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Resonant Loop Lane Control System

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INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)

This investigation was completed as part of the ITS-IDEA Program, which is one of three IDEA programs managed by the Transportation Research Board (TRB) to foster innovations in surface transportation. It focuses on products and results for the development and deployment of intelligent transportation systems (ITS), in support of the U.S. Department of Transportation's national ITS program plan. The other two IDEA programs areas are TRANSIT-IDEA, which focuses on products and results for transit practice in support of the Transit Cooperative Research Program (TCRP), and NCHRP-IDEA, which focuses on products and results for highway construction, operation, and maintenance in support of the National Cooperative Highway Research Program (NCHRP). The three IDEA program areas are integrated to achieve the development and testing of nontraditional and innovative concepts, methods, and technologies, including conversion technologies from the defense, aerospace, computer, and communication sectors that are new to highway, transit, intelligent, and intermodal surface transportation systems.

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RESONANT LOOP LANE CONTROL SYSTEM

Principal Investigator
E. WILLAM BUSH

IDEA Product for ITS

A new system of detecting the position of a vehicle relative to the center of the roadway lane has been developed. This system utilizes a phase detection process in the vehicle to determine the position of the vehicle relative to a resonant circuit (loop) installed in the center of the lane as shown in Figure 1.

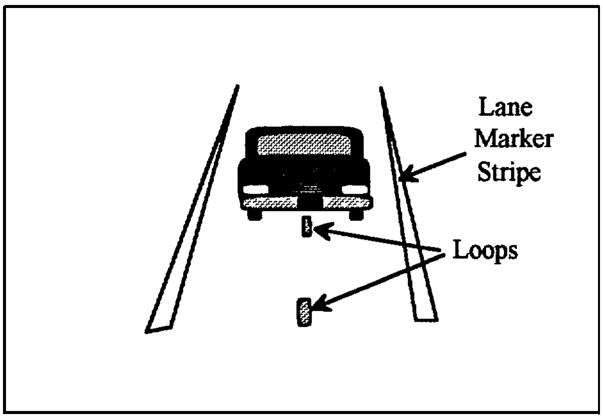

Figure: 1 System configuration

As the vehicle proceeds down the lane the position detector provides an output signal voltage which is positive if the vehicle is on the left side of the loops or negative if the vehicle is on the right side of the loops. When the vehicle reaches the center of the lane the voltage nulls out. This voltage is used to provide the driver a steer left or steer right meter indication or the voltage is used as feedback in a servo control mechanism to actually steer the vehicle. A similar function is currently performed by the speed control implementation presently in most vehicles. The speed control system includes a manual override provision and the lane control system would also include a manual override provision.

The objective of automatic servo controlled steering is to keep a vehicle exactly in the center of the road without driver assistance. Without the constant pressure of the tedious steering task, the driver has more time to prepare for and react to unexpected or unanticipated events that may occur.

Concert and Innovation

This new resonant loop vehicle positioning system concept evolved from observations of the signal return from a passive resonant circuit. When signal energy is inductively coupled into a resonant tank circuit the tank circuit inherently emits energy. This energy interchange provides the basis for the vehicle positioning system. Figure 2 shows that the phase and polarity of the inductively coupled signal from the vehicle transmitter coil into the road coil depend on the position of the road coil relative to the transmitting coil. No signal is induced into the road coil if it is centered directly below the vehicle transmitting coil. The induced current into the road coil is clockwise if the coil is on the right side of the transmitting vehicle coil and counter clockwise if the road coil is on the left side of the transmitting vehicle coil.

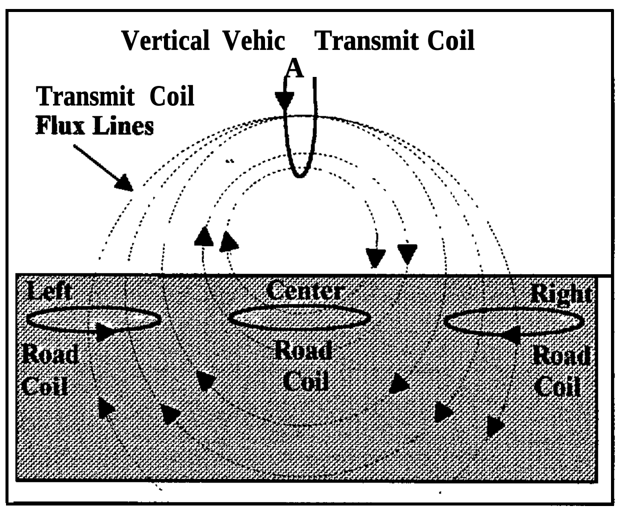

Figure: 2 Vehicle to road link

The secondary induction coupling from the road coil into the vehicle receive coil is shown in Figure 3. Note that the receive coil is mounted horizontal and at right angles to the transmit coil

