California AHMCT Program
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California Department of Transportation

REQUIREMENTS FOR THE AUTOMATED APPLICATION OF MAGNETIC MARKERS FOR AHS (DRAFT COPY)

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AHMCT Research Report
UCD-ARR-94-04-01-94

Interim Report of Contract
DTFH61-93-C-00189

April 1, 1994

* This work was supported by Federal Highway Administration (FHWA) Contract Number DTFH61-93-C-00189 and by the California Department of Transportation (Caltrans) Advanced Highway Maintenance and Construction Technology Program at UC-Davis.

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Disclaimer / Disclosure

This work was supported by Federal Highway Administration Contract No. DTFH61-93-C-00189 and by the California Department of Transportation (Caltrans) Advanced Highway Maintenance and Construction Technology Program at UC-Davis.

1. Introduction

A system is needed to install discrete magnetic markers in a roadway. These markers will be used as both a guidance reference and an information database for lateral control in an automated highway system (AHS). This document contains the preliminary design information for a discrete magnetic marker installation system.

1.1 Background

Recently, the Partners for Advanced Transit and Highways (PATH) developed a lateral control system [1] to be used as a part of their full Intelligent Vehicle Highway System (IVHS) architecture. This lateral control system is now in the stage where large scale implementation systems need to be developed. PATH's system uses an Intelligent Roadway Reference Systems (IRRS); a system is needed to install these markers quickly and reliably. The task of developing the requirements for this system was given to the Advanced Highway Maintenance Construction and Technology (AHMCT) Center; a group which has built similar automated systems in the past. The results are contained in this report.

PATH's system uses permanent magnets for reference markers. The magnets are used in two different ways to maintain lateral control. The first way provides **guidance reference.** The magnets define a path for the vehicle to follow; they are positioned at regular intervals along the center of the AHS lane. Sensors on the vehicle are spaced on either side of the path (See Fig. 1.1) to determine how far the vehicle is away from the lane's center line. The steering angle of the system would then be corrected to center the vehicle. The markers are placed close enough together to ensure the vehicle will not "miss" a marker's magnetic field (M-field) and lose the path.

The second function presents a **preview reference**. The polarity of the magnets are used to code binary information about the roadway. The magnetometer sensors would distinguish between positive and negative charge, and the vehicle's navigation system would treat this information as ones and zeros. Information about upcoming curve geometry would be previewed by this system, allowing the vehicle to correct steering.

The hall effect magnetometers currently being used have a sensing range of 80 cm from the marker, with high resolution sensing within 25 cm of the marker [2]. The sensors will be mounted approximately 15 cm above the road surface. A sketch of the sensing range is shown in figure 1.1.

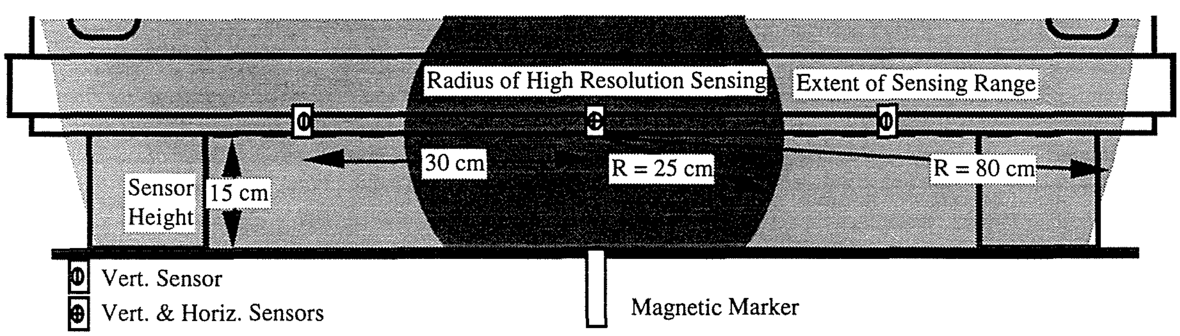

Figure 1.1: Range of Sensors

1.2 Report Structure

This work is presented in three parts. The first is the **Functional Specifications**, which specify the desired output for the system. The second section, **Strawman Concepts**, presents preliminary conceptual design ideas on how the SYSTEM will function. Because the operation of a SYSTEM would require several independent steps, concepts focus on ways to perform each task. These task-oriented strawman concepts can be integrated into a complete system after the most viable subsystems are chosen. Finally, the **Operational Specifications** give some guidelines on the design of SYSTEM equipment.

2. Functional Specifications

2.1 Placement/Tolerances

The following dimensions and tolerances for marker placement have been proven to be satisfactory in field tests conducted by PATH [2]. (See Fig. 3.1.1)

- **Longitudinal Spacing** - Markers to be placed 1 meter apart, ± .0125 m. In the most recent tests, markers were spaced 2 meters apart, and satisfactory results were obtained.
- **Lateral Placement** - Markers are placed on lane center line, allowing for deviation of .0125m.

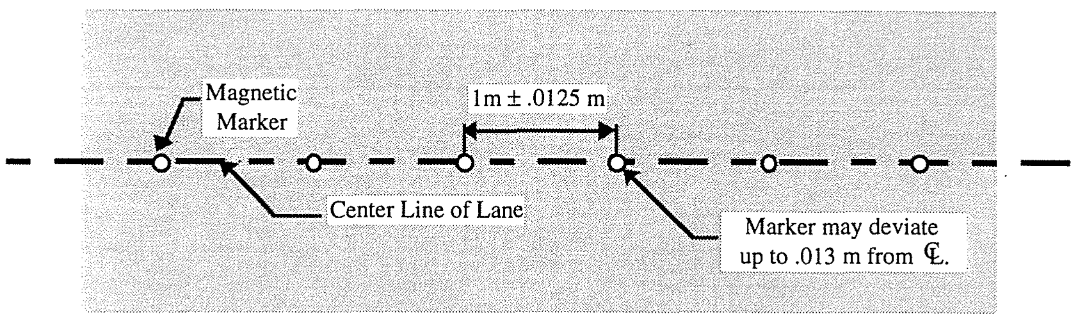

Figure 3.1.1: Normal Marker Placement

These experimental results are specific to the particular control program used in [2]. Since that report recommends that other control programs be evaluated, it would be advantageous to have a better understanding of what the dimensions of the marker placement are derived from, so that new dimensional requirements could be anticipated.

Table X shows the dimensions and tolerances needed to specify discrete marker placement for an IVHS system. The determining factors listed for each dimension are the elements that will determine what the values are. A brief description follows:

Longitudinal

- **Spacing** - Spacing is the distance between two markers in the longitudinal direction. The major concern with spacing is to ensure that the markers are close enough together to prevent the vehicle from slipping off the path by missing a marker. This would be determined by the vehicle's dynamic characteristics, (velocity and yaw angle) and the ability of the geometry previewing control to keep the vehicle moving in the right direction.

Another characteristic that would have bearing on the maximum tolerable spacing would be the compactness of the discrete marker's preview information coding. Scenarios may arise where a lot of information has to be coded into a small area, such as for a compound turn on a grade. For these specific areas, the standard spacing distance may have to be reduced, which would sacrifice the accuracy of the speed measurement factor.

The speed measurement factor simply requires that the markers be spaced evenly, so that the time of travel between markers can be easily be converted into a measure of vehicle speed.

Table: Dimensions & Tolerances and How They Are Determined

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

The minimum marker spacing distance would be determined by the magnetic field characteristics and sensing ability. The markers would have to be spaced far enough apart for a discrete signal to be read from each marker. Since it is cost effective to maximize the spacing rather than minimize it, these factors are not used for normal spacing requirements. They may come to play, however, in tolerancing for unusual configurations, such as dedicated lane entering and exiting markers.

• **Spacing Tolerance** - This is the lateral direction tolerance for the above dimension, and values must be chosen so that they do not exceed the above requirements. Tolerance that shortens the 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 length was already maximized. Any tolerance that increases spacing should therefore be tested.

• **Cumulative Tolerance** - The cumulative error is the sum of the spacing errors after a number of installations. This 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 like route number. To control this, marker positioning references should be updated at the *end* of preview information, and markers should be installed from that point in the direction that goes *against traffic flow*.

Lateral

• **Centering Tolerance -** The centering tolerance specifies how far off of the centerline the reference line of the markers can be. This tolerance would be limited by how close the widest vehicle can come to the edge of the road. This tolerance is also interrelated to the bandwidth tolerance.

• **Bandwidth Tolerance** - The bandwidth tolerance refers to how far the markers can be located from their reference line. This tolerance would add to the amount of lateral error the vehicle would have, based on the sensitivity of the guidance reference control of the system. Bandwidth error would add to the lateral positioning error of the car, so the tolerance would also be limited by the centering tolerance.

• **Alignment Tolerance** - The alignment tolerance is the allowable lateral distance between two consecutive markers. A vehicle that followed the markers exactly would zig-zag when following markers installed with alignment error. With a large enough error, this zig-zagging motion would become noticeable to the passengers and would be considered unacceptable. The control program may not follow the markers exactly, however. Sophisticated algorithms that use principles like fuzzy logic could even ignore certain amounts of deviation for a smoother ride. For this reason, the guidance reference system would be a factor in determining the tolerance.

Vertical

• **Depth Dimension and Tolerance -** Markers should be installed so that their tops are flush with the pavement surface. This does not apply to markers in casings that are designed to be mounted on top of the pavement.

Rotational

• **Angular Dimension and Tolerance** - Markers should be installed so that the center axis of the cylindrical magnet is perpendicular to the road surface. Field test data would be necessary to provide a tolerance for angular tilt. Achieving angular precision should not be a problem, however; commercial installation drills *without* angular precision control can achieve angular precision of roughly 2° or better.

2.2 Magnetic Marker Casing

In order to protect the ceramic magnets from damage due to installation, weather, traffic, etc. some type of protective casing may be necessary. The casing would also be used to facilitate installation procedure by providing an easily installable and anchorable geometry. Any casing used would have to fulfill the following requirements:

• **Field Strength Weakening** - The magnetic field should be observable from 80 cm away from the marker, with high resolution sensing from 25 cm away from the marker, as described in the introduction. Any casing used 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 held consistently in the same position inside the casing, with a tolerance of .05 cm.
• **Environmental Concerns** - Any adhesives or other materials used in the construction of the casing and bonding to the magnets should be used in a way that would comply to all California environmental codes.
• **Casing Cost** - Casings should be designed to be as inexpensive as possible, without loss of functionability. Marker and casing assemblies should be produced in large quantities to limit costs.

2.3 Bonding to Pavement

• **Bonding Stability** - Markers should be rigidly attached to the pavement. Movement of the marker over time would constitute an additional positioning error source.

• **Sealant Characteristics** - The following characteristics for sealants were taken directly from [3], which describes the characteristics that manufacturers feel would be desirable in a sealant for inductive loop detection systems:

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

2.4 Coding Requirement

• **Marker Coding** - 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 the delivery of the correct polarity marker at the installation site.

2.5 Acceptable Degradation Standards

• **Marker Integrity** - Application should not cause damage to marker that would impede functionality or accelerate degradation.

• **Pavement Integrity** - Application should not cause damage to the roadway that would reduce its service life.

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

2.6 Cost

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

3. Strawman Concepts

3.1 Magnetic Marker Casing Options

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

3.1.1 Magnetic Nail Markers

Subsystem: Magnetic Marker Casing

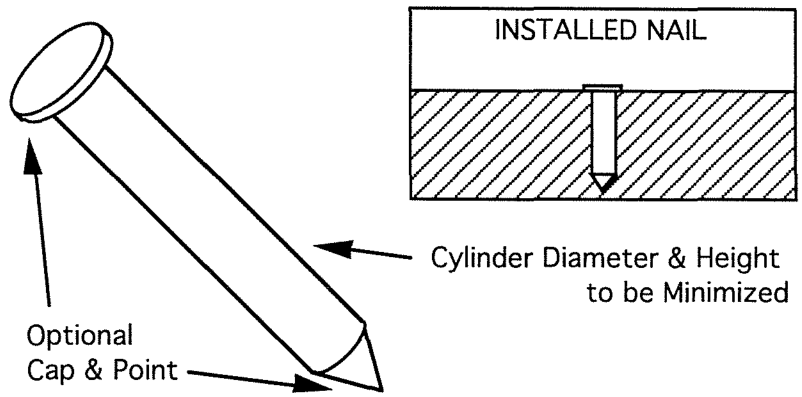

Figure 3.1.1.1: Magnetic Nail Marker

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 in order 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.

An optional feature for the nail marker would be the addition of a chamfer or point on the end that would be facing downwards. The point will help guide the nail into a premade hole in the pavement. This guidance would increase the allowance in misalignment error, so a smaller diameter hole could 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 could cut into the soft asphalt. (See Fig. 3.1.1.2)

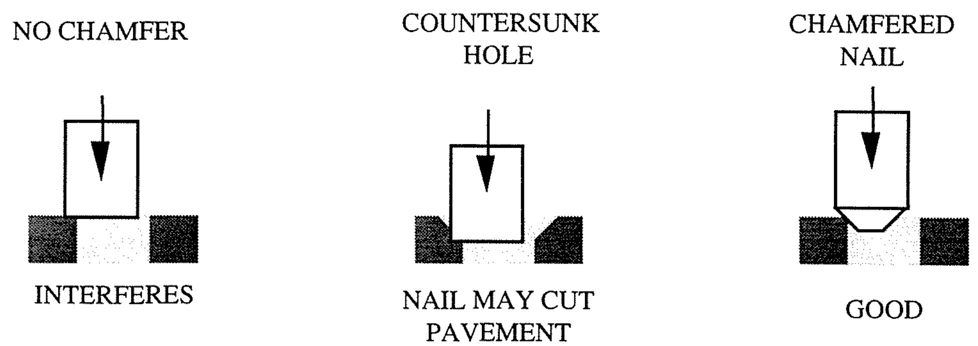

Figure 3.1.1.2: Effects of Chamfering Technique

Another optional feature for the nail would be the addition of an oversized flat cap 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 may also be used to aid handling of new nails and removal of old nails, providing a convenient geometry to grasp. An example nail with both the optional point and cap is shown in figure 3.1.1.1.

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

3.1.2 Magnetic Dot Markers

Subsystem: Magnetic Marker Casing

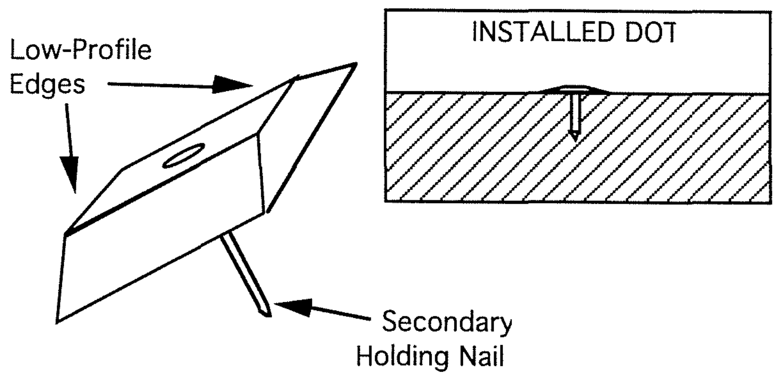

Figure 3.1.2.1: Magnetic Dot Marker

Description:

The magnetic dot marker would be a marker that is attached to the surface of the roadway, rather than imbedded in the asphalt. (See Fig. 3.1.2.1) Rounded, low profile edges on the marker would allow traffic to pass over it without dislodging it or damaging the casing.

