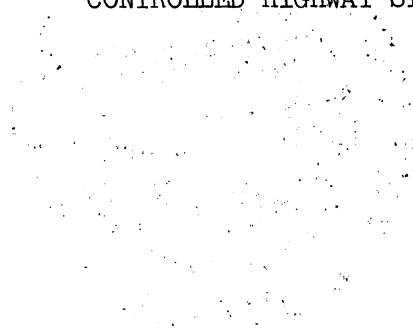


THE UNIVERSITY OF MICHIGAN
INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

THE DEVELOPMENT OF AN AUTOMATICALLY
CONTROLLED HIGHWAY SYSTEM



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FOREWORD

The rapidly growing number of automobiles in the United States today has encouraged the development of an Automatically Controlled Highway Vehicle (ACHV). The following paper describes the investigation and development of such a system in a senior engineering project course at The University of Michigan.

In an attempt to give the student a unique experience in design education, the course description read as follows:

"A student team of ten senior and graduate engineering students will be responsible for the design of an automatic highway vehicle guidance and control system, including:

- (1) Development of detailed system requirements taking account of economic constraints.
- (2) Specification and/or design of sensors for vehicle position, velocity, and spacing.
- (3) Development of a method for processing data and generating normal command signals.
- (4) Specification and/or design of vehicle control actuators.
- (5) Development of entry and exit control methods.
- (6) Development of emergency override operation and other safety features."

Realizing that an exhaustive study and development of the total system would be impossible in the fourteen weeks allotted for the course, it was decided to reduce the system requirements as will be described below.

However, care was taken to ensure that the over-all activities of the group included a broad range of the original problem, giving each individual an opportunity to work in a specific area, rather than concentrating a

total effort on one particular concept or sub-system.

The initial student assignments were as follows:

Project Engineer.....	James W. Albers
Vehicle Parameters.....	Richard S. Morrison
Speed Control.....	Charles L. Martin
	William. E. Schroeder
Spacing Control.....	Lok-Seng Oei
	Robert B. Roberts
	Alfred R. Webster
Steering Control.....	James W. Albers
Servo-Mechanisms.....	Joseph A. Van Zale
Actuators.....	Gerald L. Walker
Over-ride.....	Charles L. Martin
Economics, Marketing, and Future Proposal.....	Harold W. Reick

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I. BACKGROUND

A. Traffic Safety

Recently there has been a great deal of discussion concerning traffic safety, and much is being done in an attempt to curtail the ever increasing death and injury toll throughout the nation. Driver education, vehicle safety checks, traffic law enforcement and many other programs are being increased, but the fatality rate is still climbing. Table I shows the traffic deaths in the past few years as well as the deaths per 100 million vehicle miles. What it does not show, however, is the number of persons injured to the extent of disability beyond the day of the accident. In 1964, this figure was 1.6 million which is greater than the population of Milwaukee, Wisconsin, and yet this figure is only approximately one half of the total injuries. Again looking at Table I, we see that the death rate per 100 million vehicle miles has been reduced greatly in the past 20 years. But since 1961, it has remained relatively constant, and for the first half of this year, it is exactly the same as last year. Thus with people traveling more and more miles each year, and with the ever increasing number of drivers, highway deaths and injuries soar upward. At the present time it can be said that:

1. Motor vehicle accidents are the third leading cause of death in the U.S.
2. More American lives have been lost in motor vehicle

accidents than in all the wars in which the U.S. has been engaged.

3. More children die as a result of motor vehicle accidents than from any other cause.
4. Half of the victims of motor vehicle deaths are in the prime of life between the ages of 15 and 44 years old.

The question remains as to the cause of these deaths and what can be done to lower the accident rate.

There are many reasons accidents occur. Mechanical failure of the vehicle is one, but it is responsible for a very minor portion of the total number of accidents. The greatest cause of accidents is due to human negligence in the form of speeding, drunk driving, daydreaming, falling asleep, etc. It has long been known that the driver is the weakest link in the vehicle transportation system. The majority of safety programs being initiated or accelerated are directed toward educating or alerting the driver. However, these programs have proved ineffective as the statistics reveal. Before trying to find a program that would reduce the fatality rate, let us look at another serious problem associated with vehicle transportation.

B. Traffic Congestion

Control of traffic flow constitutes a major problem for today's traffic engineers. Rush hour traffic in urban areas as well as the profuse holiday and weekend traffic along interstate and major highways lead to congestion and loss of

time, tempers and lives. Ideally, if all the vehicles were traveling at a uniform speed and spacing, more people would travel further in less time and with fewer accidents. To effect this ideal condition with each driver in full control of his vehicle is statistically impossible. In a limitedly successful attempt to obtain control of traffic flow, Detroit has recently installed a television surveillance and signalling system through which controlled can watch and attempt to change the traffic flow along one of the city's major freeways. Drivers are prodded along, guided by lighted overhead speed signs which indicate the speed at which they "should" be traveling as decided by a computer in the control center. If an accident blocks off a lane, a controller will switch on a red X above the blocked lane for a distance preceding the accident in hope of diverting traffic from the blocked lane, thus preventing further collisions and reducing the inevitable bottleneck caused by the accident. The system has reduced travel time by 10% or more, but unfortunately it cannot force the driver to obey the speed signs or switch lanes as directed. As a result, many vehicles travel the expressway with little or no consideration for the overhead signs, slowing down only when forced to do so by the leading vehicle. Drivers frequently cut in and out of lanes at their own will, reducing their speed and thus creating a wave of congested traffic which can be witnessed on the television monitors in the control room. Nevertheless, this system is a step in the right direction in that it at least makes a serious attempt

to control traffic flow. The only reason it fails to do a 'perfect' job is that it again deals with the human element. Thus far the two major vehicle transportation problems have been discussed; the increasing death and injury rate, and traffic congestion. It has been shown that the driver is the major cause of these problems, and we now consider possible solutions to these problems.

C. Electronic Highways

An obvious solution would be to reduce the number of vehicles using the traffic lanes. The validity of this method was manifested during World War II when gasoline rationing reduced the travel mileage while the death toll dropped by approximately 37%. But the present trend is for more and more highway travel while at the same time automobile sales are at an all time high. This solution, although efficacious, would undoubtedly be unacceptable to the public, to say nothing of the automotive industry which constitutes a major portion of our economy. Therefore, a more feasible solution must be sought.

