coding, see the appendices of the technical report.[3]

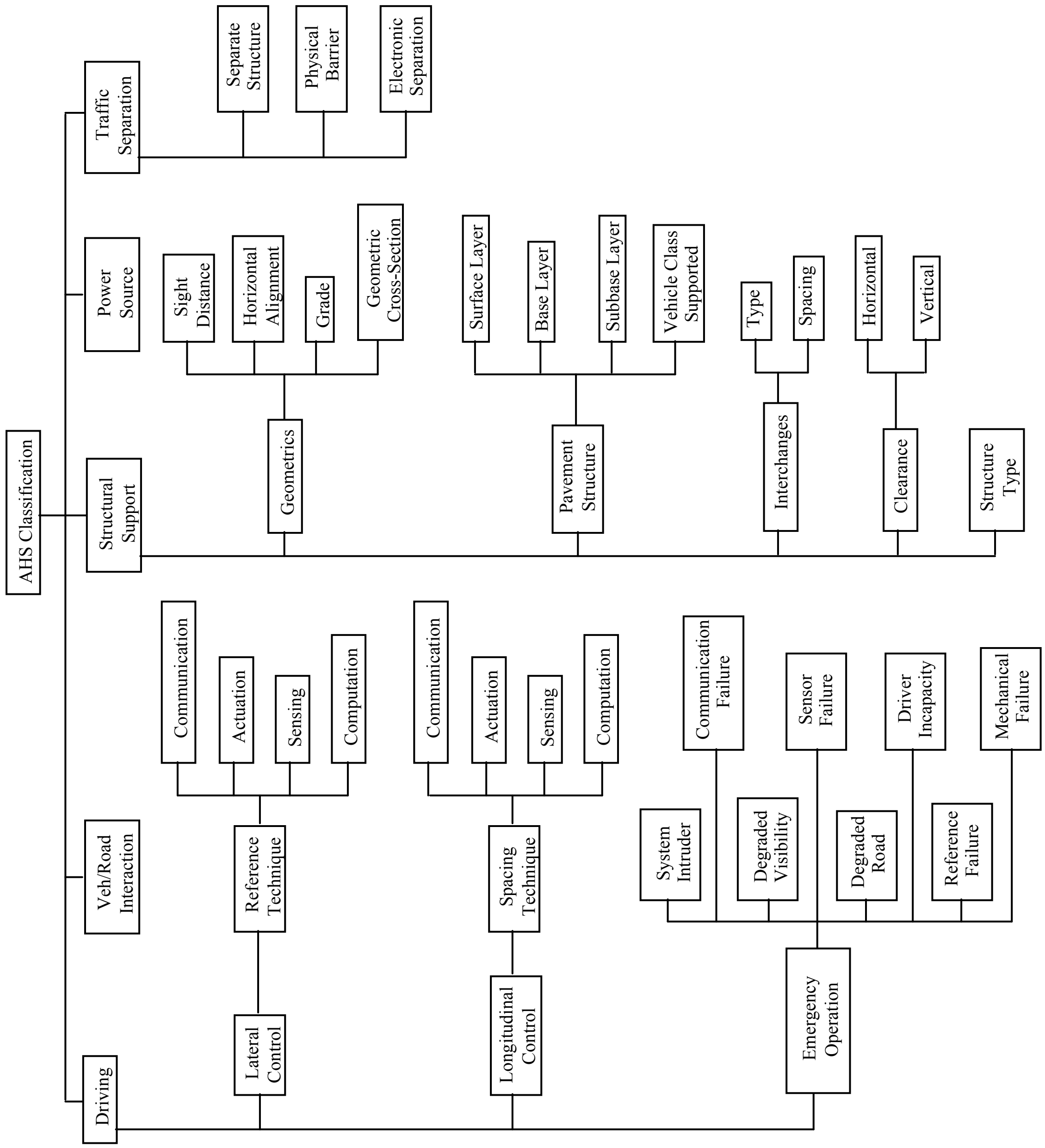

Figure 51. Detailed overview of the AHS classification.