The idea for a magnetic marker dot came from the existing Bott dots, which are low profile raised pavement markers used to make driving lane edges more visible. One of the major difference between a magnetic dot and a Bott dot (aside from one containing magnets) is that the magnetic marker must be a much more 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. That would not be the case for the magnetic markers.

The magnetic markers require a much stronger bond with the highway. In addition to the adhesion of the dot to the road with bitumen, (as is used on the Botts) the dots will be held down with a wire nail. Note that the nail may be redundant, since the dots would be placed in a lightly trafficked area. The magnetic markers would also have the advantage that the magnetic dot markers would be placed in the center of the lane, rather than the edges, the magnetic markers would receive much less wear from vehicle tires than would the lane marking dots.

Advantages / Disadvantages:

+ Easiest of all concepts to install.
+ A continuous installation system could be used. (A system that does not stop while installing)
+ Out of all concepts, this would damage the pavement the least.
+ Dots could possibly be used for secondary optical scan.
+ Easiest to replace/update for new road configuration.
+ Depth of installation would be very easy to control.
+ Higher location of magnets give stronger signal to vehicle.
- Most exposed system, since magnets are above the surface of the pavement.
- Dot markers may be expensive.

3.1.3 Bare Magnetic Markers (No Casing)

Subsystem: Magnetic Marker Casing

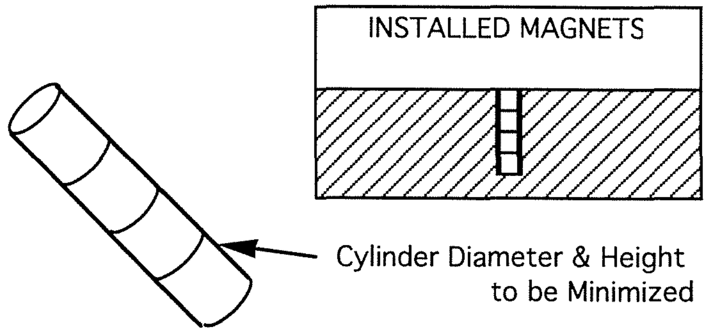

Figure 3.1.3.1: Bare Magnetic Markers

Description:

This system features the four marker magnets glued together and installed in the pavement without any casing. (See Fig. 3.1.3.1) Some form of sealant would be needed between the magnets and the pavement. The advantage of this system would be the inexpensive markers. However, damage during handling, installation and usage would be problems. Should the marker ever need to be removed, it could be easily drilled out.

Advantages / Disadvantages:

+ Least expensive markers.
+ Magnets won't protrude past pavement surface; they will be worn down to the surface level.
- Magnets could be easily damaged from handling/installation/traffic.
- System would have to be sealed in pavement.
- Installation depth would be difficult to control.

3.1.4 Receptacle Nail Marker

Subsystem: Magnetic Marker Casing

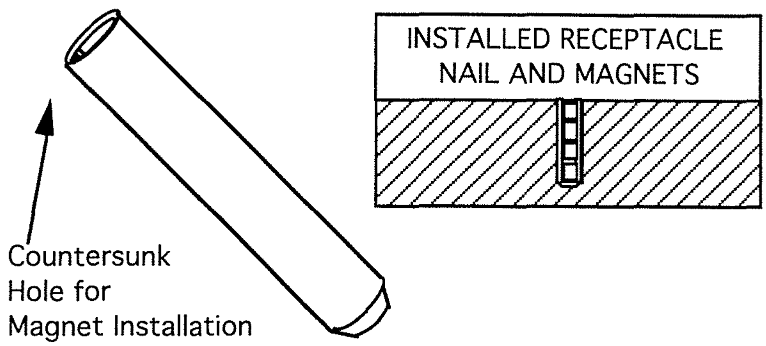

Figure 3.1.4.1: The Receptacle Nail

Description:

The receptacle nail (See Fig. 3.1.4.1) is a variation of the nail presented in section 2.1. The difference is that the nail is installed *without the magnets.* Magnets would be installed and sealed in the nails in a later process. The main advantage of this system would be the ability to easily change magnetic coding after the full system is installed. This would be useful in situations where, for example, a new exit is added, or a lane is closed.

Advantages / Disadvantages:

\+ Markers could 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 hole in the pavement.
\- Installation of magnets and casings are two separate processes.
\- Magnets may easily be damaged when being installed into the casings.

3.1.5 Assessment of Magnetic Marker Casing Options

Each of the concepts presented for casings has its own distinct advantages and disadvantages. Table 3.1.5.1 shows a comparison of the systems for various performance criteria. Since all of the characteristics of the magnets to be used are not yet known, and hence the dimensions of the casings cannot be estimated, the results shown in the table are somewhat speculative. An explanation of the criteria follows.

Table 3.1.5.1: 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 approximate number of chronological steps needed to install the markers while the vehicle is stopped. Refer to section 3.3 to view possible installation techniques. Casings that required more than one sequential step while stopped were given the worst rating. Casings that could be installed without stopping were given the best. The speed of installation will be a critical factor in system design; as can be seen in the cycle time requirements in section 4.

Least Damage To Road - This refers to the amount of cutting, drilling or reshaping of the pavement that is necessary 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 light 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, would be given the best mark. Some preliminary analysis of the effects of drilling holes in the pavement was done to get an idea as to how critical a factor this would be. (See Appendix A) So far, no evidence has been found that would show that drilling large holes in the centerline would significantly reduce the pavement's life. Further testing is, however, recommended.

Flexibility to Change - If, for any reason, the coding of an area must change on either a temporary or permanent basis, the magnets would need to be replaced. The flexibility criterion refers to the relative ease of removal of the casing. The dots and cartridge magnets could be removed without great disturbance to the pavement or complex operations, and were given the highest marks. The bare markers are fairly flexible since they could be drilled out, but the plain nail would probably need some complex procedure.

Endurance in Installation - The endurance in question is the damage resistance of the magnets. A heavy-duty casing, such as the nail, would protect the magnets the most during installation. The dot may be considered light-duty, since it would most likely be made of plastics or ceramics. Systems that don't provide protective casing protection at all when the magnets are installed would 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 when they are used for AVS 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. Lack of protection from shifting pavement is classified as "worst". The bare markers would only have the compliance of the bonding sealant to protect them from pavement shifting. Since asphalt pavements are considered to be flexible, this is an important concern.

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

3.2. Positioning Systems

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

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

Lateral and longitudinal positioning are, in most cases, treated as two different systems, since they need to be referenced off of different classes of landmarks. The lateral systems are referenced w.r.t. road geometry, and the longitudinal systems are referenced w.r.t. previous marker installation sites.

Positioning Type

Lateral systems are systems that can place the installation unit over the centerline of the lane. Listed for each lateral system are the sources of centering and alignment error. Centering error is a measure of how far the reference center of the maker could be from the center of the road. The alignment error describes how far off of a central reference line the marks may be.

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

Positioning Method

Direct Comparison Methods - Direct comparison methods refer to operations where either the referencing of the positioning system to landmarks, or the positioning of the installation unit, or both is done by a human operator. Direct comparison methods generally are the simplest; so they are typically the most inexpensive and easiest to maintain. The operator may cause more error, however.

Automatic Calibrated Methods - Methods of this class have all referencing and final positioning methods automated. The references used with these systems would 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 site landmarks.

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Positioning Landmarks

The following is an outline of the landmark reference systems that are treated in this report:

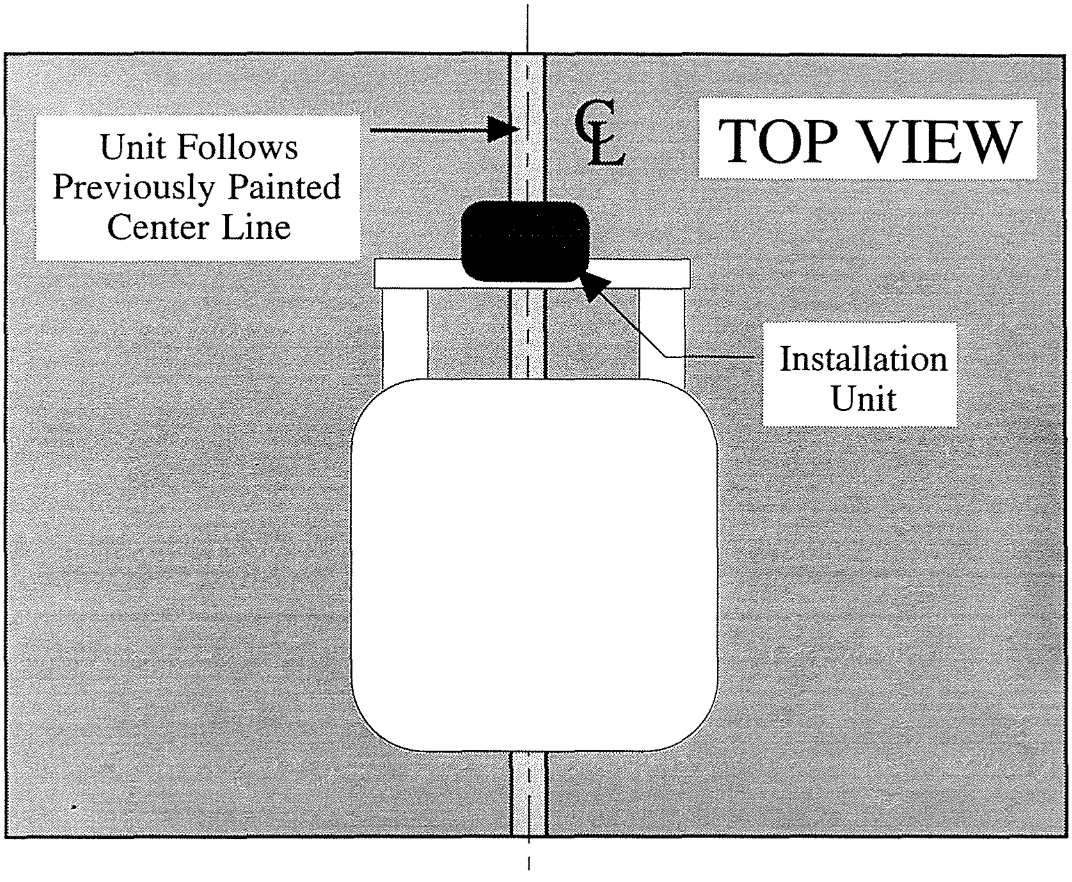
Lateral Type
- Direct Comparison Method
  - Center Line Reference
  - One Edge of Pavement Reference
  - Two Edges of Pavement Reference
- Automatic Calibrated Method
  - Two Markers at Edge of Pavement Reference

Longitudinal Type
- Direct Comparison Method
  - Last Installation Site
- Automatic 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
- Automatic Calibrated Method
  - Manufactured Group Positioning
  - Laser Guidance

3.2.1 Painted Line Follower
Type: Lateral Reference (Center Line) Location System - Direct Comparison Method



3.2.1.1: Painted Line Follower

Description:
The Painted Line Follower (See Fig. 3.2.1.1) rides along a previously painted center line. The magnetic markers would be installed along the center of this line, with the operator locating the center of the line by eye. Some form of linear slide may be needed to adjust the position of the installation device.

The painted line would be laid out using a technique similar to conventional lane demarcation methods. A much narrower line than the lane marking lines could be used, since this line will only be used as a surveyor's reference.

REQUIREMENTS FOR AUTOMATED APPLICATION OF MARKERS

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 variations are minimized.
+ Painted line may be used for other purposes.
- Line surveying error could keep line off of true center.
- Line may not be exactly on lane center.
- System relies on human operator.
- Requires measuring operation, line painting operation, then installation operation.

Referenced W.R.T.: Painted Center Line

Centering Error:

$e_{\text{Edge of Pavement Survey}} + e_{\text{Center Line Painting}} + e_{\text{Operator Placement}}$

Alignment Error:

$e_{\text{Center Line Painting Smoothness}} + e_{\text{Operator Placement}}$

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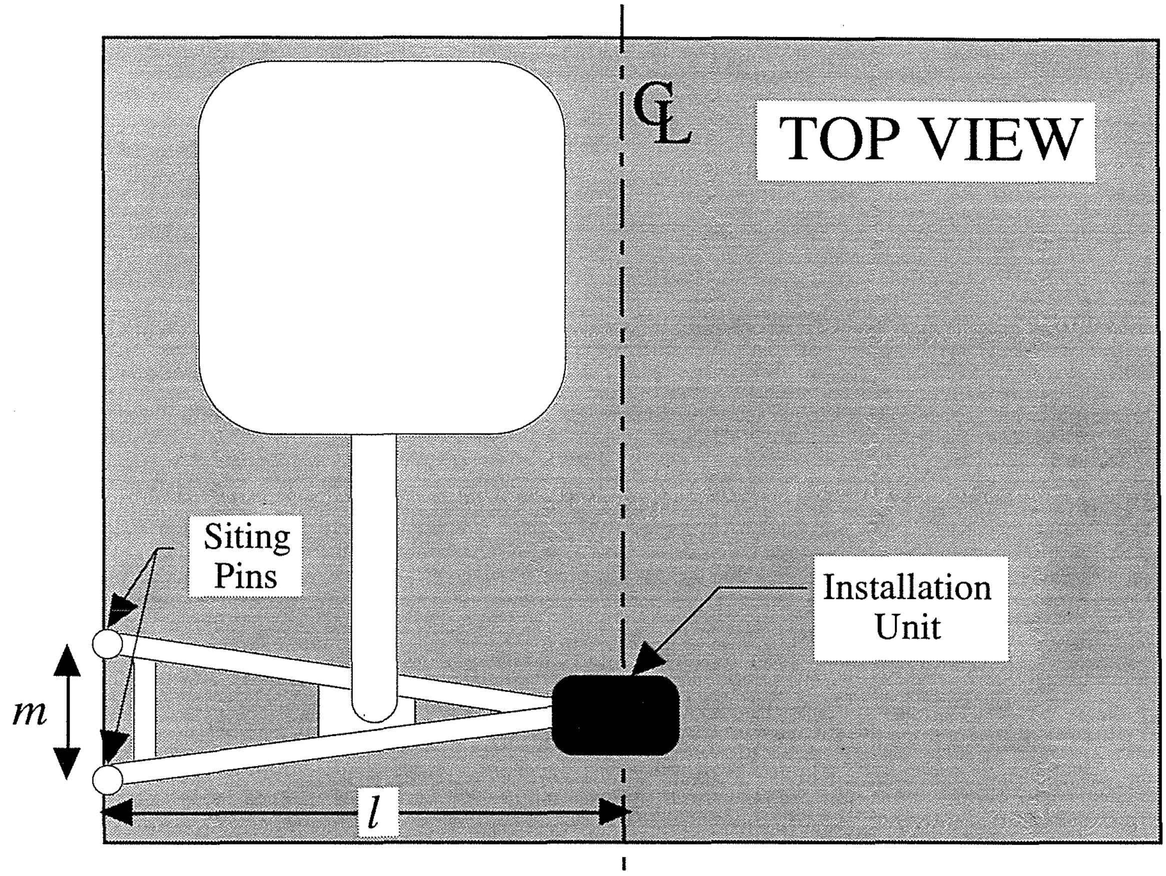
3.2.2 Ruled Edge Locator