Another approach to the problem is the use of electronic warning devices to alert the driver of necessary speed changes, accidents ahead, or other useful information. But such systems must assume the drivers will strictly obey all signals received visually by signs, or audibly through the car radio, for a completely successful operation. As was shown in the Detroit installation, this does not really happen. Although

these systems help to a significant degree, they are not the ultimate solution to the traffic problems. What then is the best solution?

As we have seen, the human element is the greatest cause of traffic difficulties. It would seem logical that a system of vehicle transportation which does not depend upon the driver, but on something more reliable which would receive and execute control signals without misjudging, mistaking, or ignoring them would be the best possible solution. To design and build a system whereby a passenger could step into his vehicle, push a button, and let the vehicle take him to his destination is perhaps the ultimate system. However, this system is an engineering impossibility at this time. But a system can be designed and constructed for a limited access highway whereby the driver, once on the highway, could push a button and let the vehicle drive itself. When the driver wanted to leave the system, he could release the automatic control and manually leave the highway along one of the normal exiting ramps. Eventually this system could be modified to include automatic exiting at a predetermined destination. Let us look at the reasons supporting the installation of such a system.

Were not the interstate type highways designed and built to lower traffic fatalities and reduce congestion? Why would an automatic system be useful on such a road where it would seem least needed? Again consider the statistics. In 1963, over 31% of the traffic deaths resulted from single car

accidents, most of these involving cars running off the road and most frequently, occurring on good level roadways. It is known that expressway driving tends to lull a driver into a hypnotic-like state, possibly putting him to sleep. Also, after a person has been driving on an expressway, he has a tendency to maintain his speed after leaving the system and while driving on a secondary road. The Bureau of Public Roads recently found that the fatality rate had quadrupled on older highways near the interstate systems, which substantiates this viewpoint. If an automatic system were in use, the "driver" would emerge from the system relaxed and alert, not mesmerized, and thus would be a better driver upon exiting the system. Also, an automatic system on a freeway would keep the traffic moving at a uniform rate and would reduce congestion during dense traffic conditions where normally people would be accelerating and decelerating in waves of congestion. In addition, an automatic system would reduce travel time and increase the volume of traffic a given highway could handle. The passengers would enjoy a smoother, faster ride with none of the many normal driving tensions. But most important, the fatality rate due to human negligence could be reduced.

D. Consumer Acceptability & Economic Feasibility

Before such an electronic system could be mass produced and highways converted, a study must be made to determine consumer acceptability and economic feasibility of a proposed system. Consumer cost is of prime importance and is the

limiting factor in designing an acceptable system. Also, there are psychological factors which must be examined. Some drivers might resent the loss of control of their vehicle or might object to having antennas or other electronic apparatus mounted on their automobiles. Therefore, the appearance of such installations must harmonize with that of the vehicle. There are many other questions concerning consumer acceptability that remain unanswered or unknown.

To determine how much a consumer would be willing to pay for a system, what he would expect for his money, and what his general reaction to an automatic vehicle guidance system would be, a thorough marketing study must be conducted. The importance of such a study is affirmed by the fact that the automobile manufacturers conduct such a study before making any major modifications. For example, public opinion prohibits car manufacturers from replacing the steering wheel with safer steering handles or knobs. However, the method of obtaining useful information from the public is not as simple as it may seem. In the early 1950's, if a car manufacturer would have asked a person if he would be willing to pay an extra \$150.00 for a car that automatically shifted, the majority of answers would have been "No;" and, yet, today most cars have automatic transmissions.

One of the leading automobile manufacturers conducts their marketing research by asking the people to describe their needs. This approach is more informative than asking

for their opinions. They follow this with a study on how present products fulfill the needs of the consumer and then try to come up with a product that will give greater satisfaction. Any method of marketing requires "sampling" from which a decision to produce or not to produce is based. In this particular project the need for the automatic highway is understood, but a study must eventually be made to find if the consumer's need for the system exists, and if so, to what extent.

There exists one remaining problem to resolve--financing the modification of existing roadways. Appropriations must come from State and Federal Funds. This again means looking for the most economical solution. The proposed system should not require destruction of present highways or addition of new lanes. One could, however, consider drilling holes and/or making diamond saw cuts in the highway, so long as the strength and reliability was not disturbed.

A Bureau of Public Roads official indicated that funds could be made available for installation of the system provided it was deemed a necessary improvement. Eventually the U.S. Congress would have to pass new legislation to cover installation costs on a nationwide basis. The approach that must be used, however, is to first build a closed test track to thoroughly test the system as well as publically demonstrate it. The next step would be to modify an extensive stretch of highway and to test many experimental vehicles under all

conditions of traffic and weather. The success of these tests would then serve as a basis for further expansion of roadway and the actual marketing of the automatic vehicle.

TABLE I

<u>YEAR</u>	<u>No. of Deaths</u>	<u>Death Rate/100 million miles</u>
1933	31,363	15.6
1941	39,969	12.0
1953	37,955	7.0
1961	38,091	5.2
1962	40,804	5.3
1963	43,600	5.5
1964	47,700	5.2
1965 (First 6 Mo.)	21,920	5.2

All Statistics from Journal of Civil Engineering
October 1964 pages 38-40

or

Traffic Safety Magazine
September 1965

II. VEHICLE DYNAMICS

A. Introduction

Before a control system can be developed, it is important that the vehicle and its parameters be investigated. Once this has been completed, certain assumptions can usually be made to simplify the fundamental problem - that of controlling the vehicle. The following discussion will introduce the assumptions that will be made, and justify their validity by considering the range and magnitude of error that can be expected.