INVESTIGATOR PROFILE

E. WILLIAM BUSH May 9, 1995
PRINCIPAL INVESTIGATOR
Compuline Inc. La Jolla California

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signal returning from a road coil would reverse phase every 8 ft. Since the range utilizing the 60 MHz components could exceed 8 ft. an ambiguity would be introduced. This ambiguity would be avoided, however, if the system operational range were designed to be less than one half the wave length.

At this point the system design was again reviewed with respect to optimizing the operational frequency, taking into consideration the problem with the extraneous signals and the range ambiguity. Lowering the frequency would avoid the ambiguity problem but would again introduce the problem of achieving a reasonable antenna radiation resistance. It was also well appreciated that the primary reason for going to the 60 MHz frequency from the original 11 MHz was to achieve satisfactory antenna radiation.

Another possible approach was to abandon operating with the radiation field and communicate with the road coil utilizing either the static field or the inductive field. Since these fields drop off much faster than the radiation field it meant reducing the range. It was then recognized and appreciated that an accelerated drop in signal level with respect to range offered an advantage. The resulting reduced range eliminated reflections from surrounding objects except in the immediate vicinity of the vehicle. This advantage justified the lower operating frequency providing the resulting receiver sensitivity and dynamic range were satisfactory.

Operating in the near field of the antenna requires an understanding of the three components of the electromagnetic field. This is clarified by referring to the basic electromagnetic field equation

$$E_\theta = \frac{1}{4\pi\epsilon}\left(\frac{1}{r^3}+\frac{jk}{r^2}+\frac{k^2}{r}\right)\sin\theta p_0 \in^{j(\omega t-kr)} \quad [2]$$

where E_θ is the electric field potential, r is the range, θ is the vector angle, π $\in$ are constants, ω is 2π times the frequency, and k is 2πtimes the wave length λ. The three terms in the parenthesis represent the three partial fields (1) the *"static field"* varying inversely with r^3, (2) the *"induction field"* varying inversely with r^2, and (3) the *"radiation field"* varying inversely with r. Values for these terms were calculated and plotted in Figure 4 using feet for range and $2\pi\lambda$ for k. The frequency selected for the evaluation was 1.8432 MHz. which equates to a wave length (λ) of 533.6 ft. The results show that the static field dominates out to about 64 feet where the induction field takes over and becomes dominate. Finally the radiation field takes over at 2^{18} feet (262,144 ft) which is nearly 500 wave lengths. The three field intensity vectors were added appropriately to show the combined field intensity. This resulting field intensity was found to follow or essentially equal the largest of the three field intensity vectors. Figure 4 shows that if the system is operating at 1.8432 MHz and the range is anything less than 20 feet, the field strength will follow the static field intensity and vary inversely with r^3.

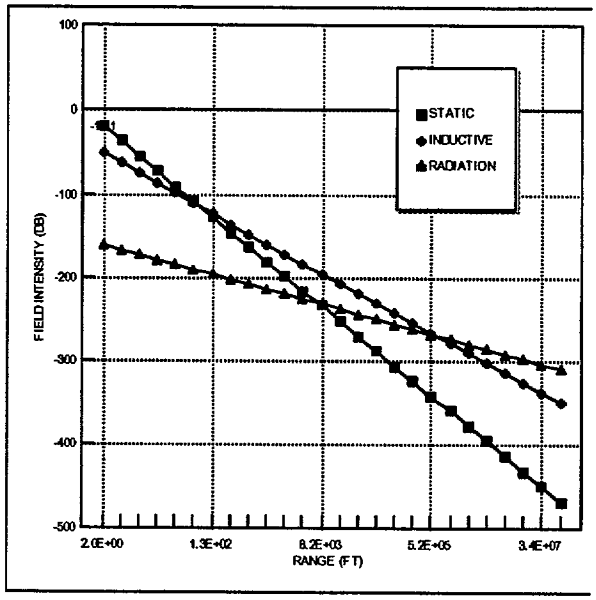

Figure: 4 Relative field intensity

Both the receiver and the transmitter were subsequently changed to operate at 1.8432 MHz. In the course of changing the frequency a second modification was made to increase the receiver dynamic range. An additional stage of AGC control was incorporated into the receiver. This improved the receiver dynamic range by providing

[2] Samuel Silver, *Microwave Antenna Theory and Design*, p.93, Boston Technical Lithographers, Inc. 1963

two cascode control stages of AGC, each providing 40 to 50 dB of signal level control.