Type: Lateral Reference (Center Line) Location System - Direct Comparison Method



3.2.2.1: Ruled Edge Locator

Description:

The Ruled Edge Locator uses one edge of the lane as a reference to find the center of the lane. (See Fig. 3.2.2.1) In this system, the lane width is assumed to be a constant, $2l$. 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 crack 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 capability 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:

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

Alignment Error:

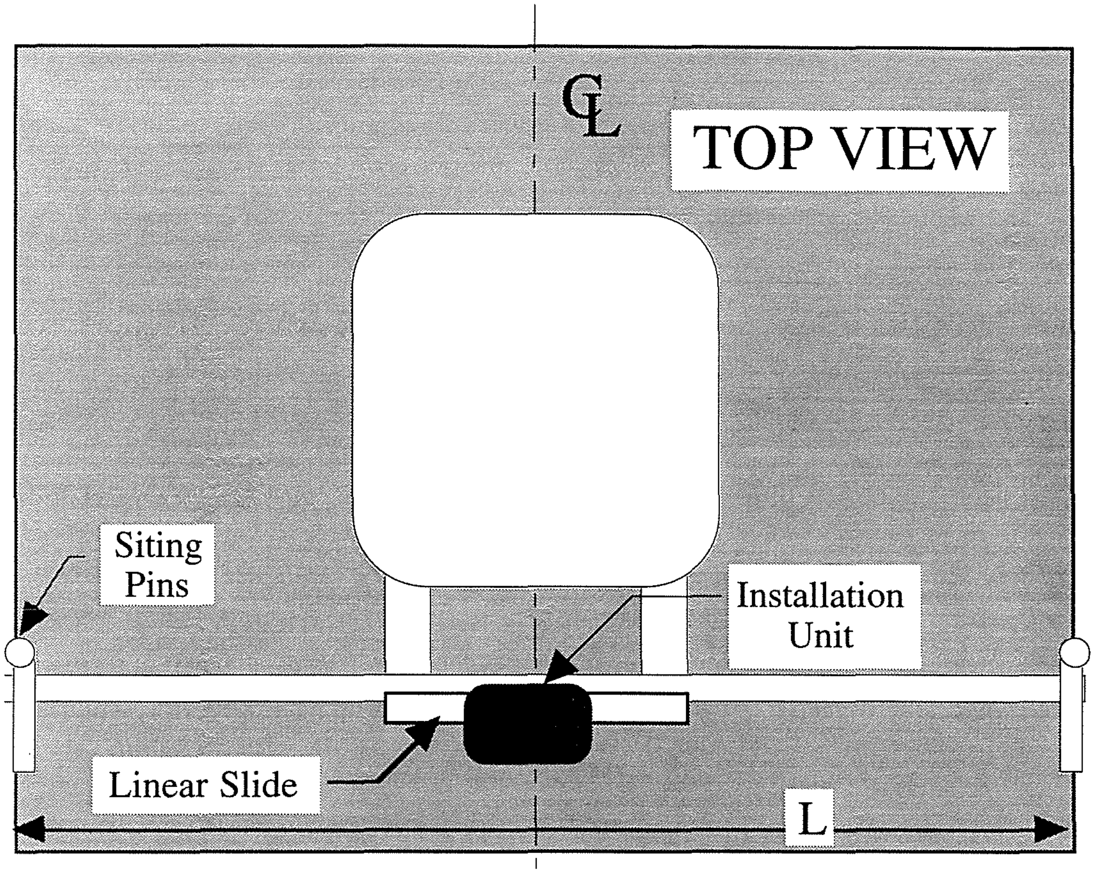
$$e_{\text{Edge of Pavement Smoothness}} + l - l \cos \sin^{-1}\left(\frac{e_{operator\ placement}}{m}\right)$$

Note:

This method may impart additional error in the longitudinal direction.

3.2.3 Averaged Edge Reference Locator

Type: Lateral Reference (Center Line) Location System - Direct Comparison Method



3.2.3.1: Averaged Edge Reference Locator

Description:

The Averaged Edge Reference system (See Fig. 3.2.3.1) uses both edges of the lane to find the center. As shown in the figure, there are sighting 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.

REQUIREMENTS FOR AUTOMATED APPLICATION OF MARKERS

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:

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

Alignment Error:

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

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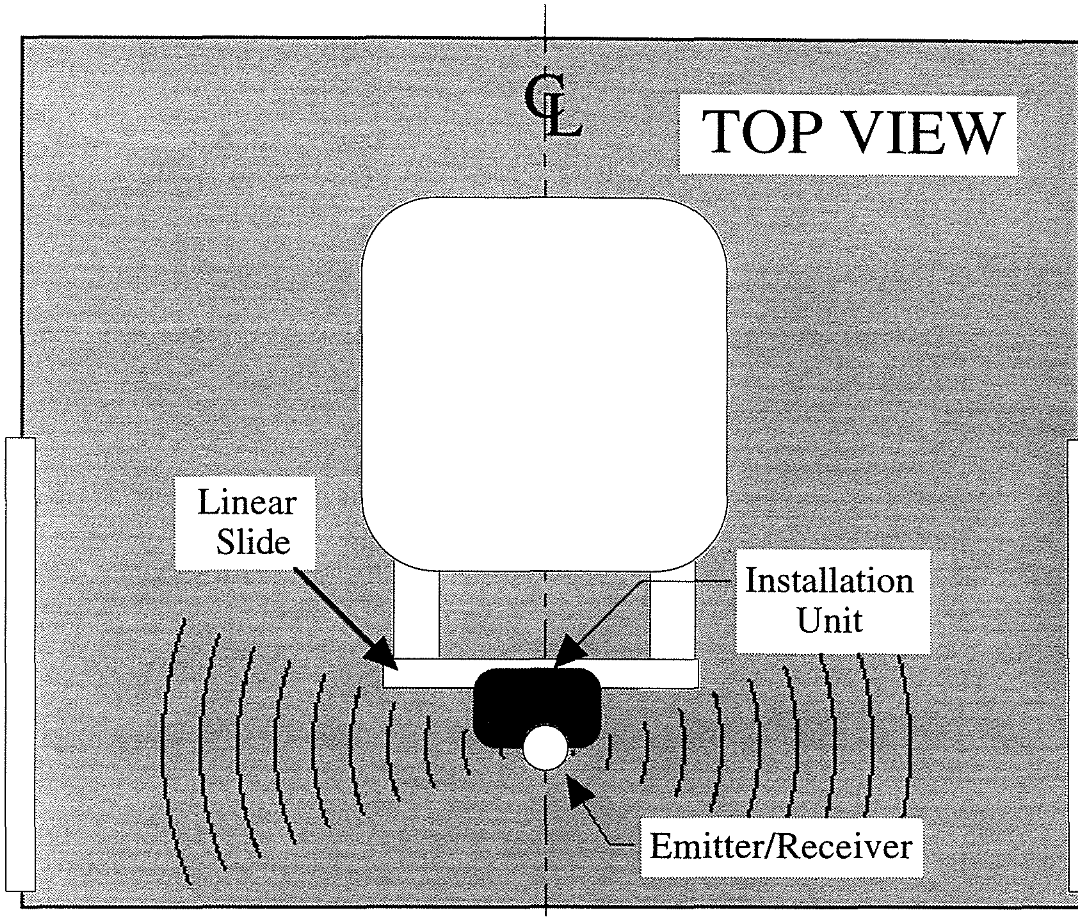
3.2.4 Reflected Wave System

Type: Lateral Reference (Center Line) Location System - Automatic Calibrated Method



3.2.4.1: Reflected Wave System

Description:

This system (See Fig. 3.2.4.1) 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 same location as 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 slower wave, (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.

REQUIREMENTS FOR AUTOMATED APPLICATION OF MARKERS

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:

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

Alignment Error:

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

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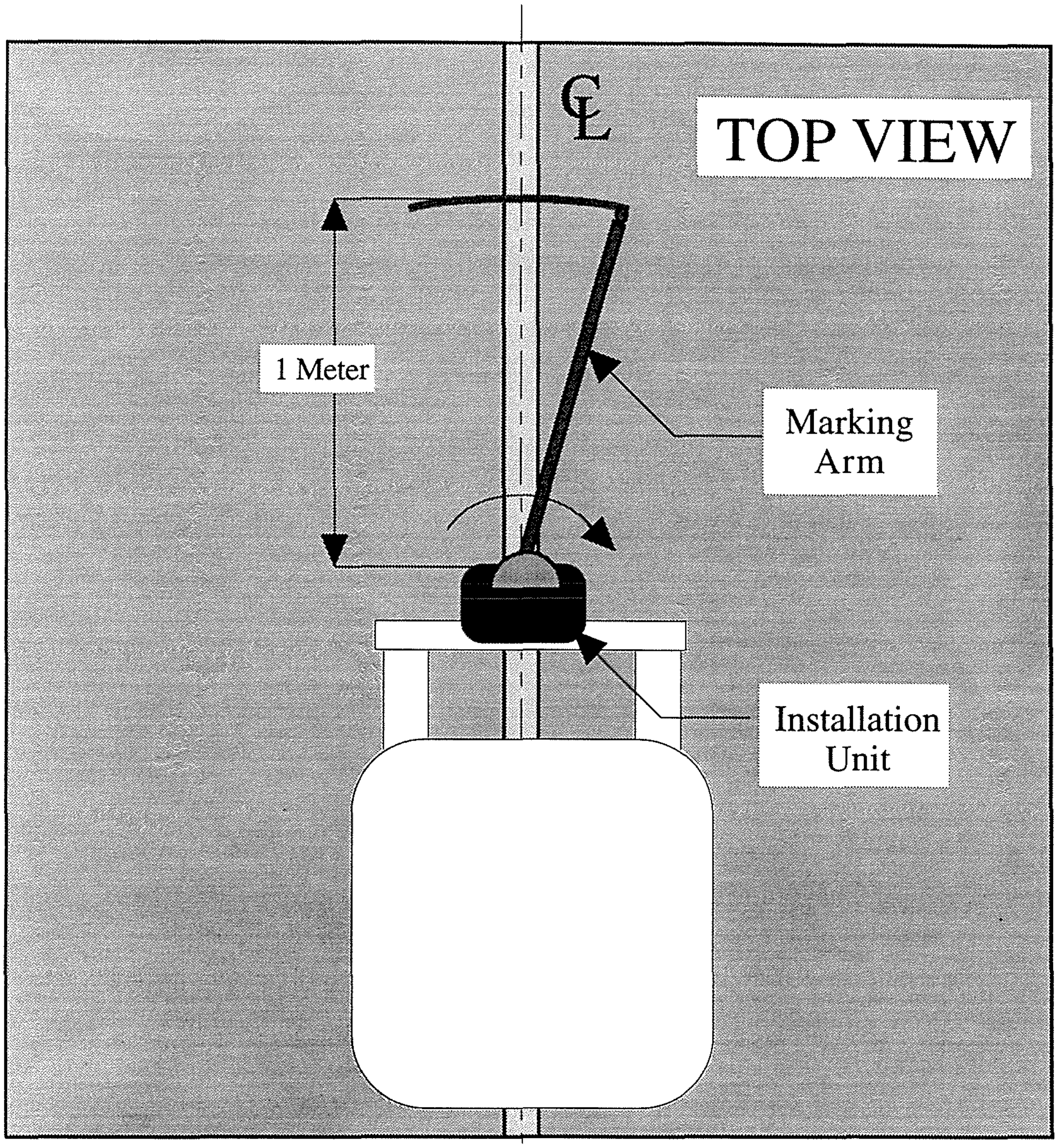
3.2.5 Foreword "Compass" Ruled Measure
Type: Longitudinal Spacing System - Direct Comparison Method



3.2.5.1: Foreword Ruled Measure

Description:

The "Compass" system (See Fig. 3.2.5.1) uses direct ruled measurement to mark the installation locations for discrete markers. The system works off of the location of the previous installation site, measuring for the location of the second marker while the first is still being installed. While the first discrete marker is being installed, a meter long arm with some sort of sketching device draws an arc across a previously marked center line. The point where the arc and the line cross will be where the next marker is installed.

A measurement is taken by using a 1m long arm with a marker at one end. The other end pivots over the installation site of the previous marker. The system allows the arm to draw a small arc with a radius of 1m over the centerline of the lane. Note that for this system, the center line must be detectable; a pre-painted center line would be the easiest for the operator to see. The point where the arc and the center line cross would be the next installation point.

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:

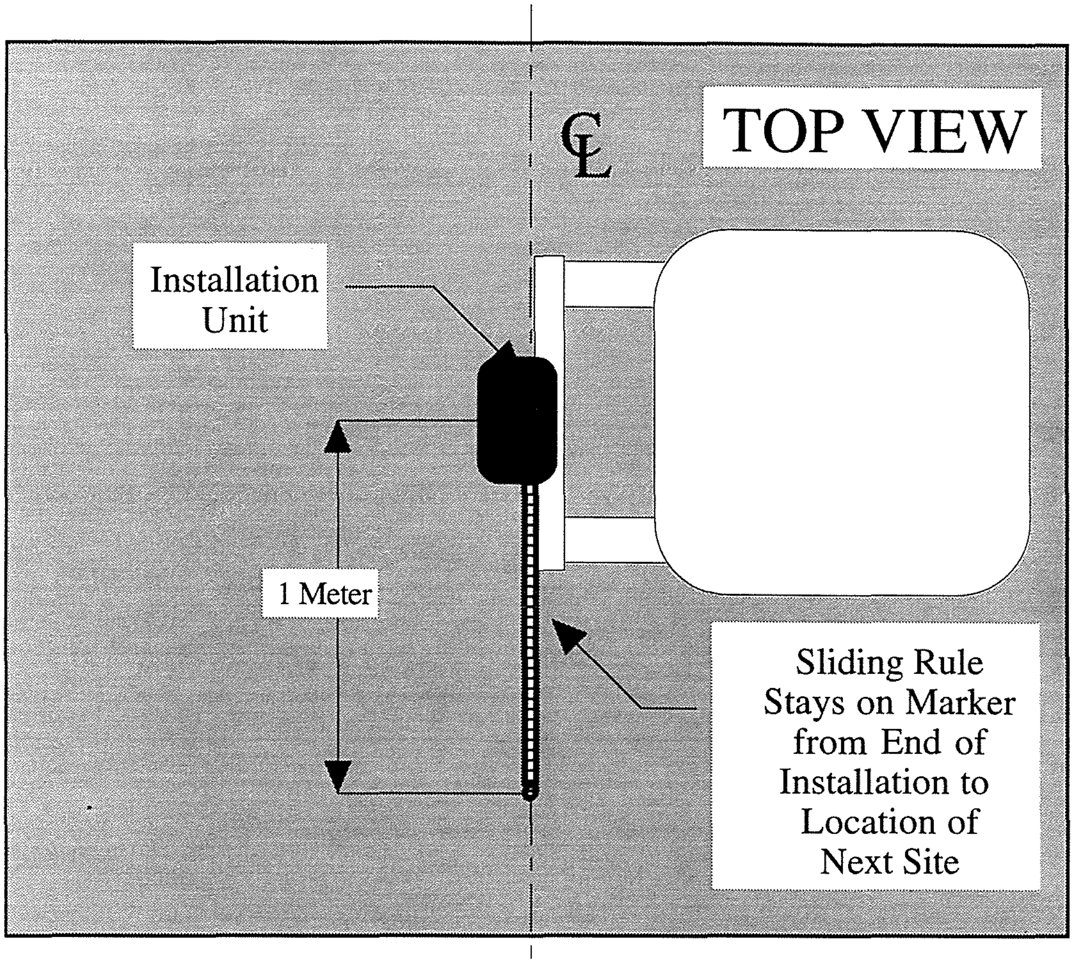
$$e_{\text{Measurement Technique}} + e_{\text{Operator Placement}}$$

Cumulative Error:

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

3.2.6 Ruled Measure from Previous Mark

Type: Longitudinal Spacing System - Automatic Calibrated Method



3.2.6.1: Ruled Measure form Previous Mark

Description:

This system (See Fig. 3.2.6.1) uses direct ruled measurement from a previously installed marker to locate the next installation site. After a marker is installed, a sliding rule is magnetically attached to its top. 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 then detaches from the first marker, and reattaches to the newly installed marker.