B. Assumptions and Definitions

It is known that the wheels of a vehicle, both front and rear, do not roll in the same plane as they are fixed while negotiating a curve. The angle(s) between these planes is a function of numerous vehicle parameters. Also, the vehicle's longitudinal axis becomes inclined with respect to the tangential velocity vector of the vehicle. With these facts in mind, it is convenient to assume for small lateral accelerations or large radius turns (i.e. turnpikes and expressways) that the aforementioned angles involved are small. Also, the response time and output signal of the control system is assumed not to vary appreciably if these angles are neglected. Therefore, the assumptions to be substantiated read: a) the wheels roll in the same plane they are fixed relative to the vehicle. b) the longitudinal inclination with respect to the tangential velocity vector can be neglected.

From geometry considerations, lines drawn perpendicular to the plane of the front wheels intersect on a line drawn through the rear axle. The intersection point is called the steering center, this system being known as the Ackermann principal of steering. It can be noted that the front wheels are never parallel when the vehicle is turning. Refer to Figure 1. Also, as mentioned previously, the rolling plane of the wheels is not the same as the plane of the wheels when the vehicle is turning. Therefore, the perpendiculars to the wheels do not meet at the theoretical steering center. It is desired to determine the magnitude of deviation in the steering center, from that of being on the rear axle center line when the rolling plane is assumed the same as the wheel plane.

It is assumed that the frequency of the control system is not of the same order as the natural frequency of the vehicle. If the frequencies are of the same order of magnitude, reinforcement will occur and the vehicle may become unstable. Calculations must be made to determine the relative ratio of frequencies to insure stability.

Aerodynamic forces are neglected. It is difficult to estimate the magnitude, direction, and rate of application of these forces. Also, without extensive testing, the center of pressure (the point where these forces act - not the same as the center of gravity of the vehicle) is difficult to determine.

FOREWORD

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- (5) Development of entry and exit control methods.
- (6) Development of emergency override operation and other safety features."

Realizing that an exhaustive study and development of the total system would be impossible in the fourteen weeks allotted for the course, it was decided to reduce the system requirements as will be described below. However, care was taken to ensure that the over-all activities of the group included a broad range of the original problem, giving each individual an opportunity to work in a specific area, rather than concentrating a

DEFINITIONS:

In cornering, a tire (front or rear) is subjected to side forces and will deflect like any other elastic body. If the tire is rolled along a flat surface in this deflected condition, it will diverge from the path that would have been in line with the wheel plane. The angle between the plane of the wheel and the divergent path is defined as the slip angle, α .⁽³⁾ See Figure 2, and "Nomenclature" Figure 3.

If the slip angles of the front and rear tires of a vehicle are equal, the vehicle's path is a straight line. However, if the front and rear tires are deflected by different amounts, the vehicle's path will be curved. Any change in curvature of the vehicle's path will result in a change in centrifugal force (i.e. a change in the forces acting on the tires). This, in turn, changes the deflection of the tires (i.e. the slip angle) which again changes the curvature of the vehicles path. This process continues until the vehicle completes the turn.⁽³⁾

"Slip angles can cause a (vehicle) to be 'steered' or deviated from its path by factors other than a change in the angle of the steering wheels."⁽³⁾ Several of these factors may be listed:

- a) Changes in centrifugal force or lateral acceleration effect the slip angles as can be seen in Figures 4, 5, and 6 for a typical vehicle.
- b) Slip angles are also determined by changes in the plane of the wheels, due to suspension deflection

NOMENCLATURE

AT	Self-aligning torque, ft. - lbf.
a	Distance of vehicle c.g. to front wheel, ft.
b	Distance of vehicle c.g. to rear wheel, ft.
I_z	Moment of inertia of total mass about z-axis, slug - ft ² .
L	Roll moment about x-axis, ft. - lbf.
l	Wheelbase, ft.
M	Total mass of vehicle, slugs.
M_s	Sprung mass, slugs.
N	Yaw moment, ft. - lbf.
p	Roll velocity about the x-axis, radians per sec.
r	Yaw velocity about the z-axis, radians per sec.
V	Forward velocity, ft. per sec.
v	Lateral velocity, ft. per sec.
Y	Force along y-axis, lbf.
Z or F_n	Vertical load on tire, lbf.
α	Tire slip angle, radians.
β	Side slip angle, radians.
σ	Camber angle, radians.
δ	Front wheel steer angle, radians.
ϵ	Roll steer, radian per radian.
ϕ	Roll angle, radian
ω_n	Circular natural frequency, radians per sec.

Figure 3. Nomenclature

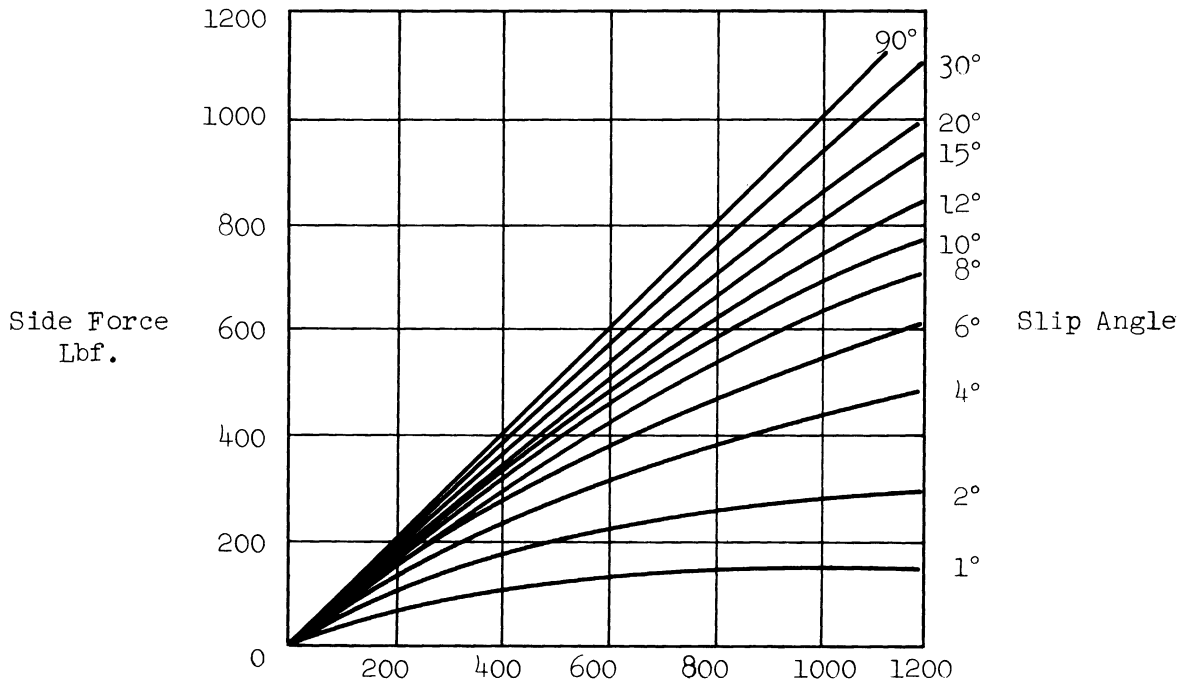


Figure 4. Slip Angle Characteristics for Typical Tire Without Camber

(From J. Hall - Reference 3)