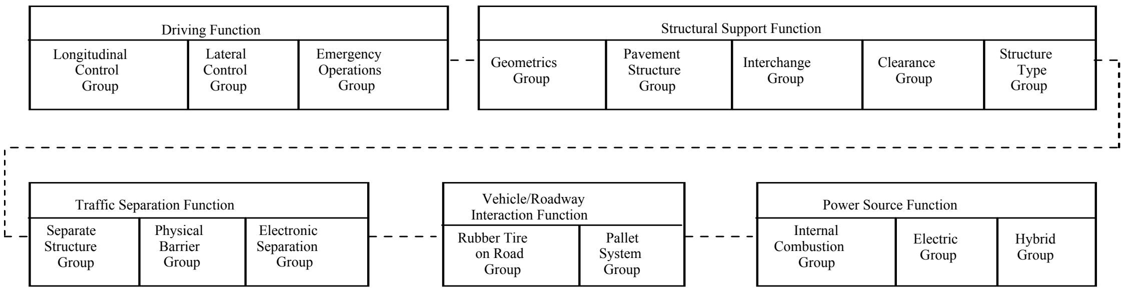

Figure 52. Top-level AHS classification code grouping.

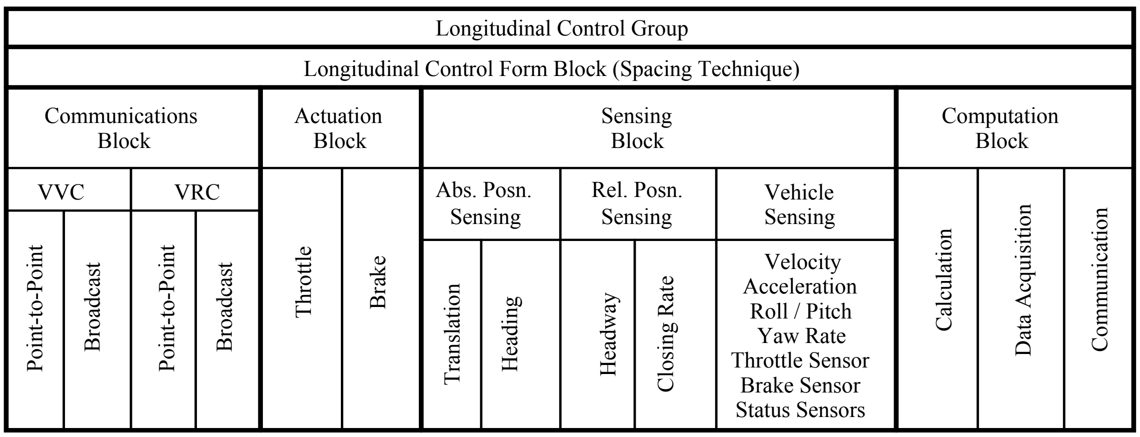

Figure 53. Longitudinal control code group.

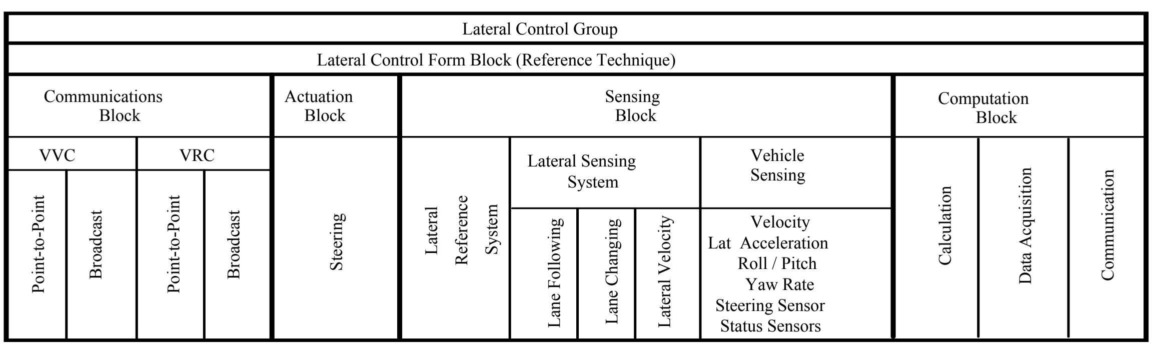

Figure 54. Lateral control code group.