REQUIREMENTS FOR AUTOMATED APPLICATION OF MARKERS

Operation:
1) Marker is installed.
2) End of sliding rule attaches to installed marker. (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:

$e_{\text{Measurement Technique}}$

Cumulative Error:

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

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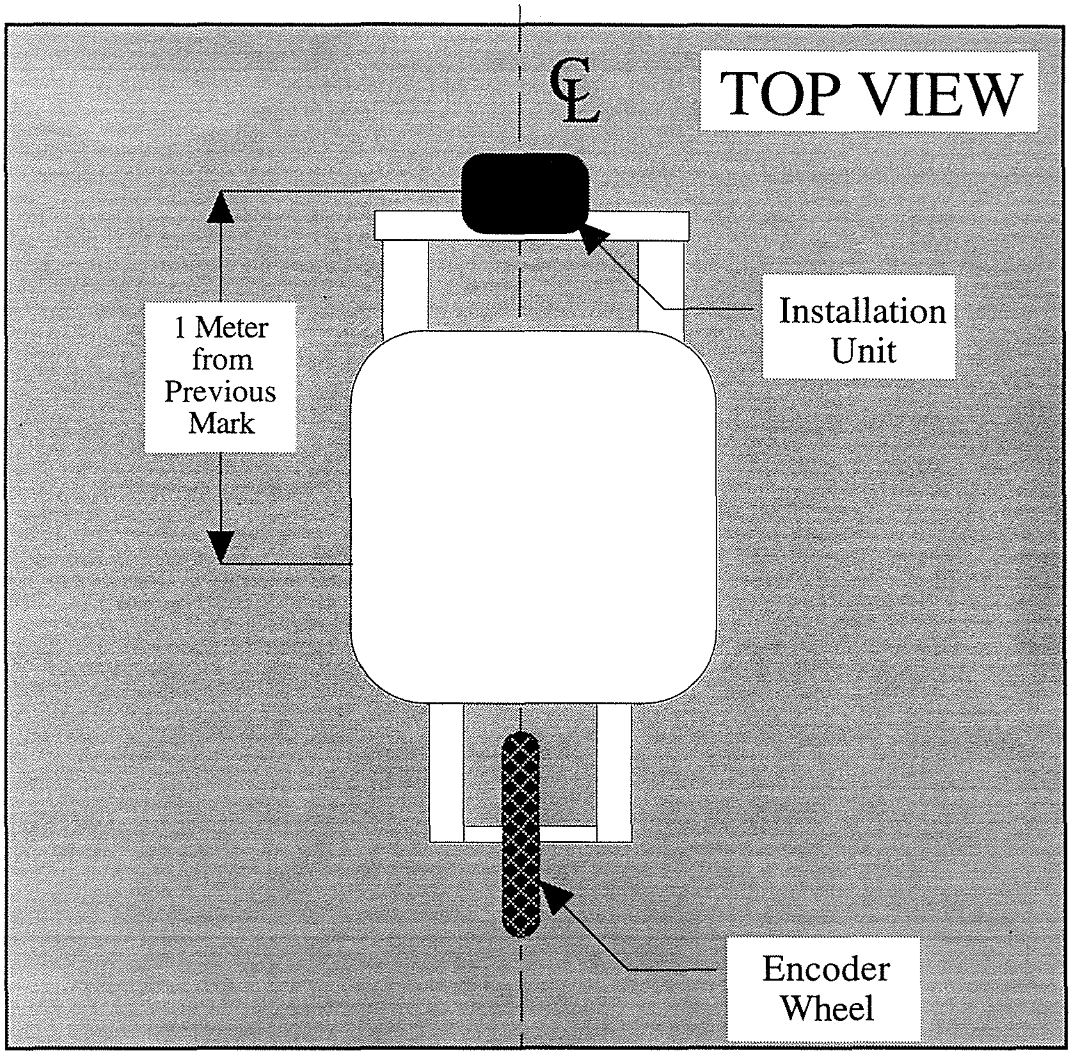
3.2.7 Encoder Wheel System

Type: Longitudinal Spacing System - Automatic Calibrated Method



3.2.7.1: Encoder Wheel System

Description:

This system (See Fig. 3.2.7.1) uses an encoder wheel to find installation locations in one meter increments. For the best accuracy, this wheel should be used on the center line of the lane, or two wheels should be equally spaced on either side of the center line, and the average of the two should be taken.

REQUIREMENTS FOR AUTOMATED APPLICATION OF MARKERS

Operation:
1) Marker is installed.
2) Truck moves foreword 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:

$e_{\text{Measurement Technique}}$

Cumulative Error:

$e_{\text{Measurement Technique}}$

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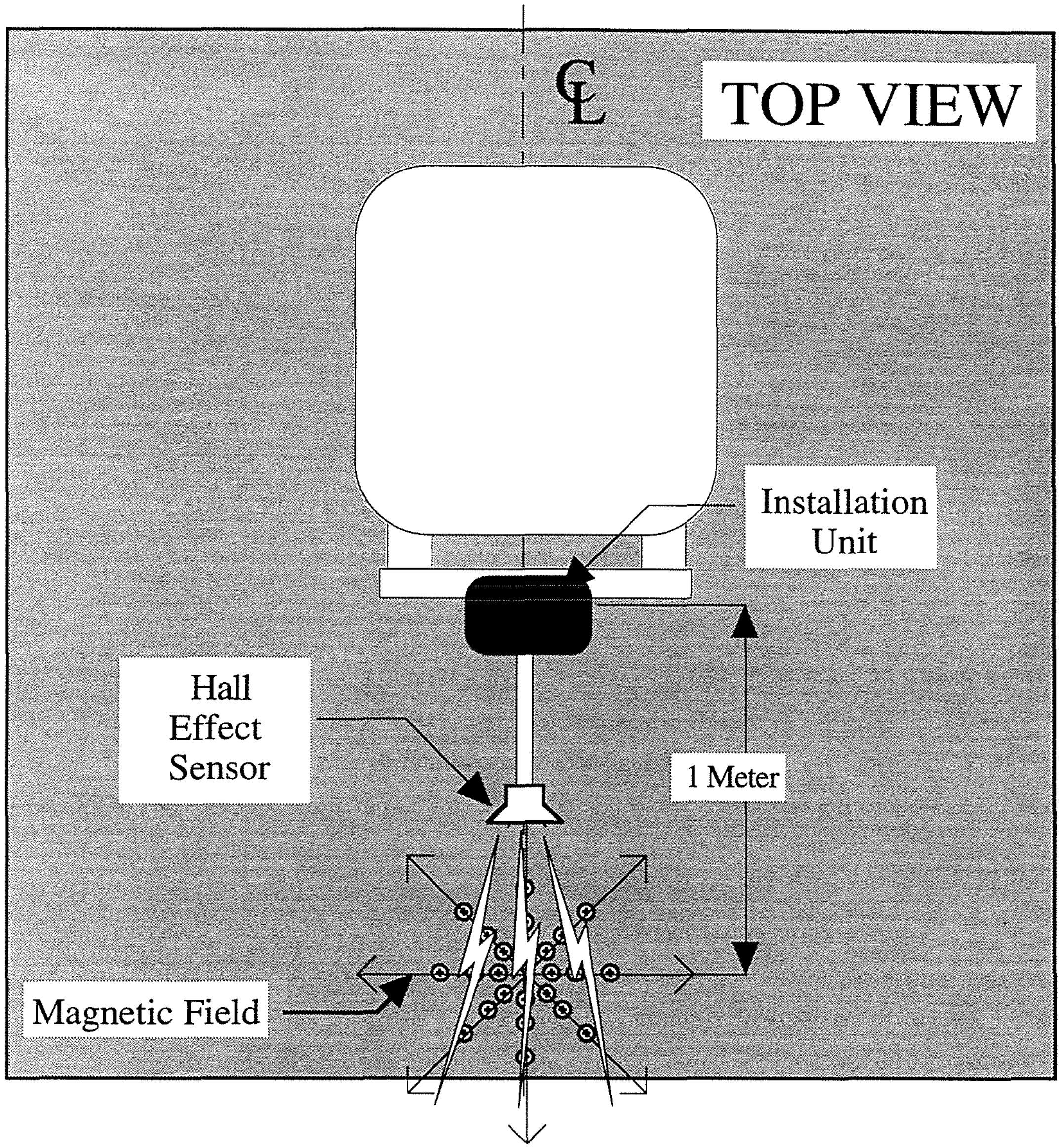
3.2.8 Hall Effect Distance Measuring System

Type: Longitudinal Spacing System - Automatic Calibrated Method



3.2.8.1: Hall Effect System

Description:

The Hall Effect System (See Fig. 3.2.8.1) 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 laid magnet. For measurements at the 1% level, a Hall effect probe is adequate [5]. The strength *B* is an experimentally determined value which will be received when the distance from the marker to the sensor plus the distance from the sensor to the Installation Unit is exactly one meter.

REQUIREMENTS FOR AUTOMATED APPLICATION OF MARKERS

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

Advantages / Disadvantages:
+ Markers are placed by a system that is similar to the guidance 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:

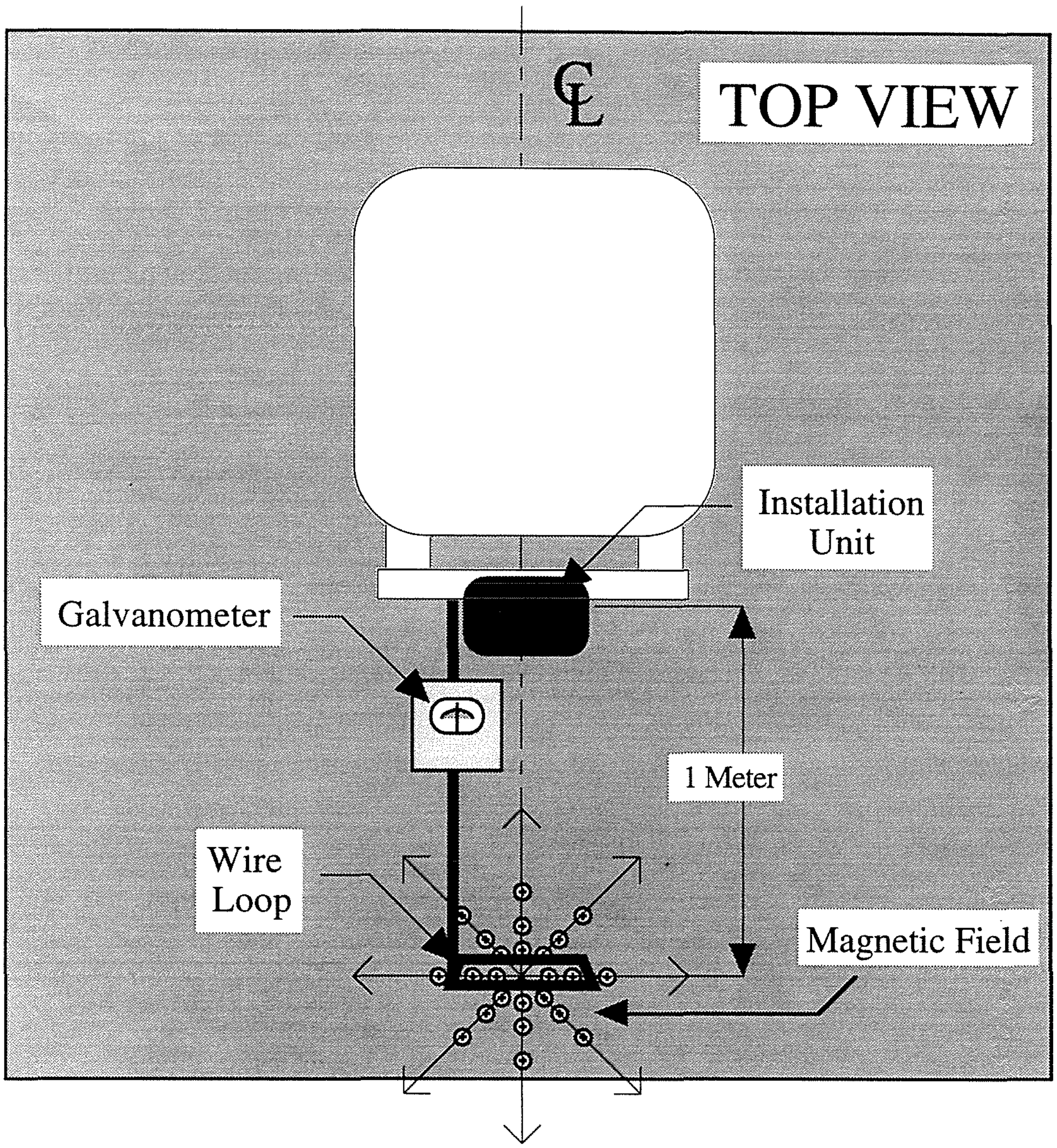
$$e_{\text{Measurement Technique}}$$

Cumulative Error:

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

3.2.9 Galvanometer Distance Measuring System

Type: Longitudinal Spacing System - Automatic Calibrated Method



3.2.9.1: Galvanometer System

Description:

The Galvanometer system (See Fig. 3.2.9.1) senses the magnetic field of the discrete marker by capturing part of the last magnet's field in a loop of wire to induce a current. The loop is oriented so that it is perpendicular to the road surface, so when the loop is directly over the marker, it will be perpendicular to the magnetic field, and the reading will drop to zero. (See Fig. 3.2.9.2) The loop of wire would be spaced one meter from the installation unit.