With the redesign to 1.8432 MHz complete, the components were assembled and system testing resumed. The primary objectives were to optimize the size of the coils in conjunction with the range measurement requirements. To this end, a series of one way range measurements were made with various size coils. A summary of the results of these tests is shown in Figure 5.

Transmit Coil	Receive Coil	2 FT. Range
3.5"dia. 2 Turn	3.5"dia 10 Turn	-40dB
3.5"dia. 2 Turn	18"dia 1 Turn	-37dB
3.5"dia. 2 Turn	3.5"dia 2 Turn	-54dB
18"dia. 1 Turn	18"dia 1 Turn	-19dB
18"dia. 1 Turn	3.5"dia 10 Turn	-23dB
18"dia. 1 Turn	6.2"dia 6 Turn	-10dB

Figure: 5 Coil comparison

At first the 3.5" diameter 10 turn coil or the 6.2 inch diameter coil appeared attractive for the road coil because of the nominal dispersion loss. Upon further analysis it was found that the return link from the road to the vehicle would not be satisfactory. This can be appreciated by referring to the transfer characteristic equation of a double tuned circuit as follows:

$\frac{E_2}{E_1} = \frac{-M}{C_2(R_1R_2+\varpi^2M^2)}$ [3] where E_2 and E_1 are the secondary and primary voltages, M is the mutual coupling, R_1 and R_2 are the primary and secondary impedance at resonance, ϖ is the frequency of rotation and C_2 is the secondary capacitance. This equation shows that the secondary voltage can be increased by decreasing the secondary capacitance. The advantage is lost in the return link because of the reduced inductive coupling of the smaller coil without the compensation of a smaller capacitance in the secondary. Figure 5 shows where a small coil is used to transmit a signal to a second coil. The resulting loss is substantially higher for the small primary coil regardless of the size of the secondary coil.

Based on the test data and taking into consideration the need for an economical installation, the coils for the system were selected as follows:

Coil	Turns	Size
Vehicle Transmit	6 Turns	6 in
Vehicle Receive	6 Turns	6 in
Road	1 Turn	11.5 in.

All of the coils were constructed using No. 12 copper wire with appropriate capacitors to achieve resonance at 1.8432 MHz.

Range measurements were made using these coils in a typical vehicle installation. The transmit and receive coils were arranged to be cross polarized with the transmit coil vertical and the receive coil horizontal as shown in Figure 6. The side by side arrangement was selected for convenience in adjusting for isolation between the transmit and receive coils. This arrangement also allowed for a radiation shield to be placed between the two coils to increase the isolation. Since the shield was ultimately found not be to necessary, the concentric mounting appears to be most appropriate for future installations. The concentric configuration only requires half the space for the vehicle antenna.

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PICTURE OF THE VEHICLE ANTENNA ARRANGEMENT (FRONT)

Figure: 6 Vehicle installation

3 K. R. Sturley, *Radio Receiver Design*, 2nd Edition, p.163, John Wiley & Sons Inc., 1953

Since the automatic steering of a vehicle exceeded the time and resources available, a meter was added to the system to provide the driver steering information. This allows the driver or requires the driver to keep the vehicle centered by following the meter indication. Initially the meter appeared to be very confusing because of noise. When a signal was present the meter was well behaved but whenever the signal was not present the meter indication was completely random. It was also appreciated that a road coil return would not always be present. The system inherently nulls out the signal return when the road coil is centered with respect to the vehicle module.

In order to avoid the meter noise problem as well as any possible constraint in the road coil spacing a sample and hold circuit was added to the receiver. This additional circuit allowed the receiver to obtain a sample when the signal was present and hold the sample signal until another sample was available. The circuit used the AGC (automatic gain control) voltage in the receiver to gate the direction signal to the meter whenever the receiver input exceeded a set designated level. A dramatic improvement in the meter response was observed with the implementation of this circuit. The meter indication remained at center scale until an error signal was detected. If a left or right signal was detected the meter held the meter indication until the next input sample was detected.