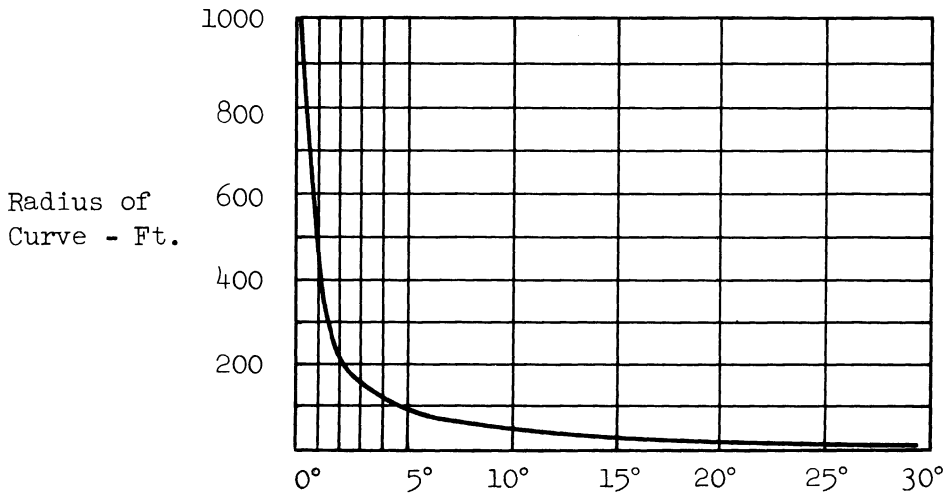


Figure 5. Difference of Front and Rear Slip Angles - Wheelbase = 9 Ft

(From J. Hall - Reference 3)

or to 'camber'. The front wheels of some vehicles are inclined with respect to the vertical. This angle is referred to as camber.⁽³⁾ See Figure 7 and 8.

- c) Due to lateral weight transfer, the vertical forces acting on the tires change, thus effecting the slip angles. Vertical forces acting on the wheels (tires) are affected by roll steer. "Roll steer effects are self-steering effects, caused by the roll of the body due to centrifugal force. Roll steer doesn't change the slip angles, but moves the wheels compensate for them."⁽⁵⁾ The two forms of roll steer are: Toe change, i.e. a change in the wheel's direction of travel, and camber change, i.e. the change in the angle between the wheel and the road surface.
- d) Changes in the vertical force due to acceleration or deceleration effect the slip angles. The vertical forces also vary for each wheel due to the weight bias of weight distribution of the vehicle. See Figure 4.
- e & f) Variations in the plane of the road surface and aerodynamic forces alter the vehicle's suspension geometry, in turn changing the slip angles of the tires.⁽³⁾ These forces are highly unpredictable and irregular.

Returning to the discussion of slip angle and the path the vehicle travels, two additional effects, namely, understeer and over steer, can be defined. If the change (rate) in the slip angles of the front wheels is greater than the change

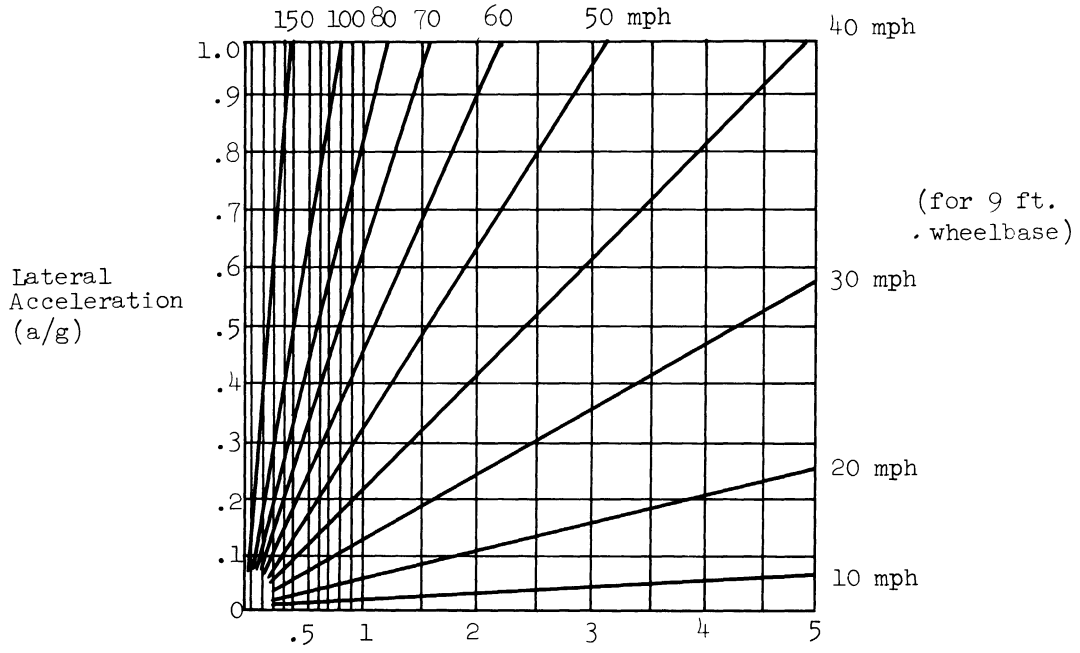


Figure 6. Angle Between Paths of Front and Rear Wheels

(From J. H

(From J. Hall - Reference 3)