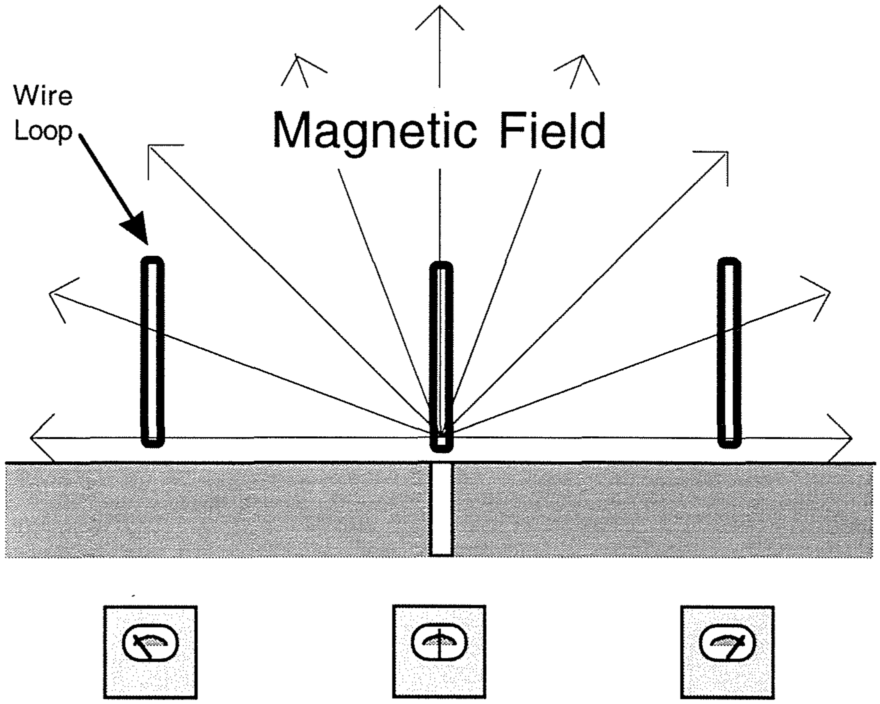


Figure 3.2.9.2: Galvanometer Readings as Wire Loop Moves Through M-Field

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:

$e_{\text{Measurement Technique}}$

Cumulative Error:

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

3.2.10 Differential Global Positioning System (D-GPS) Method

Type: Lateral & Longitudinal System - Database Method

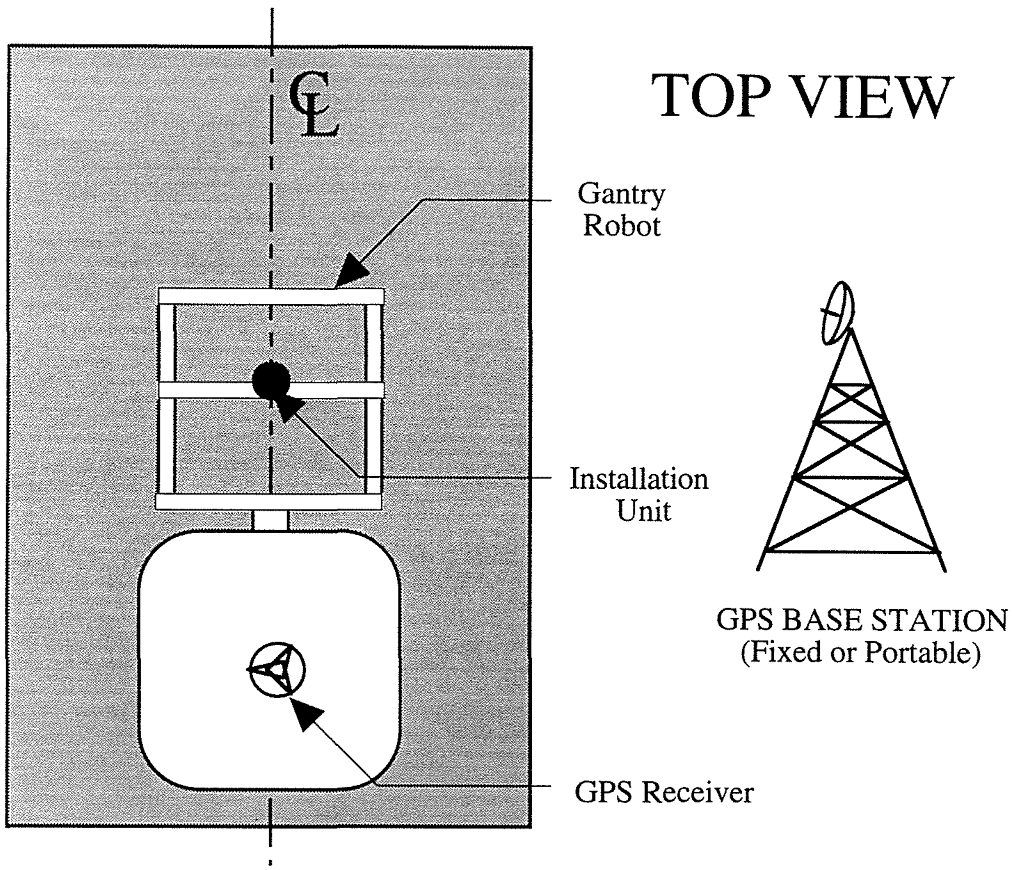


Figure 3.2.10.1: Installation using D-GPS

Description:

A Global Positioning System (GPS) could be used to control longitudinal and lateral positioning, given the coordinates of the installation locations. GPS is a triangulation system which uses the position of four orbiting satellites for reference points. In order to get acceptable working speed and accuracy (less than 1cm), it is necessary to use Differential GPS and Carrier Phase Tracking. See [5] for details on GPS strategy.

This type of system is not recommended for use on existing roads that are to be retrofitted with new markers. Refer to section 4.4 for detailed explanation.

The GPS receiver for the system would have to be set on the installation vehicle at a known or calculable distance from the installation unit. The receiver in figure 3.2.10.1 is shown as being on the vehicle itself, where it would be protected from installation vibrations. Since D-GPS surveys point locations, some way of determining the orientation of the vehicle would be needed; perhaps by using another GPS receiver. The alternative would be to mount the receiver directly over the installation unit, and damp any vibrations.

REQUIREMENTS FOR AUTOMATED APPLICATION OF MARKERS

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, or between tall buildings.
- Not recommended for retrofitting old roadways. (See section 4.4)

Referenced W.R.T.: Differential Global Positioning System

Centering Error:

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

Alignment Error:

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

Spacing Error:

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

Cumulative Error:

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

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3.2.11 Dead Reckoning Method

Type: Lateral & Longitudinal System - Database Method

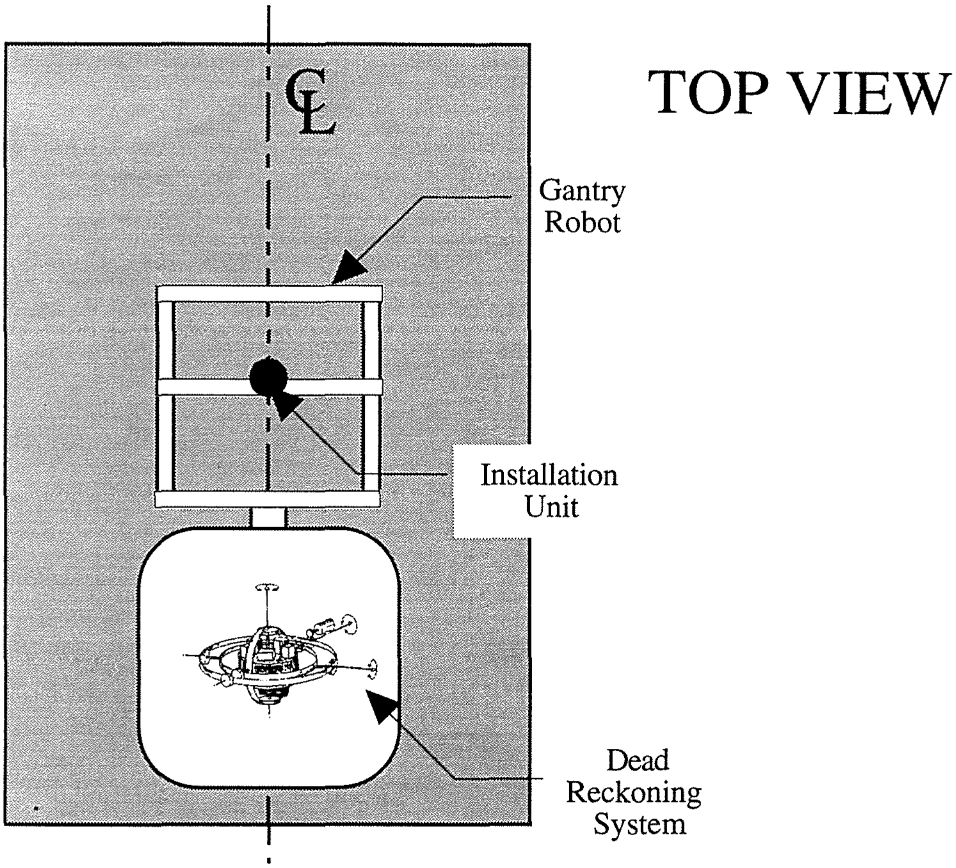

Figure 3.2.11.1: Dead Reckoning Positioning

Description:

A dead reckoning such as an Inertial Sensing System (ISS) could be used with a map of marking locations to travel from site to site. 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, (the speed, heading, time traveled, etc.) and analyzes this information to derive the new location of the vehicle. The installation unit would then be positioned w.r.t the dead reckoning system with the gantry robot to the correct coordinates. The position of the vehicle would have to periodically be resurveyed, to keep cumulative errors within acceptable bounds. This could be very powerful when combined with D-GPS.

REQUIREMENTS FOR AUTOMATED APPLICATION OF MARKERS

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. (See section 4.4)

Referenced W.R.T.: Dead Reckoning

Centering Error:

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

Alignment Error:

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

Spacing Error:

$$e_{\text{Positioning}}$$

Cumulative Error:

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

3.2.12 Two Point Reference System

Type: Lateral & Longitudinal System - Database Method

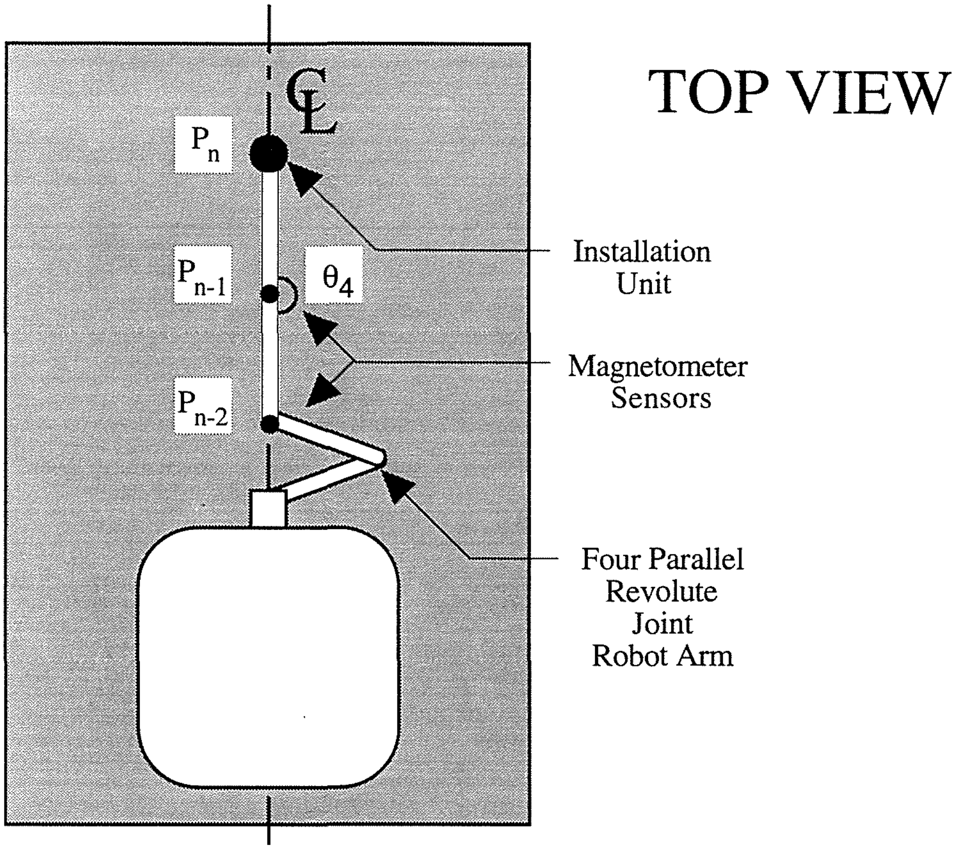

Figure 3.2.12.1: Installation w.r.t. the Last Two Markers Installed

Description:

This system 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 would be used to 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.

REQUIREMENTS FOR AUTOMATED APPLICATION OF MARKERS

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, θ_4, and positions P_n. Note that this step can take place during steps 1-4.
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. (See section 4.4)

Referenced W.R.T.: Position of previous two markers & database.

Centering Error:

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

Alignment Error:

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

Spacing Error:

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

Cumulative Error:

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

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3.2.13 Gang Installation System

Type: Special Systems for Straight Roadways - Automatic Calibrated Method

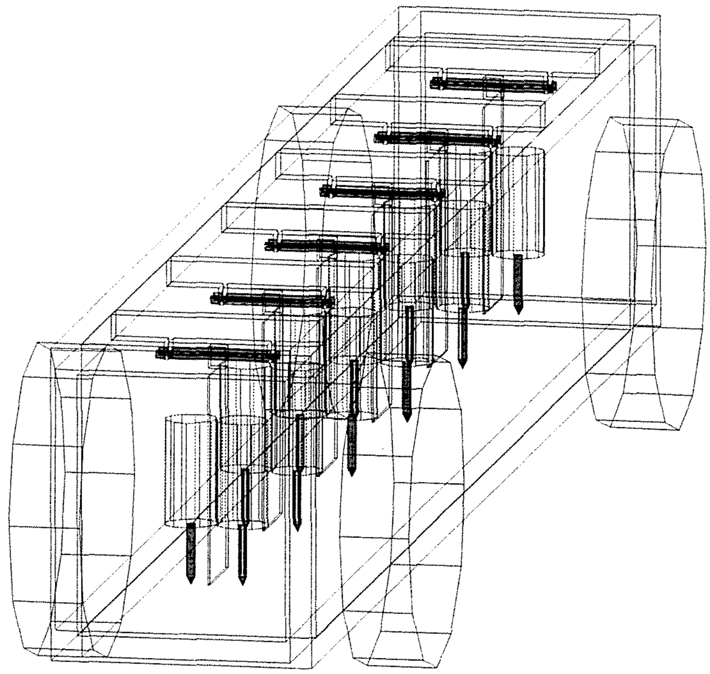


Figure 3.2.13.1: Six Station Gang Installation

Description:

The Gang Installation System (See Fig. 3.2.13.1) 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.

REQUIREMENTS FOR AUTOMATED APPLICATION OF MARKERS

Operation:
1) The gang positioning system is positioned to three degrees of freedom by the means of other positioning systems. The 3 d.o.f. would have 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.

Referenced W.R.T.: Gang Placement
Note: Repositioning the Gang Installation System would require the use of an additional positioning system.