With the sample and hold circuit functioning it was possible to efficiently diagram the azimuth range between the road coil and the vehicle. In determining how the operational range varied with azimuth angle around the vehicle coils a "foot print" diagram was found to be the most graphic and understandable. The footprint data was obtained by moving a road coil around on the road surface under the vehicle and established the profile where the received signal (AGC voltage) was constant. A typical footprint diagram is shown in Figure 7.

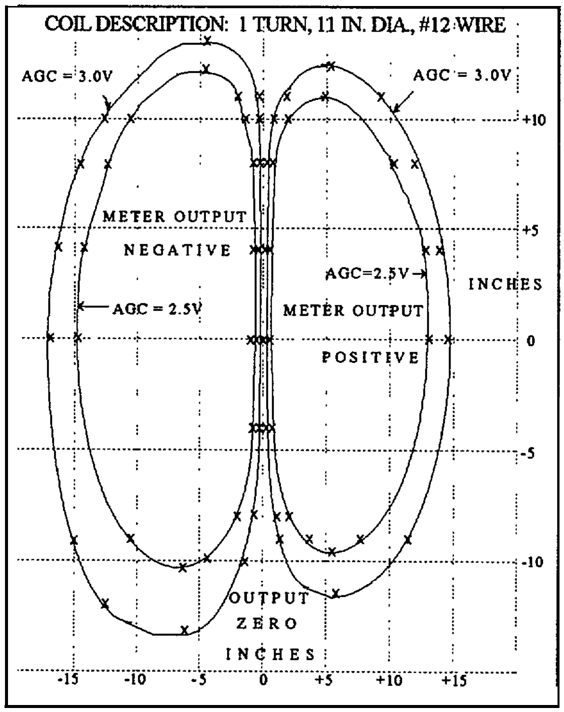

Figure: 7 Footprint diagram

The minor unbalance reflected on the footprint diagram was found to be leakage from the transmitter directly to the receiver. Both the transmitter to antenna and the receiver to antenna coaxial cable were approximately 3 feet long. This provided a small but perceptible leakage path around the antenna which produced the unbalanced signal. The prototype production configuration will eliminate this unbalance by shortening the cable runs and utilizing solid jacket coaxial cables instead of braided shield cables.

A representative range measurement taken from Figure 7 can be used to project range based on changes in the receiver sensitivity. The receiver AGC voltage provides a calibration on the received signal level into the receiver. This relationship is reflected in the receiver sensitivity curve shown in Figure 8. This curve shows the

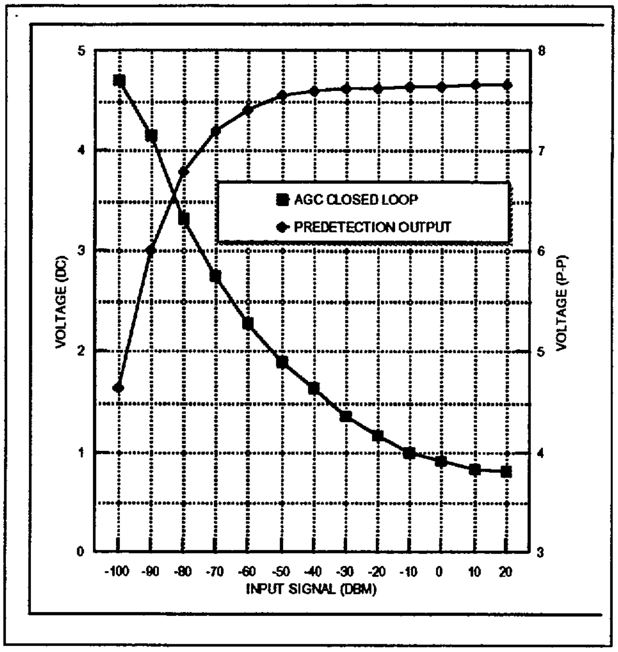

FIGURE 8 Receiver Sensitivity

receive signal level to be -68 dBM at an AGC voltage of 2.5 volts. This provides a reference point on the two way sensitivity verses range curve shown in Figure 9.