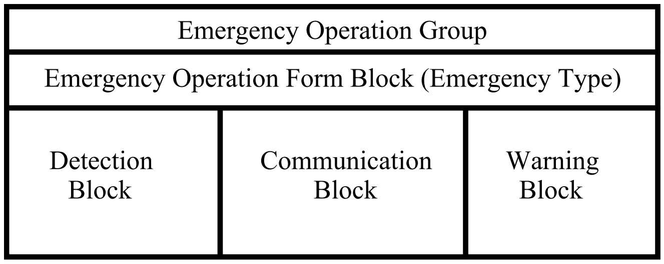

Figure 55. Emergency operation code group.

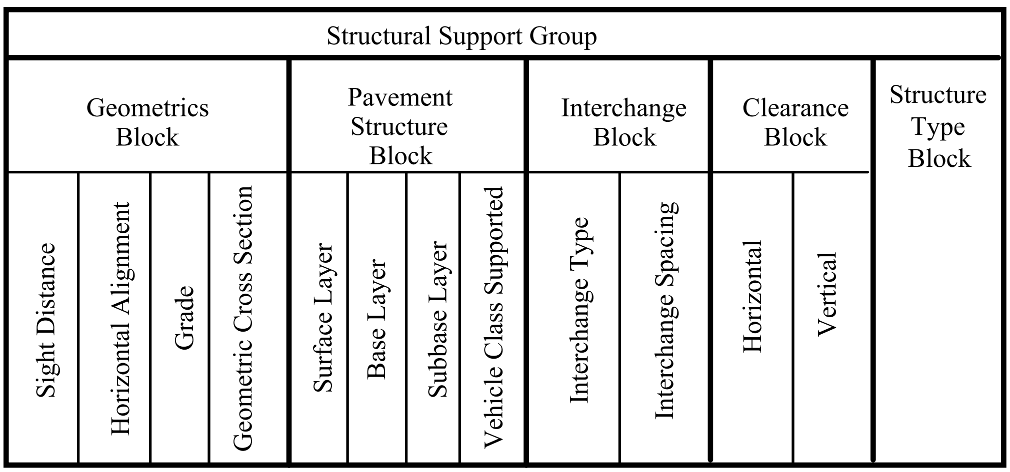

Figure 56. Structural support code group.

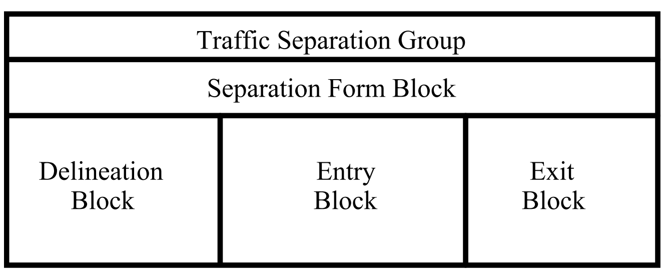

Figure 57. Traffic regulation code group.

Comments on the AHS Classification Details

A number of areas in the detailed classification bear further discussion. Some areas have not been completely classified and coded; this may indicate topics that require further research before they are well-defined. Other areas require some clarification, as detailed commentary is not provided in the appendices of the technical report.[3] These issues will be discussed here.

In the specific area of sensing of absolute translation, a number of approaches have been listed. Most of these approaches can be classified as radio-navigation techniques. Within these, GPS is clearly the most likely candidate for application in an AHS. The other radio-navigation techniques, including Loran-C, Omega, TACAN, Transit, and TACTIC, are only included for completeness. On a related note, throughout this classification, GPS should always be considered Differential GPS, as differential operation will be required to achieve the desired accuracy.

The computational requirements for lateral and longitudinal control have only been roughly indicated. The needed areas include control law calculation, sensor data acquisition, and communication support. Once again, these areas will not be mutually exclusive. In addition, the detailed physical components in these areas have not been indicated, as they will vary considerably based on implementation, and may be significantly different in the future.

The areas of vehicle / road interaction and vehicle power have not been developed in detail in the reference architecture. Most of the AHS literature has assumed that interaction will be through rubber tires on the road; as such, the concentration here is on this case, and the architecture is strongly biased in that direction. The possibility of a pallet system has been included here for completeness, and as a provision for future expansion in the classification, if this approach appears more likely in the future. Vehicle power source has been included here, but again only in a cursory fashion. Most of the classification will be only minimally influenced by the choice of vehicle power technology, with the possible exception of roadway-provided electric power, which could have significant impact on other areas. Further information may be provided from other Precursor System Analysis studies in the area of Alternative Propulsion Systems.