Centering Error:

e Manufacturing Error

Alignment Error:

e Manufacturing Error

3.2.14 Laser Guided Centering System

Subsystem: Special Systems for Straight Roadways

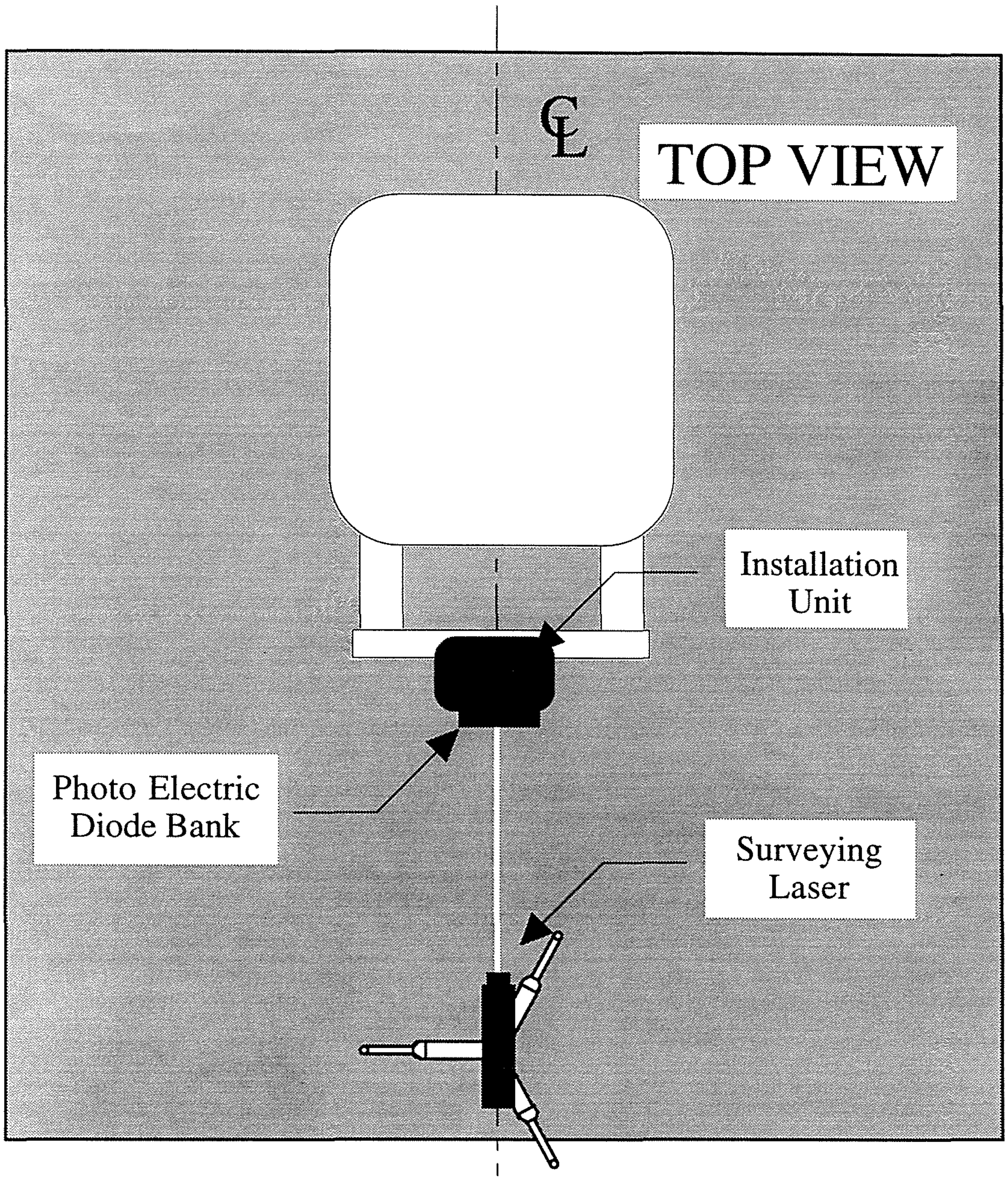


Figure 3.2.14.1: Laser Guided Centering

Description:

In the laser guided system, (See Fig. 3.2.14.1) a beam of visible red light from a He-Ne laser is fired up the center line of the road. The beam is received by a bank of photo electric diodes on the installation vehicle. The vehicle's position would be 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 [6]. 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 175-200m.
- Lasers of class 3b or higher would be a safety concern.

Referenced W.R.T.: Laser Guidance

Centering Error:

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

Alignment Error:

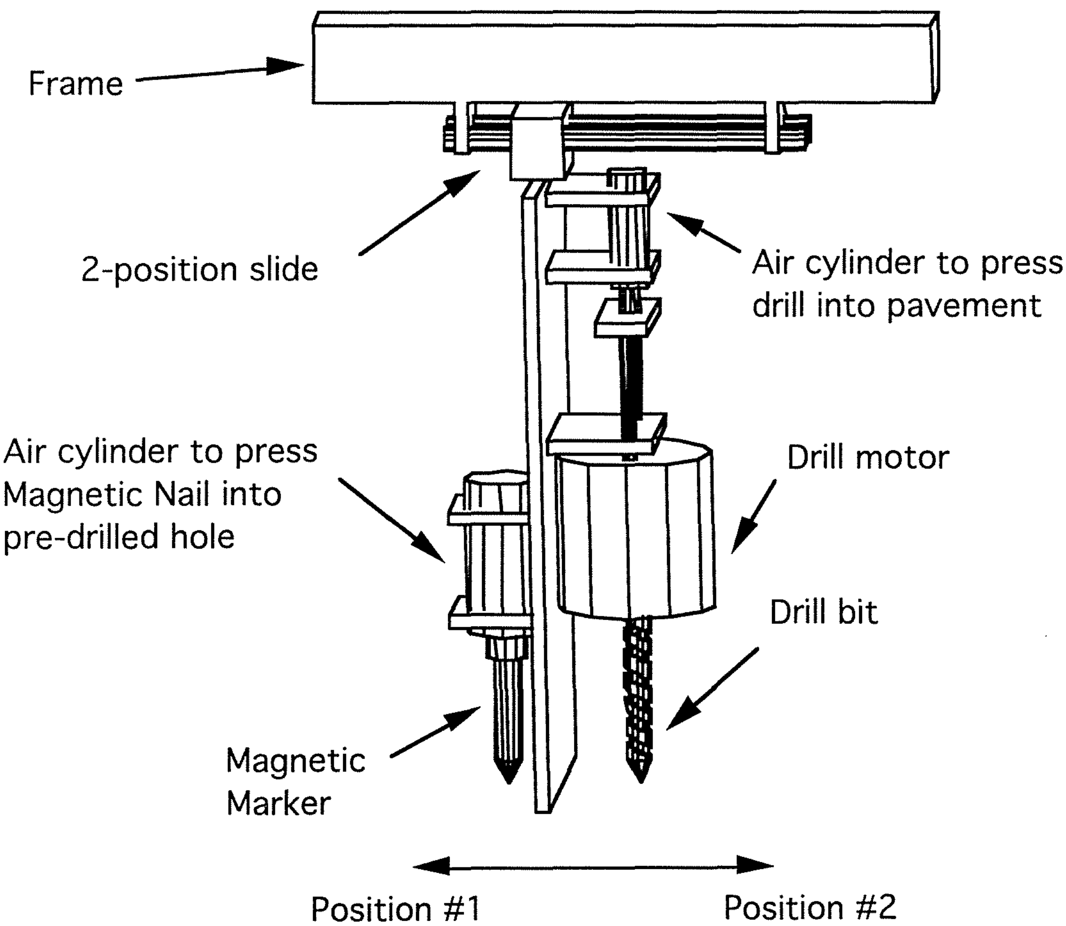
$e_{\text{Diode Sensing}}$

3.3. Marker Installation Systems

The installation system is responsible for affixing the marker to the road. This system must also perform any surface preparation of the asphalt (i.e. drilling) and ensure that the markers are installed within the requirements for depth and tilt. 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 would be controlled by having some part of the SYSTEM come in contact with the road surface as a reference.

3.3.1 Drill-then-Press Installation Unit

Subsystem: Marker Installation System



3.3.1.1: Drill-then-Press Unit

For use with the Casings:
Nail, Cartridge

Description:

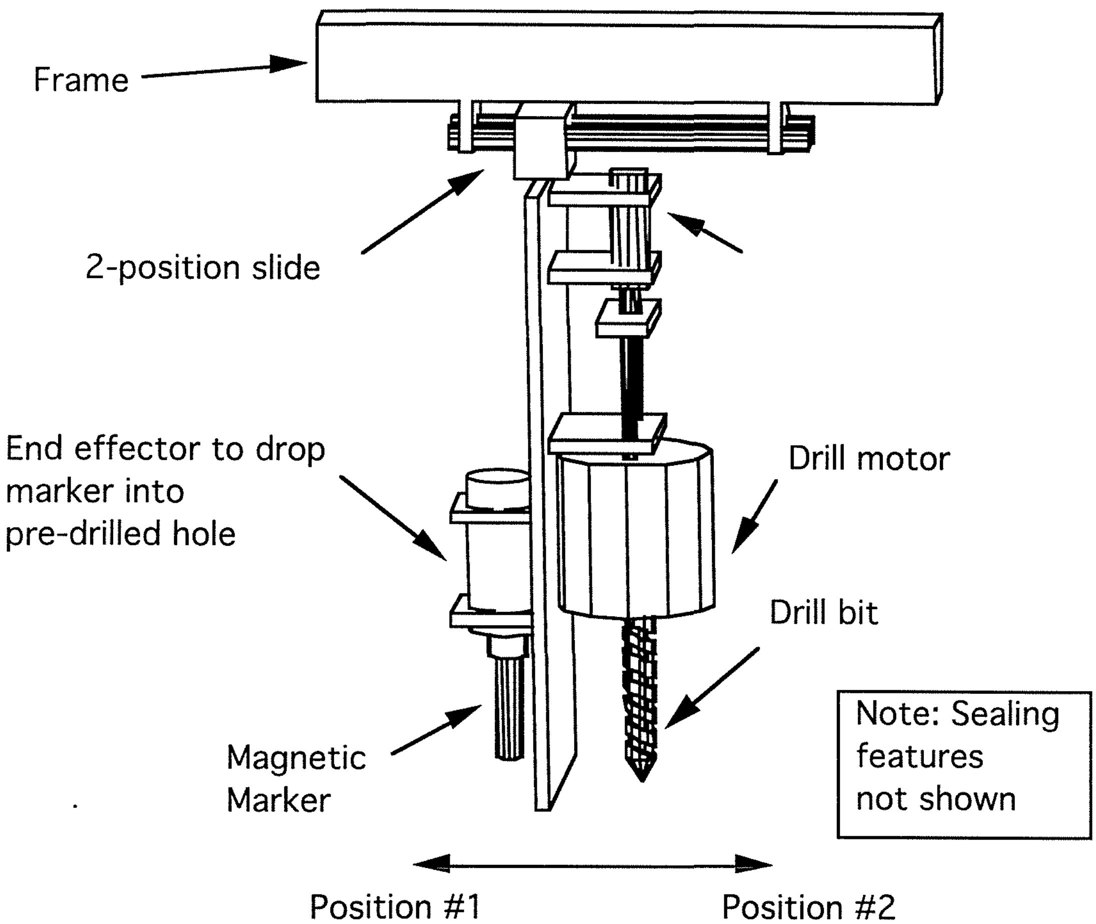
The Drill-then-Press Unit (See Fig. 3.3.1.1) first prepares an installation hole by drilling a hole in the pavement large enough for a compression fitting of the magnetic marker. It then slides to allow an air cylinder to press the marker into the hole. Because the marker is pressed into the hole, no 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.

3.3.2 Drill-then-Place Installation Unit

Subsystem: Marker Installation System



3.3.2.1: Drill-then-Place Unit

For use with the Casings:
Nail, Cartridge, Bare

Description:
The Drill-then-Place Unit (See Fig. 3.3.2.1) 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. (Note: The sealant must be pliant for the life of the marker. If the sealant is rigid, it may crack and break with the expansions and contractions of the pavement) Positioning of the marker over the hole could also be done with a rotary actuator, if a more compact system is desired.

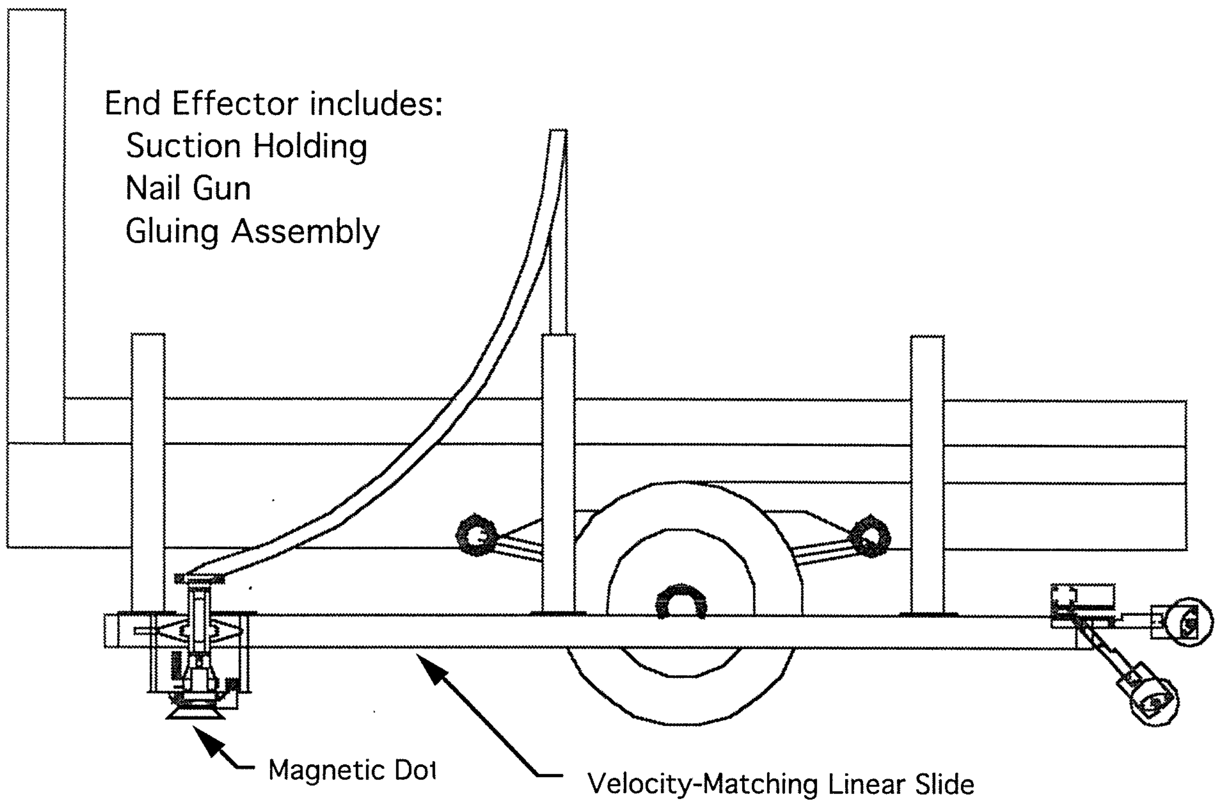
REQUIREMENTS FOR AUTOMATED APPLICATION OF MARKERS

Operation:
1) Hole is drilled with drill and air cylinder.
2) Unit positions marker over hole.
3) Unit places marker into hole, for 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.

3.3.3 Continuous Dot Laying Machine

Subsystem: Marker Installation System



3.3.3.1: Continuous Dot Layer

For use with the Casings:
Dot

Description:
This unit will continuously install dot type markers. (See Fig. 3.3.3.1) 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. While it is 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 matches speed of vehicle on the linear slide.
3) Bitumen is pumped out 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.