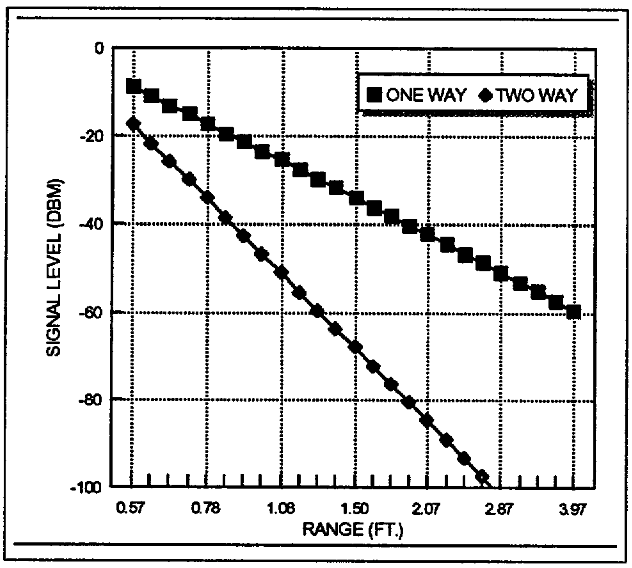

Figure: 9 Range sensitivity

The slope of the two way ranging curve is 36 dB per octave and the slope of the one ranging curve is 18 dB per octave, which represents the dispersion loss operating in the static near field. With the road coils, vehicle coils, transmitted power and receiver sensitivity implemented, the range is shown to be limited to something less than 2.87 feet. Later actual road tests under these operational constraints were conducted. The results of these tests established that the design as defined and implemented provided acceptable performance.

Road tests were conducted in a parking area where a painted center line was visible with parking spaces marked on 13 foot centers. Road coils were placed on the center line at each parking space marker or 13 feet apart. Two rows of 25 coils were laid out with sufficient space between the two rows for a vehicle to conveniently make a U turn and proceed down the next row of coils. A picture of the road coils is shown in Figure 10.

PICTURE

OF

ROAD COILS

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Figure: 10 Road Coils

As the test vehicle was driven up and down the rows of road coils two methods of recording the results were implemented. A strip chart recorder was used to record the direction error signal to the meter and a video camera was used to record a panoramic view from the back seat of the test vehicle. The picture in Figure 11 shows the view recorded by the video camera. As the vehicle proceeded

Picture of

Vehicle Interior

From

Back Seat

Figure: 11 Vehicle picture

down a row of coils the video shows the positive and negative meter needle swings, following and correlating with the vehicle position on the left or right side of the center line.

The strip chart recorder tape also shows the left or right error signal as the vehicle proceeds down a particular row of road coils. These tape recordings can be followed along with the video to see the corresponding deviations and the correlation that exists. A reconstructed copy of the data recorded by the strip-chart recorder is shown in Figure 12. Two runs are reproduced. In each case the strip-chart recorder speed of recording was constant so the horizontal transitions of the pen represent the 13 feet between the road coils. The vertical transitions of the pen represent the time the vehicle was passing over the road coils. In each case the vehicle is seen to accelerate from the beginning of the run to the end.

The charge and discharge time in the sample and hold circuit was an arbitrary selection. The discharge time constant was approximately 6 seconds and the charge time-constant was approximately 100 ms. Optimum values will await further testing. It is anticipated that the time constants will be dynamically scaled and adjusted in proportion to vehicle speed.

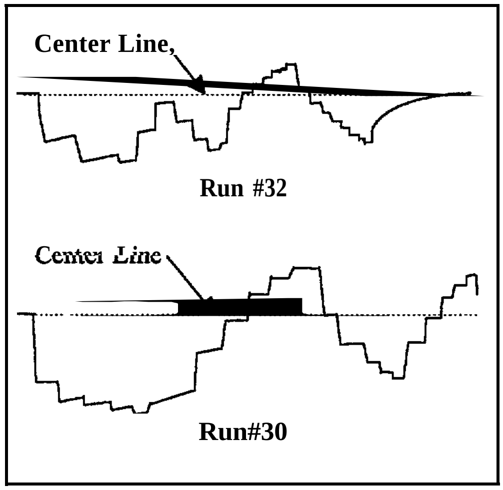

Figure: 12 Road test data

The phase detector output in the vehicle is very sensitive. The width of the null at the center varies with the sensitivity setting of the AGC cutout. The higher the sensitivity, the narrower the null becomes. During the tests, the center null was set to be approximately one-half inch wide. Within the one-half inch wide area, the phase detector output is zero. As soon as the road coil goes outside the null area the phase detector output quickly goes to full output. The servo system should therefore make steering corrections based on a reasonable "g" load which the car and passengers can accommodate safely and comfortably. It is possible that the receiver AGC could be used to further define the vehicle position relative to the center line of the lane. A profile of the AGC voltage versus distance from the lane center is shown in Figure 13.