Within Structural Support, the area of sight distance may require further investigation. The figures given in the three areas are taken from,[34] and are based on human driver responses. At the very least, these numbers may need to be modified for the case of automated longitudinal control. In addition, the concepts themselves may require rethinking as they apply to an AHS. Passing distance will only be applicable in rural areas. The inclusion of "Unknown" as an option for these areas should alleviate any difficulties.

Conclusions

The AHS Reference Architecture and Classification System presented here can be used in many ways. The classification can be used to delineate AHS Representative System Configurations to the level of detail required. It can also be used to completely specify an AHS, down to the physical components to include in the roadway, the vehicle, and elsewhere, providing a complete bill of materials. The classification can also form the basis for a knowledge-based expert system to aid in AHS research and analysis. It represents a unified classification of the current and foreseeable possible AHS configurations. Finally, the classification can be expanded to include additional functions as needed in the future. This is an important feature, as AHS research is still in its early stages, and many changes are likely over the coming years.

APPENDIX C: SIMULATION OF DMMP CONCEPT

To illustrate the prototype system presented in this report, a three dimensional computer simulation was produced. This simulation shows the mechanism moving through the steps necessary to install magnetic nails. The simulation was created using a Silicon Graphics workstation and a 3D modeling software package called IDEAS. Once created, the simulation was recorded on video tape.

To create the simulation using IDEAS, each part of the mechanism was designed and drawn to scale in three dimensions. Once all parts of the design were drawn, they were placed in assemblies and each of these assemblies were constrained to move as single entities. With all of the assemblies built and placed in their correct positions, they could be moved with respect to each other. Each of these movements was defined by joints and constraint equations governing the velocities and accelerations at each joint. All of the assemblies moving at the correct times and velocities created the simulation of an actual mechanical system. One view of the mechanism as modeled in IDEAS is shown in figure 58.

The force and stress data associated with these parts and assemblies moving through their motions was not recorded on the video tape, but is available from the simulation. For example, the drilling into the pavement causes significant stress at the welded joints of the sliding mechanism the drill is attached to. The stress values can be directly approximated using the simulation. In addition, the welded joint could be optimized for thickness or size of weld. All of this data is available from the simulation because of its three dimensional design using IDEAS.

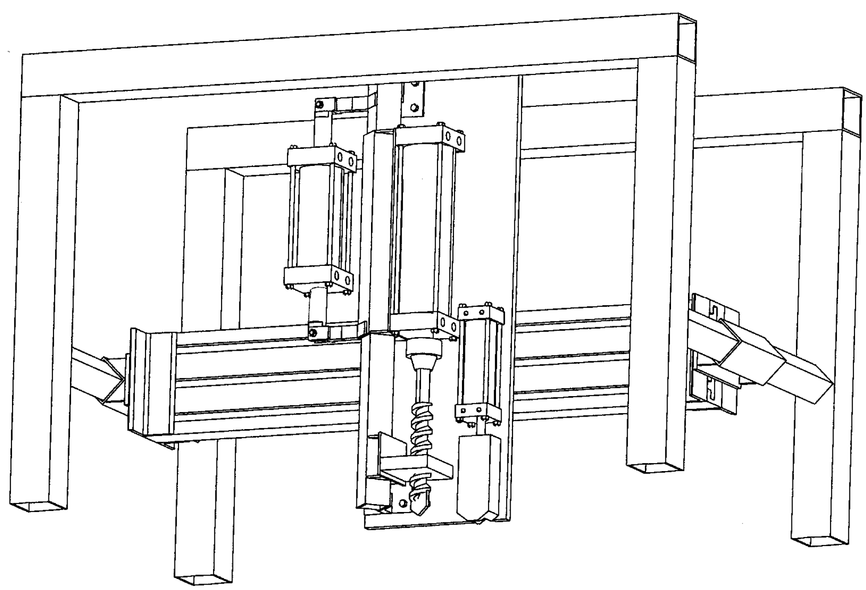

Figure 58. The magnetic nail placement mechanism.

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