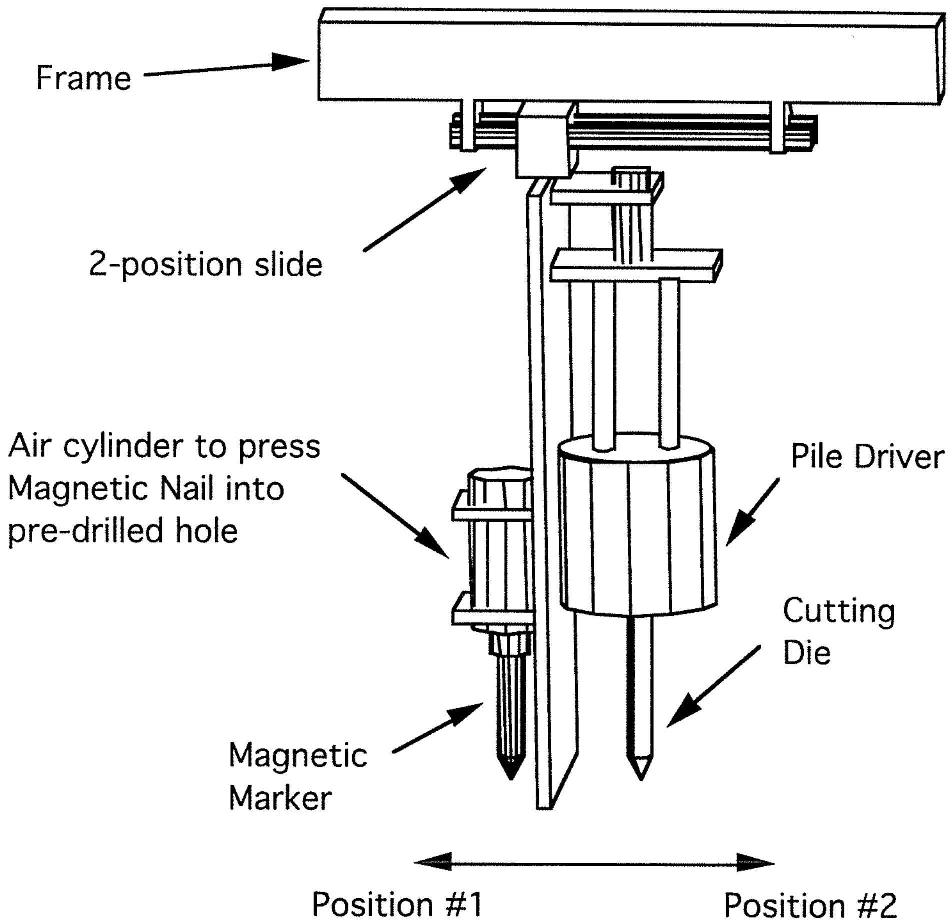
Advantages / Disadvantages:
+ Continuous marking system.
+ Similar system has already been built and tested.

REQUIREMENTS FOR AUTOMATED APPLICATION OF MARKERS

- Matching vehicle speeds is difficult.
- May be difficult to integrate with reliable positioning systems.
- System may not have good curve-following abilities.

3.3.4 Pound-then-Press (Place)

Subsystem: Marker Installation System



3.3.4.1: Translating Pound-then-Press Unit

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

Description:

The Pound-then-Press (Place) Unit (See Fig. 3.3.4.1) 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, and 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 pound able 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.

REQUIREMENTS FOR AUTOMATED APPLICATION OF MARKERS

Operation:
1) Hole is drilled with drill 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.

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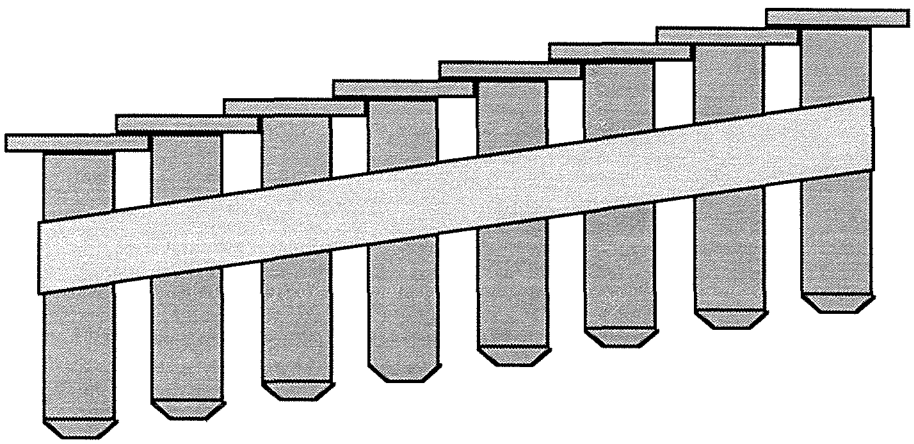
3.4 Feeding and Storage Systems

Handling of the magnetic markers may be difficult, since the markers will want to stick together. A system is needed that can keep the markers neat and orderly during storage, and can keep them neat as they are presented to the installation unit.

3.4.1 Pressure Sensitive Adhesive Strips

Subsystem: Feeding and Storage System



3.4.1.1 Markers Joined With Pressure Sensitive Adhesive

For Use With The Casings:

Nail, Bare, Cartridge

Description:

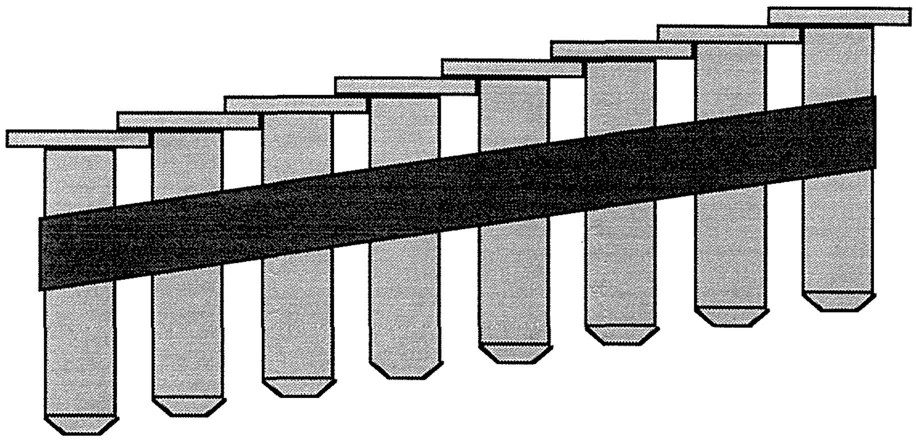
Strips of pressure sensitive adhesive would be applied to one or two sides of a row of markers, which have been laid out in an orderly fashion. (See Fig. 3.4.1.1) Spacing and orientation of the nails would be determined by the casing geometry and the separation system. A large number of markers could be stored by rolling the taped markers into rolls, or by folding the strips neatly.

Advantages / Disadvantages:

+ Inexpensive system.
+ Easy to apply.
- Adhesive may be heat sensitive.
- May have problems due to markers slipping.

3.4.2 Thermal Adhesive Strips

Subsystem: Feeding and Storage System



3.4.2.1 Markers Joined With Thermal Adhesive

For Use With The Casings:

Nail, Bare, Cartridge

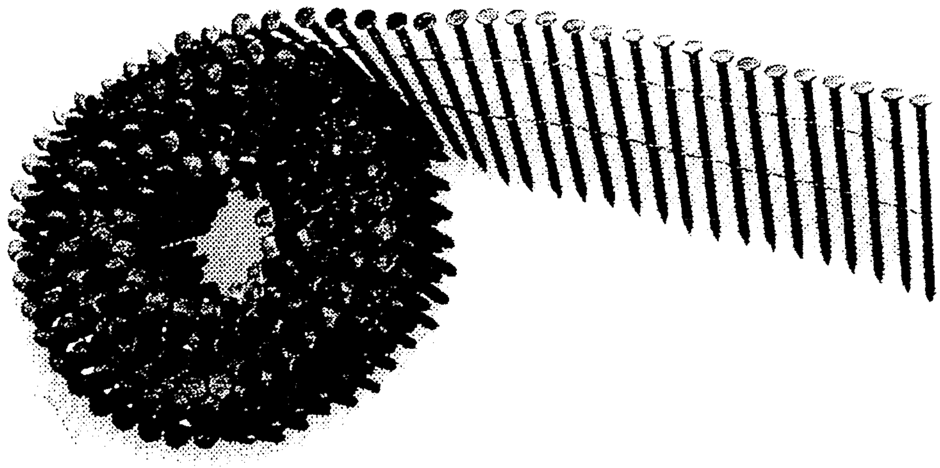
Description:

Strips of adhesive would be applied to one or two sides of a row of markers under high temperatures. (See Fig. 3.4.2.1) 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 system.
- Application procedure more difficult than with pressure sensitive adhesive strips.
- May have problems due to markers slipping.

3.4.4 Wire Braised on Nail
Subsystem: Feeding and Storage System



3.4.4.1 Markers Joined by Braised on Wire

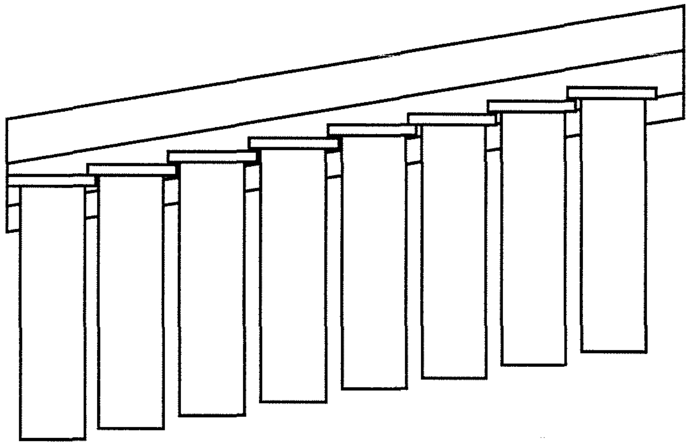
For Use With The Casings:
Nail, Cartridge

Description:
Nails are joined by one or more thin wires that are braised directly onto the marker's casing (See Fig. 3.4.4.1) 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.

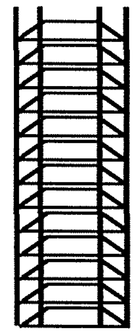
Advantages / Disadvantages:
+ Wires are very flexible for bending.
+ Markers are very securely joined.
- Wires need to be cut or melted off before installation.
- Burrs from braising may interfere with installation.

3.4.5 Gravity Fed Channels

Subsystem: Feeding and Storage System



3.4.5.1 Nails in Gravity Fed Channels



3.4.5.2 Column of Dots

For Use With The Casings:
Nail, Cartridge, Dot

Description:

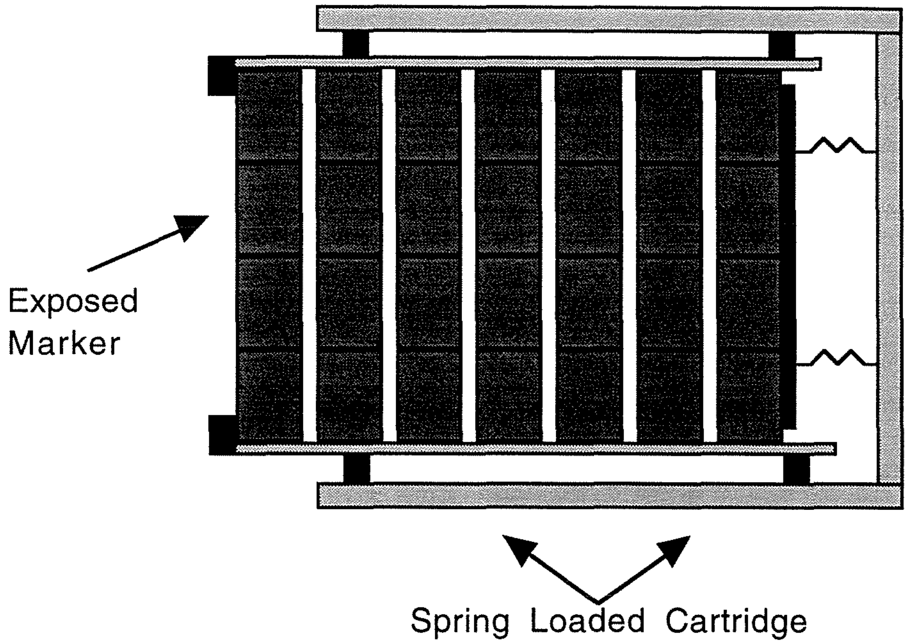
Markers are held in non-ferrous channels which both hold the markers in order, and allow the markers to slide down under their own weight. Figure 3.4.5.1 shows several nails that are held by their heads. Channels could be machined that would contain the nail in a variety of configurations. (stacked end-to-end, side-to-side, etc.) In operation, the bottom marker would be removed to let the next marker slide in place.

Advantages / Disadvantages:

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

3.4.6 Loaded Cartridge System

Subsystem: Feeding and Storage System



3.4.6.1 Loaded Cartridge System Powered with Springs

For Use With The Casings:
Nail, Bare, Cartridge

Description:

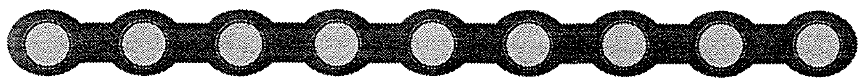
Markers are stored in machined channels, and are presented by the application of some mechanical force. During operation, the exposed marker would be removed, and the mechanical force would push all of the other markers forward. An example is shown in figure 3.4.6.1.

Advantages / Disadvantages:

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

3.4.3 (Disposable) Plastic Chamber Strip

Subsystem: Feeding and Storage System



3.4.3.1 Markers Joined With Plastic Chamber Strip (End View)

For Use With The Casings:
Nail, Bare, Cartridge

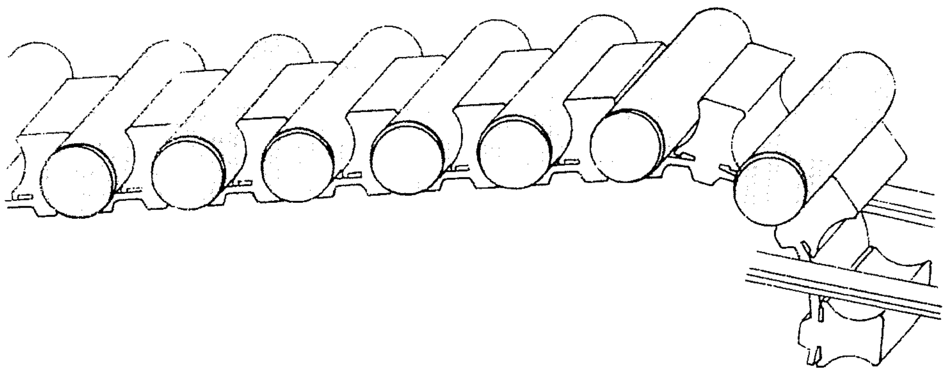
Description:

Markers would be joined with a disposable plastic strip attached approximately at the midsection of the marker. (See Fig. 3.4.3.1) 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 the plastic retainer rings hold together a six-pack. 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:
+ Good grasping of the marker.
- Assembly may be expensive.