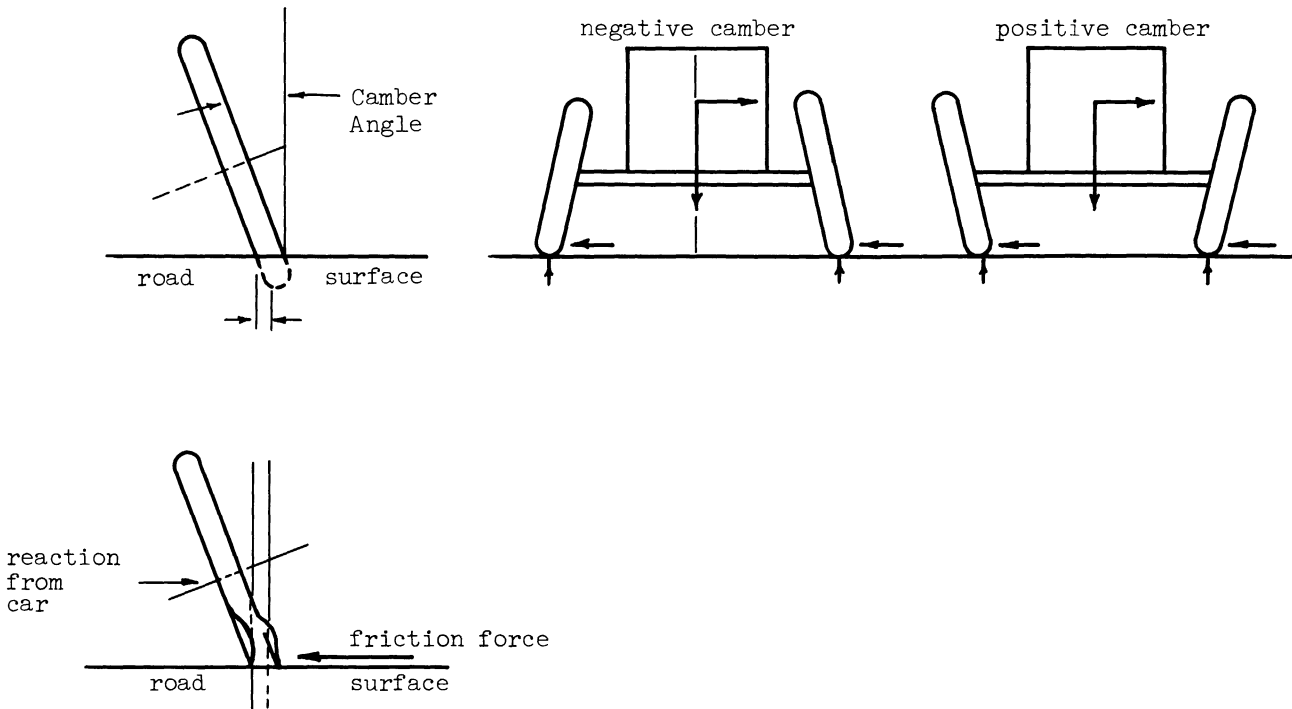


Figure 7. Schematic of Wheel Camber

(From J. Hall - Reference 5)