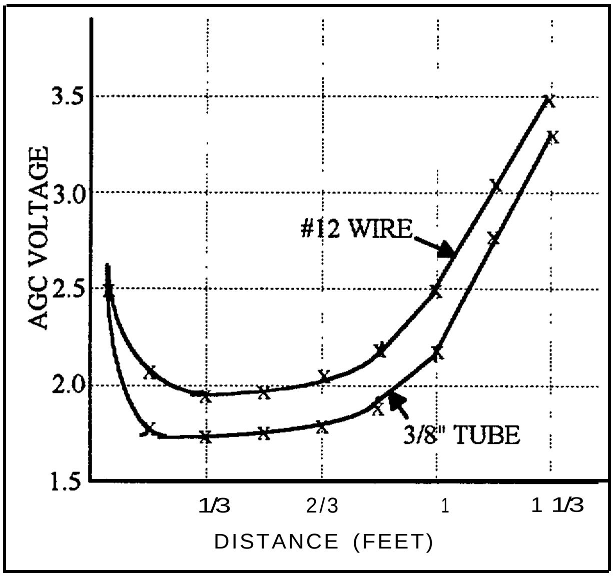

Figure: 13 Receiver AGC versus range

The AGC versus range data shown in figure 13 was taken at right angles to the lane center line with the range measured from the center of the vehicle transmit and receive coils.

The ultimate selection of a system for lane control will be based on achieving the desired functionality at the minimum cost. It is therefore necessary and essential to access the costs associated with the resonant loop system. A major element and possibly the dominant portion of the system cost is associated with the roadway modification requirements.

The loops could be buried when the road is surfaced or installed by grinding a shallow trench in an existing road surface similar to the method presently used to install reflector markers. Loops could be produced that closely fit the trench as shown in Figure 14.

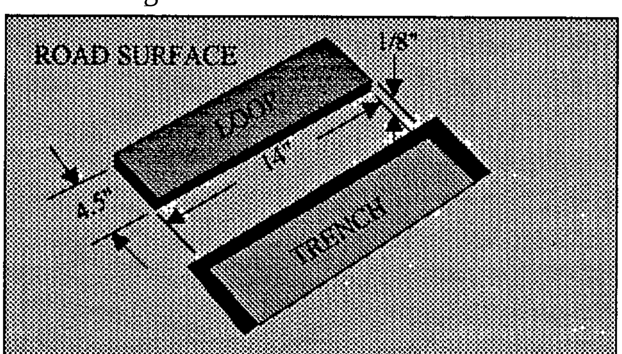

Figure: 14 Loop installation

This will facilitate a simple and relatively quick installation. The trench would be produced by a grinding process followed by the adhesion of the loop assembly into the trench with a bituminous compound at 425° F. The bituminous compound cools quickly and the adhesion is firm in a few seconds.

Cost estimates for the installation were found to vary, to some degree, depending on personal appraisals. Estimates were obtained from:

1. CALTRANS, District 11 Office of Engineers
2. PENHALL, Pasadena Contractor
3. WORKS, Palm Springs Contractor
4. PACO, San Diego Contractor

The actual costs are only obtained by establishing a specification which defines the quantity, location, etc. and followed by a competitive procurement. Historical data furnished by CALTRANS show the average cost for reflector markers installed during 1994 was $9.33. This included 16 separate contracts with quantities per contract varying from 5 markers to 8,520 markers. The procurements do not identify or separate the cost elements but estimates indicate that the grinding represents about 75% of the total cost or about $7.00.