3.4.7 Reusable Chain Cartridge

Subsystem: Feeding and Storage System



3.4.7.1 One Style of Reusable Flexible Chain

For Use With The Casings:
Nail, Bare, Cartridge

Description:

Markers are stored in some sort of reusable flexible cartridge chain. One style is shown in figure 3.4.7.1., where markers are automatically released through bending in one direction. Another option would be to have a chain that could bend both ways, but markers would have to be pulled out of. This chain would hold markers in the same way ammunition is sometimes held by chains for automatic weapons.

Advantages / Disadvantages:

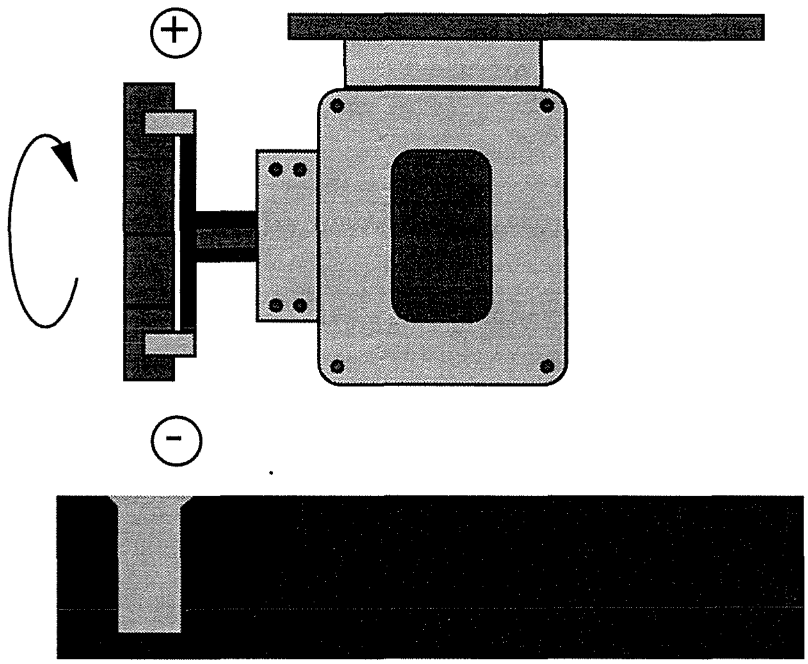
+ System is reusable
+ Markers are securely held.
+ Good bending flexibility.
- Manufacture & Loading of the chains may be expensive.

3.5 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. Coding information for which polarity marker is needed at a given site would either be stored electronically, or preordered in a cartridge in the storage system.

3.5.1 Polarity Rotator Device

Subsystem: Separation and Sorting System



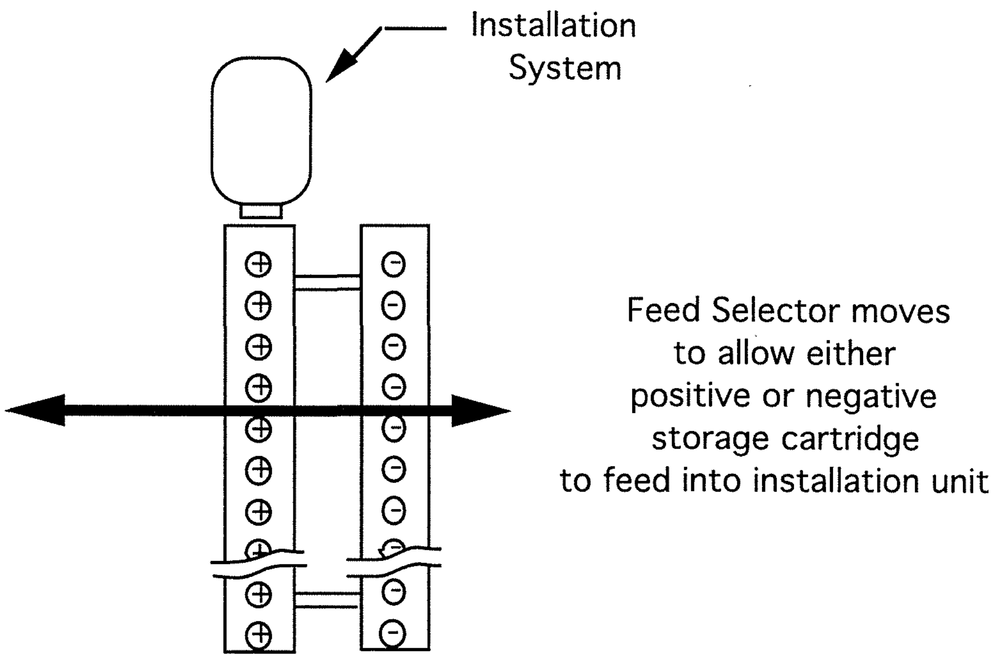
3.5.1.1 Polarity Rotator with Bare Marker

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. (See Fig. 3.5.1.1) Markers fed into this system would have to 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.

3.5.2 Feed Selector
Subsystem: Separation and Sorting System



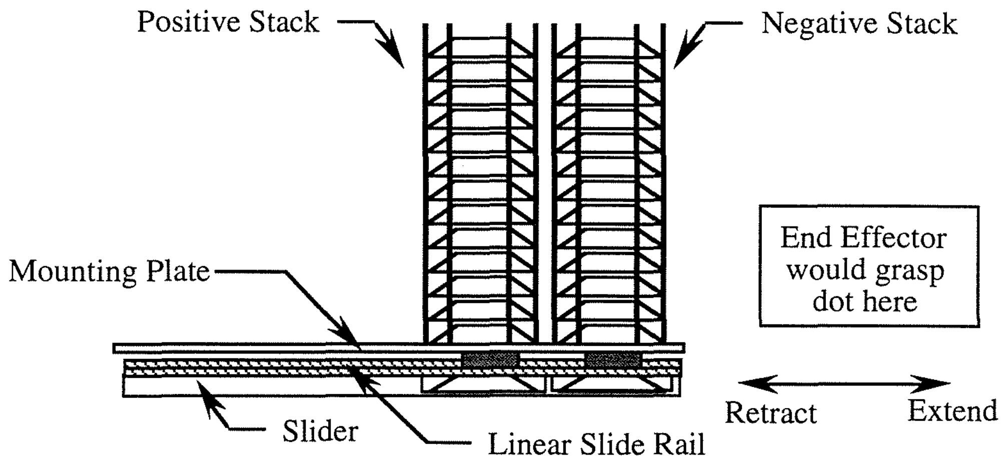
3.5.2.1 Feed Selector System

For Use With The Casings:
Nail, Cartridge, Bare

Description:
This system would change between feeds of unipolar markers. (See Fig. 3.5.2.1) 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.

3.5.3 Gravity Loaded Dot Feeder [7]
Subsystem: Separation and Sorting System



3.5.3.1 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 would then return and reload. (See Fig. 3.5.3.1)

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

3.6 Pre-Installation Inspection Systems

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.

3.6.1 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.

3.6.2 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.

3.6.3 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 if the marker is positive or negative.

3.6.4 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.

4. Operational Specifications

4.1 Cycle Time

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

Assuming a one meter spacing, every second that it takes for an operation to move from a previously installed marker, locate the site for the new marker, and install the new marker adds .27 hours to the time to install 1 km of markers. Considering that in an eight hour shift, a work crew has to travel between the dispatching area and the work area, perform pre-operational inspections, set up, break down, etc., only about five hours of marker installation work may get done. The cycle speed necessary to put down *only one kilometer's worth* of markers per shift would be 18.7 seconds.

4.2 Onsite Packaging and Feeding

- **Marker Coding** - 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 the delivery of the correct polarity marker at the installation site.
- **Holding Capability** - Packaging should be able to accommodate at least one kilometer's worth of markers. For precoded storage, 1000 markers must be held in order. 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 either positively or negatively.

4.3 Safety

- **Traffic Safety** - Installation procedure must comply with standard construction procedures [8] for issues such as traffic barrier placement, dust control, etc.
- **Worker Safety** - automated workspaces should have appropriate safeguards such as fencing and trip devices [9]. Risk assessment techniques should be applied [9].

4.4 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 [10]. Any operation that must conform to an existing roadway would either have to use landmarks on the roadway itself, or be re-surveyed immediately before installation. It is because of the requirement of t he additional surveying step that database systems are not recommended.

Although surveying information such as D-GPS is accurate enough to locate an object on the Earth's surface to within 1 cm, the position of that object moves over time due to a variety of disturbances. A point in California could move 1 cm/year due to tectonic shifting of the Pacific rim plate alone. 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.

4.5 Reliability

- **Maintainability** - 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 stopping capabilities should be provided for 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.

4.6 Maintenance

- **Quality Control & Regular Inspection of Markers** - During installation, a safety checking station should check the polarity of the markers. After markers are installed, follow-up vehicles should judge if they are correct, and sense if they are deteriorating. The follow-up inspection vehicle would be considered a separate system to itself, and not a part of this 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** - 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.

4.7 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 as the system is used for installation, such as power used, fuels used, and manpower. These costs are cumulative, and efforts should be made to keep these costs at a reasonable level. Since the greatest operation cost would most likely be manpower, the most efficient way of controlling these costs would be to minimize the cycle time.

4.8 Additional Requirements

- **Bridge / Unusual Roadway System** - 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.

[1] Zhang et. al., "An intelligent roadway reference system for vehicle lateral guidance / control," in *Proc. 1990 Am. Contr. Conf.,* San Diego, CA, May 1990, pp. 281-286.

[2] Peng et. al., "Experimental Automatic Lateral Control System for an Automobile", *PATH Research Report,* UCB-ITS-PRR-92-11, Nov. 1992.

[3] de Laski A.D., Patsonson P.S., "Traffic Detector Field Manual", FHWA Report, FHWA-IP-85-2, April 1985.

[4] Horowitz P, Hill W., "The Art of Electronics", *Cambridge: Cambridge University Press*, 1989, p. 1007.

[5] Zanutta R, "Working Paper, Research Review of GPS for AHS Applications", SRI International, Nov. 1993

[6] Bell F., *Surveying and Setting Out Procedures*, Cambridge: Ashgate Publishing Company, 1993, pp. 89-103.

[7] Jee S., *Part Presentation for the Automated Raised Pavement Marker System,* University of California, Davis, 1992.

[8] CALTRANS, "Construction Manual", 1992, Sections 2-30, 6-10, & 6-12.

[9] Prasad H. R., "Safety Standards", in *International Encyclopedia of Robotics: Applications and Automation, Volume 3,* 1988, pp. 1428-1439.

[10] Rodgers, J. A., Senior Land Surveyor, State of California Department of Transportation (CALTRANS), *Telephone Interview,* March 1994

Appendix A

Tensile Stress Analysis of Pavement with Hole in Center of the Lane

Stress in the roadway can be modeled using Boussinesq's equation. This is a prediction of the effects produced in a semi-infinite, elastic, isotropic and homogeneous layer loaded on its upper surface by a uniform pressure, p, over a circular area of radius, r. The results directly under the load at a depth of z are:

$$\sigma_H = \frac{p}{2}\left[(1+2\upsilon) - \frac{2(1+\upsilon)z}{\left(r^2+z^2\right)^{0.5}} + \frac{z^3}{\left(r^2+z^2\right)^{1.5}}\right]$$

where υ is Poisson's ratio. This results in stress distribution of the type illustrated in Fig. 1.

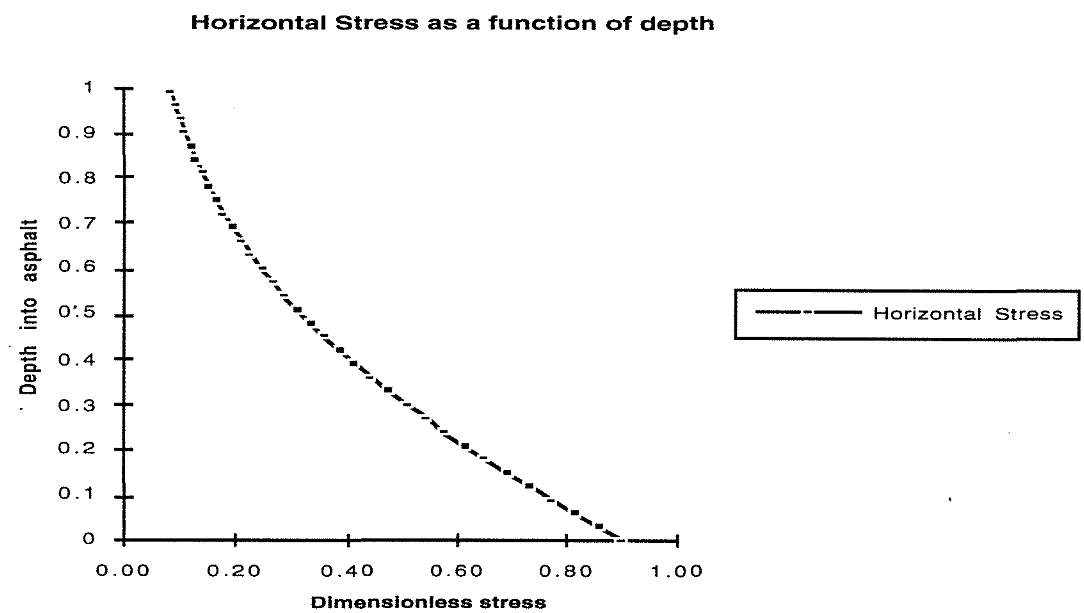


Fig 1

From The Handbook of Road Technology, Volume 1, by M.G. Lay, Table 11.1 and the example from page 197, we can get a good idea of the stresses in the roadway caused by a typical loading. In this example, a wheel load of 40 kN is assumed and the tensile and compressive strains are computed. Under this 40 kN force, the horizontal stress at the surface is 2.3 MPa.

The horizontal stress calculated above was obtained for a roadway without imperfections. However, the placement of the magnetic markers in the roadway will cause a stress concentration at each of the markers. From the Mechanical Engineering Design textbook, by Shigley and Mischke, we can obtain the theoretical stress concentration factor applicable. From Table A-15 we get a value of 3 for the theoretical stress concentration factor. This implies that the tensile stress at the surface around the magnetic marker is approximately three times that of the horizontal stress without the marker present or approximately 6.9 MPa.

From emperical results and curve fits of data obtained from testing, a value of 75 MPa has been obtained for the maximum tensile load that a typical section of asphalt can withstand. To accomodate for the pounding of vehicles and other miscellaneous factors, the 75 MPa value should be divided by two to give a value of the working tensile strength of approximately 40 MPa. This value is more than 5 times as great as the calculated tensile stress due to vehicle loads. This suggests that the cutting of holes in the asphalt will have little to no effect on the strength of the roadway.

References:

Handbook of Road Technology, Vol. 1, M.G. Lay, Stress calculations

Journal of Materials and Civil Engineering, Vol. 5, No. 1, Feb. 93, By: Minh Do, Omar Chaallal, Pierre-Claude Aïtcin. Working tensile strengths

Characterizing the Road-Damaging Dynamics of Truck Tandem Suspensions, By: Thomas Gillespe, at UMTRI, Tensile vs. Compressive strengths.