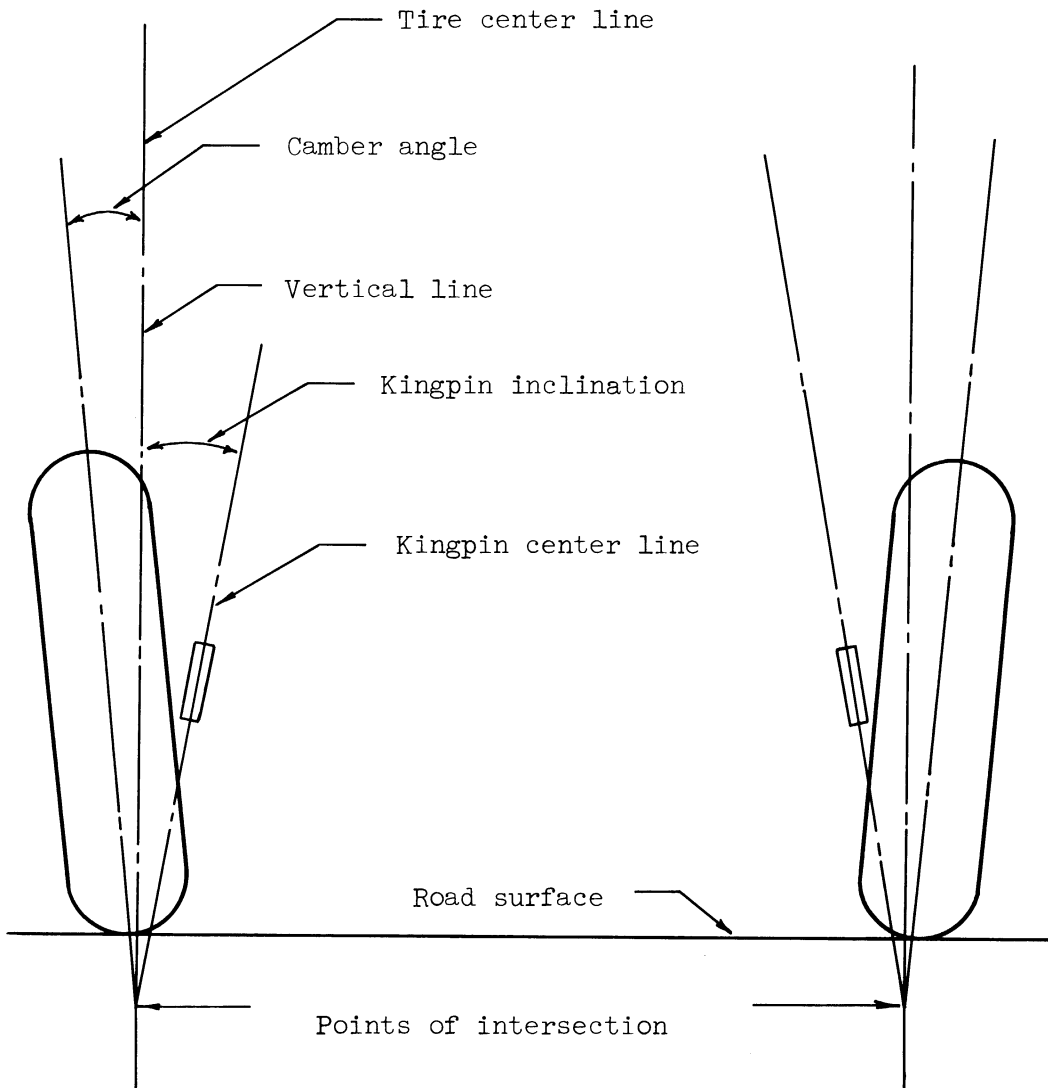


Figure 8. Camber Angle and Kingpin Inclination

(From I. Frazee and E. L. Bedell - Reference 6)

in slip angles of the rear wheels, the radius of curvature of the vehicle's path becomes larger. The centrifugal force is reduced and the vehicle eventually is brought back to a state of equilibrium. Such an understeering vehicle "will seek that radius which results in a balance of forces independent of the driver's reactions"⁽³⁾. On the other hand, if the change in slip angles of the rear wheels is greater than the change in slip angles of the front wheels the vehicle will steer into a path of decreasing radius of curvature and increasing centrifugal force which further reduces the curvature. If the rate of change of these slip angles in this oversteering vehicle are sufficiently rapid, the vehicle could become uncontrollable. If the rate of change of the front and rear slip angles is equal, the condition is called neutral steer.⁽³⁾ An additional definition of oversteer and understeer, which is more precise but more difficult to visualize, will be given. A vehicle will "understeer if the change in steer angle, δ , per unit change in lateral acceleration is greater than the change in steer angle per unit change in lateral acceleration for a neutral steer vehicle. If the change in steer angle per unit change in lateral acceleration is less than for a neutral steer vehicle, the vehicle will oversteer."⁽⁷⁾ Understeer and oversteer are demonstrated by the steady state properties shown in Figure 9. It is known that an oversteering vehicle becomes unstable at a speed which the steer angle due to rollsteer and slip

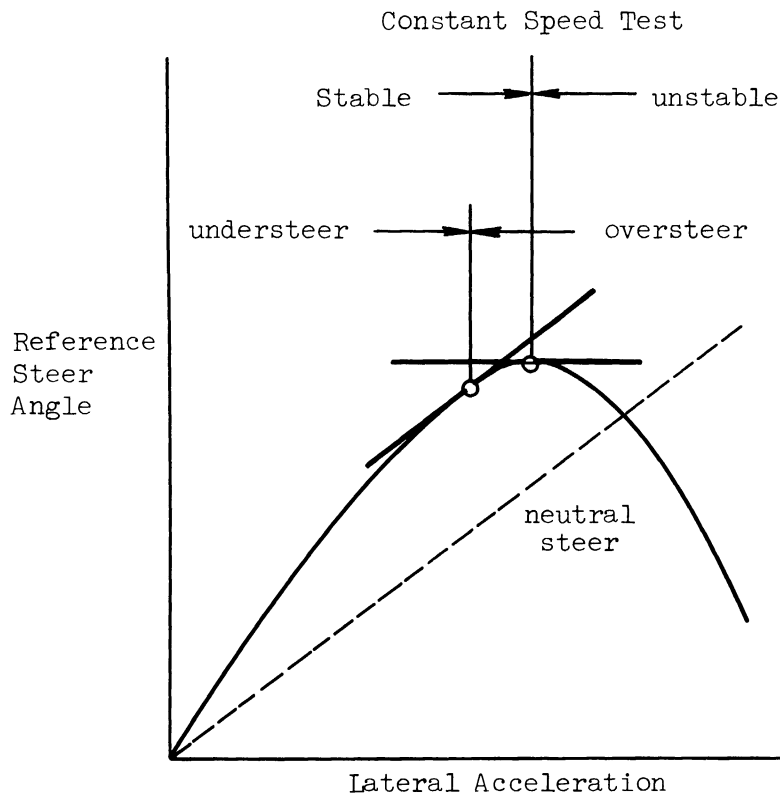


Figure 9. Effect of Understeer and Oversteer

(From D. L. Nordeen - Reference 7)

angle effects equals the steer angle due to the geometry of the turn.⁽⁷⁾ To avoid the complexities of an oversteering vehicle, a understeering vehicle, such as a great percentage of American sedans, will be chosen.

Side slip angle, β , is the term used to describe a vehicle's inclination to its velocity vector (i.e. the angle between the body and the tangent to the path). Its value is the ratio of the vehicle's lateral velocity, v , to its forward velocity, V .⁽⁸⁾

C) Mathematical Assumptions, Equations, and Calculations

A "linear (mathematical) model is valid for predicting the effects of changes in any of the chassis and tire parameters for maneuvers which have lateral accelerations of less than 8 ft/sec^2 ".⁽⁷⁾ It is known that the approximate minimum expressway radius is 3,000 feet which corresponds to approximately .11g lateral acceleration at 70 mph.⁽³⁾ Therefore, the lateral accelerations in this problem are well below the 8 ft/sec^2 limit and linear equations will be applicable.

The vehicle may be assumed to have constant forward velocity, V . "The constant speed test is really more meaningful because we drive more nearly at constant speed... We find very few driving maneuvers for which we control lateral acceleration by controlling forward speed."⁽⁷⁾

The co-ordinate system used will be fixed on the vehicle and moving with it. "The x axis is parallel to the ground through the point where the (vehicle's) actual rolling axis

intersects the z-axis, which, in turn, is perpendicular to the ground through the center of gravity of the whole (vehicle)".⁽⁹⁾ See Figure 10.

It is desired to find the relative magnitude of the slip angle, α , and the steering angle, δ . Refer to Figure 2. The slip angle and steering angles are related by the following equations:⁽⁴⁾

$$\alpha_F = \beta + \frac{ar}{V} - \delta + \epsilon_F \phi$$

$$\alpha_R = \beta - \frac{br}{V} + \epsilon_R \phi$$

where subscripts F and R refer to the front wheels and rear wheels respectively.