Since the volume of the road material to be extracted for the road coil loops would be only 22% of the volume currently being extracted for the reflective markers, the grinding time would be reduced a commensurate percentage. The grinding costs are amplified by the safety aspects of a typical installation. Five vehicles are typically involved in the road installation process including: (a) two vehicles to identify the lanes with the reflector markers, (b) a crash cushion "attenuater" truck, (c) a monitoring pickup truck and (d) the actual installation vehicle. With the labor and equipment required during the grinding and installation process, any savings in time translates into significant cost savings. Taking into consideration the reduction in the grinding time but adding time for the adhesion process estimates were found to vary from $4.00 to $5.00 for the installation.

The cost for the road coil assembly is estimated to be comparable to the reflective markers. Both reflective markers and the loops would be molded assemblies. A cost tradeoff would consist of the elimination of the glass reflector and the addition of the electrical components required for the resonant circuit. These electrical components consist of a #12 wire 30 inches long and a capacitor. The present lane reflector markers sell for less than $2.00 in large quantities.

Combining the installation with the loop assembly cost the overall cost appears to be $6.00 to $7.00 per loop providing the number of loops installed is 15,000 or greater. These figures can only be considered rough estimates which will ultimately be validated by an actual contract procurement.

Costs for the resonant loop system vehicle module are principally made up of the coil assembly and the electronic circuits. In both cases the existing breadboard provides very little beyond a functionality basis for a future production unit.

The existing coil assembly was constructed with the transmit coil and the receive coil separated. Now that the electrical isolation has been relaxed with the addition of the “sample and hold” circuit, a concentric coil assembly would be possible and more economical. Tooling fixtures will be necessary to insure the required orientation tolerance. Once the fixtures and processes are designed the coil assembly would be comparable to a transformer with a six turn primary and a six turn secondary winding. Certainly the cost would be in the less than $10 range.

Costs for the receiver and transmitter electronics will depend on the availability and/or development of LSI (large scale integration) circuits, Comparable circuits in the VHF (very high frequency) range are currently available for less than $5.00 each.

Plans for Implementation

Implementation of a lane control system is going to require adopting a national and quite possibly an international standard. It is therefore possibly prudent and proper to only consider the next step in proving the viability and applicability of the resonant loop system with respect to this ultimate standard. A statement of work for the immediate future would include the following:

1. Design and fabricate a consolidated concentric vehicle coil. Test the revised coil assembly utilizing the existing breadboard electronics.
2. Define the interface with existing vehicle automated steering control systems.
3. Conduct an operational simulation analysis to establish the optimum system configuration. This simulation will include an analysis of road coil spacing and road curvature with respect to the vehicle speed.
4. Design and fabricate three prototype units. This effort will result in detailed manufacturing drawings for the prototype configuration.
5. Install the revised prototype module in a servo controlled vehicle.
6. Road test the automatically steered vehicle. The road test will be designed to validate and verify the results of the simulation analysis.

NOTES

[1] **Richard C. Dorf,** *Electrical Engineering Handbook,* p. **863 · CRC PRESS, Boca Raton Florida, 1993**

[2] **Samuel Silver,** *Microwave Antenna Theory and Design,* **p.93, Boston Technical Lithographers, Inc. 1963**

[3] **K. R. Sturley,** *Radio Receiver Design,* **2nd Edition, p. 163, John Wiley & Sons Inc., 1953**