Because of the Ackermann steering principal, each wheel will have a slightly different steering angle. For calculation purposes these angles will be assumed equal.

The front roll steer term, $\epsilon_F \phi$, is usually equal to zero because the roll steer of both front wheels is opposite and cancels when stabilizing bars or tie bars are used. The quantities, b, a, and ϵ are known for a given vehicle. The velocity, V, is assumed to be the maximum legal speed of 70 mph. (103 ft/sec).

To calculate the slip angles and the steering angle, additional equations are required. The equations of motion or inertial reactions can be written for the vehicle about its center of gravity and then transposed to the co-ordinate

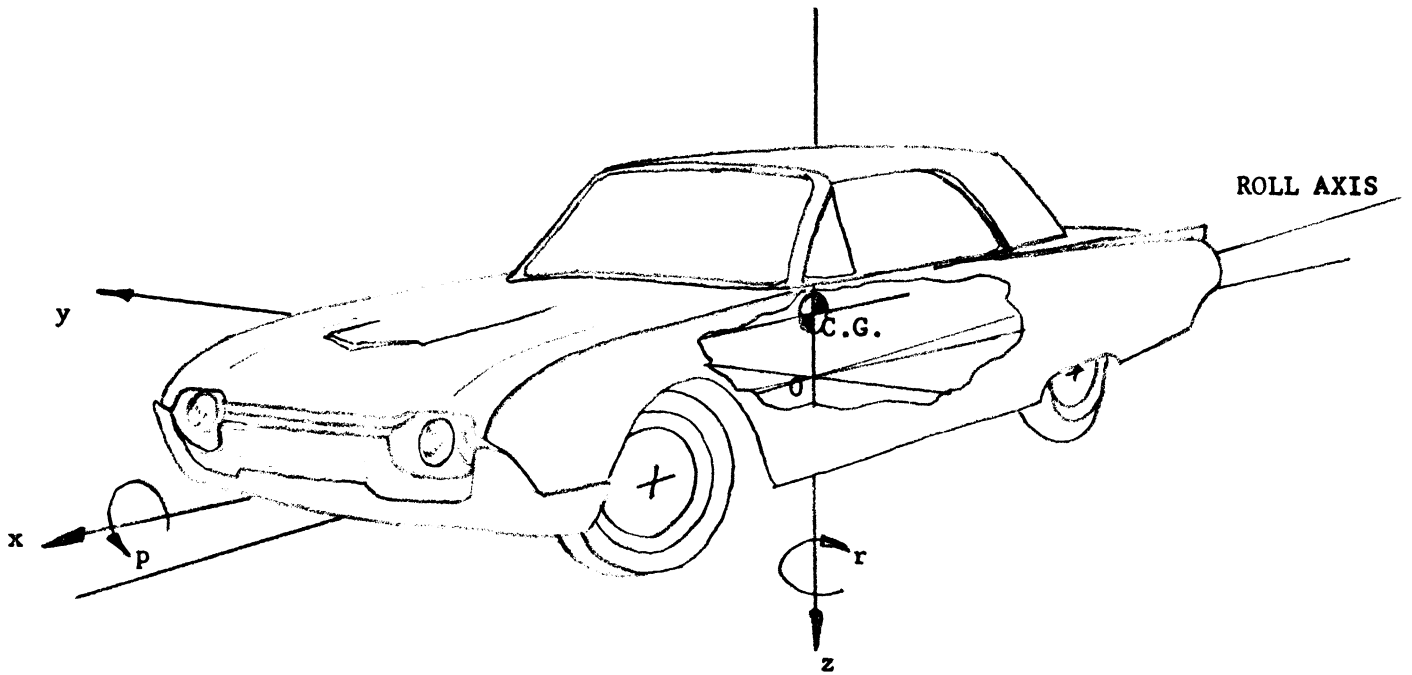


Figure 10. Co-ordinate System

(From F. N. Beauvais, C. Garelis,
and D. H. Iacovoni - Reference 4)

system fixed on the vehicle. These equations are: (9)

$$\begin{aligned}\Sigma Y &= M(\dot{v} + Vr) + M_s h \dot{p} \\ \Sigma N &= I_z \dot{r} + I_{xz} \dot{p} \\ \Sigma L &= I_x \dot{p} + M_s h(\dot{v} + Vr) + I_{xz} \dot{r}\end{aligned}$$

If steady state is assumed the equations become: (10)

$$\begin{aligned}\Sigma Y &= MVr \\ \Sigma N &= 0 \\ \Sigma L &= M_s(hVr)\end{aligned}$$

These inertial reactions can be equated to the summation of the external forces (reactions between the road and the tires). The equations when expanded can be expressed as: (9)

$$\begin{aligned}\Sigma Y &= \frac{\partial Y}{\partial \beta} \beta + \frac{\partial Y}{\partial r} r + \frac{\partial Y}{\partial \delta} \delta + \frac{\partial Y}{\partial \phi} \phi \\ \Sigma N &= \frac{\partial N}{\partial \beta} \beta + \frac{\partial N}{\partial r} r + \frac{\partial N}{\partial \delta} \delta + \frac{\partial N}{\partial \phi} \phi + \frac{\partial N}{\partial p} p \\ \Sigma L &= \frac{\partial L}{\partial p} p + \frac{\partial L}{\partial \phi} \phi\end{aligned}$$

If steady-state and large radius turns are assumed, the roll steer effects will be small and can be neglected. (10) Letting,

$$Y_\beta = \frac{\partial Y}{\partial \beta}, Y_r = \frac{\partial Y}{\partial r}, \dots \text{etc,}$$

the equations under these conditions are:

$$MVr = Y_\beta \beta = Y_r r + Y_\delta \delta$$

$$0 = N_{\beta} \beta + N_r r + N_{\delta} \delta$$

The steady state non-rolling equations can be solved simultaneously for the steering angle, δ . (10)

$$\delta = r \left[\frac{N_{\beta}(Y_r - MV) - Y_{\beta}N_r}{Y_{\beta}N_{\delta} - N_{\beta}Y_{\delta}} \right]$$