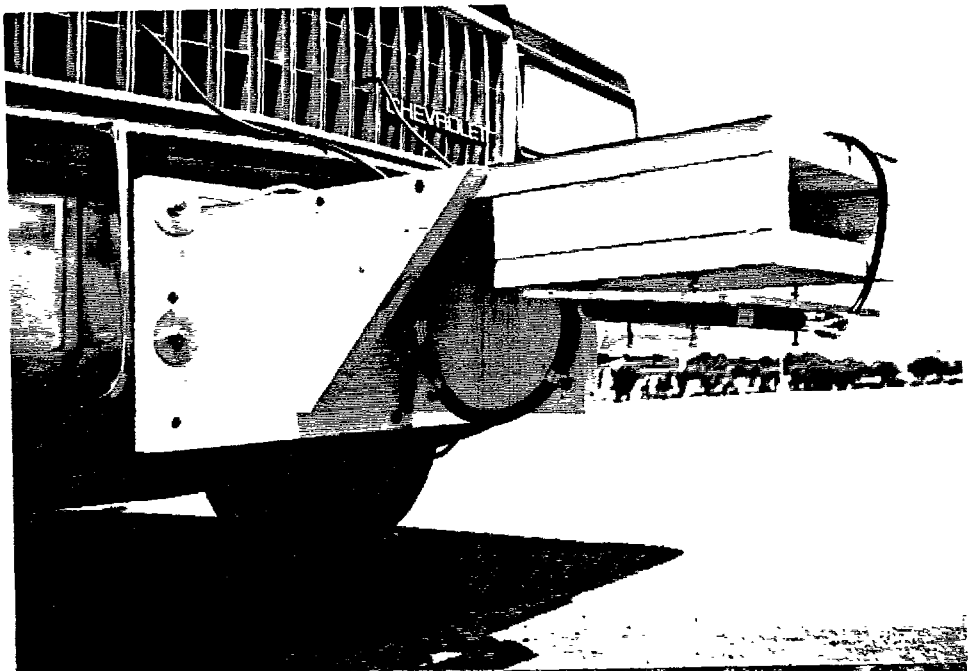

fig 6

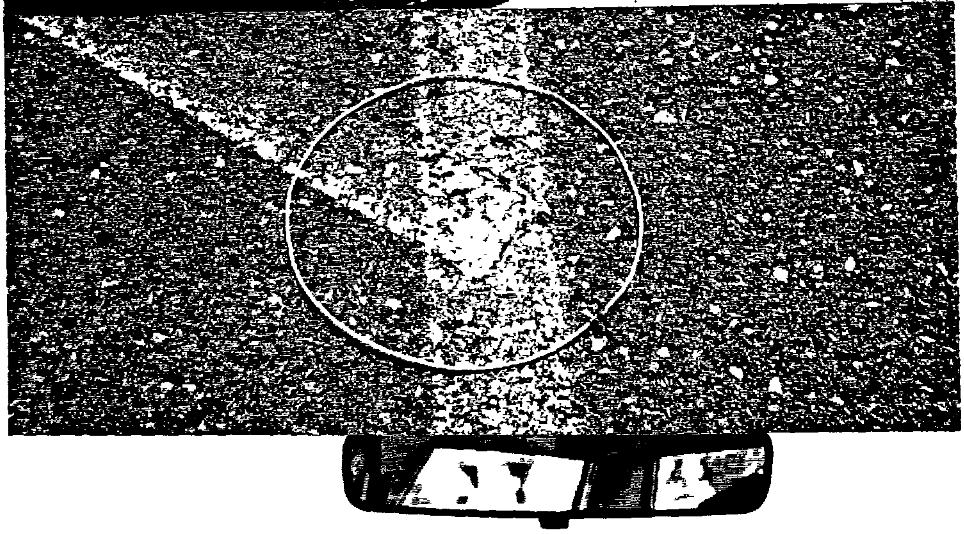

fig 10

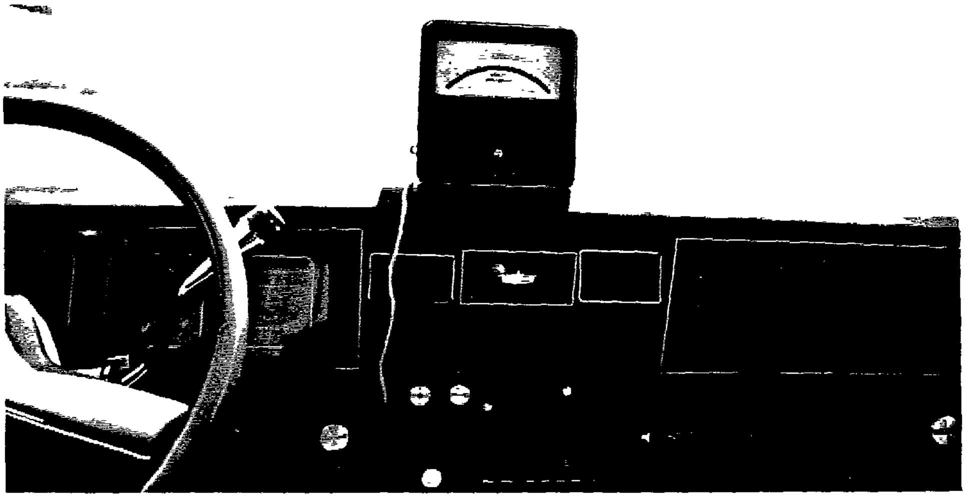

fig 11

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