The external reaction terms Y_{β} , Y_r , Y_{δ} , N_{β} , N_r , and N_{δ} can be expressed as functions of the assumed linear tire and suspension characteristics. (9)

$$Y_{\beta} = C_1 + C_2 = C$$

$$Y_r = C_1 \frac{a}{V} - C_2 \frac{b}{V}$$

$$Y_{\delta} = - C_1$$

$$N_{\beta} = aC_1 - bC_2 + \frac{\partial AT}{\partial \alpha_F} + \frac{\partial AT}{\partial \alpha_R} + \frac{\partial x}{\partial x} (C_1 Z_F + C_2 Z_R)$$

$$N_r = C_1 \frac{a^2}{V} + C_2 \frac{b^2}{V} + \frac{\partial AT}{\partial \alpha_F} \frac{a}{V} - \frac{\partial AT}{\partial \alpha_R} \frac{b}{V} + \frac{\partial x}{\partial Z} \left(\frac{Z_F C_1 a}{V} - \frac{Z_R C_2 b}{V} \right)$$

$$N_{\delta} = - aC_1 - \frac{\partial AT}{\partial \alpha_F} - \frac{\partial x}{\partial Z} Z_F C_1$$

"AT" is the self aligning torque. The lateral force generated between the tire and the road for small slip angles is approximately triangular. See Figure 11. The result force distribution is offset to the rear of the central wheel plane, therefore accounting for the aligning torque. The offset distance is approximately 1 1/2 inch. (2) "Although the aligning torque is a function of slip angle, camber angle, and

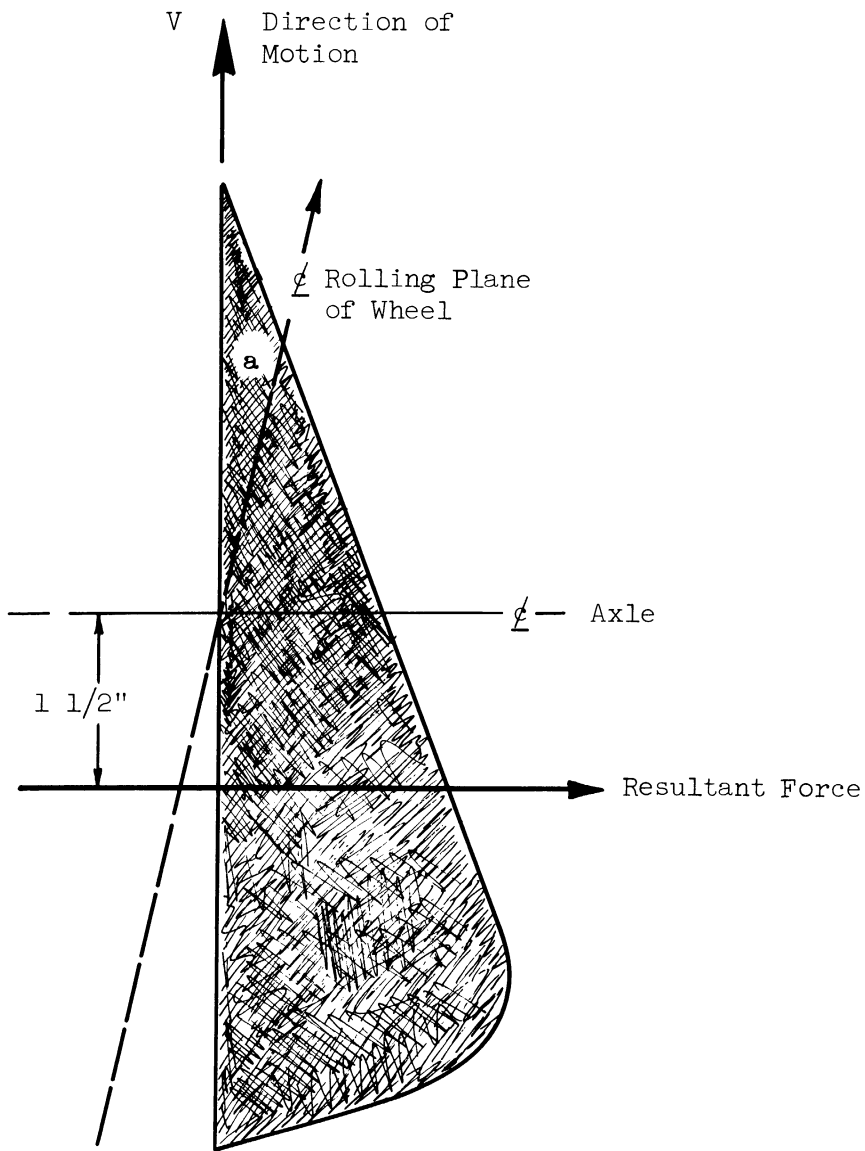


Figure 11. Distribution of Lateral Force of a Rolling Tire

(From J. R. Ellix - Reference 10)

vertical load, its effect on the overall vehicle behavior is relatively small"⁽¹⁾. The quantity $\frac{\partial AF}{\partial \alpha}$ can be found from the slope of the curve of AF vs. α under the conditions of operation. (Such curves may be found on Page 5 of SAE 295-C, 1961 report.) For this discussion, the self-aligning torque will be ignored.

The terms, $\frac{\partial x}{\partial Z}$, are the result of rolling resistance arising from unsymmetrical loading. If the loading is symmetrical these terms are zero.

Substituting the external reaction terms into the steering angle equation, the following equation results:⁽²⁾

$$\delta = \frac{(a+b)r}{v} + \frac{Mv_r}{a+b} \left(\frac{a}{C_2} - \frac{b}{C_1} \right)$$

similarly for side slip angle:

$$\beta = \frac{\delta(aC_1) - \frac{r}{v} (C_1a^2 + C_2b^2)}{C_1a - C_2b}$$

Using these two equations and those developed previously relating the slip angle, steering angle, and side slip angle, (neglecting roll) namely,

$$\alpha_F = \beta + \frac{ar}{v} - \delta$$

$$\alpha_R = \beta - \frac{br}{v}$$

the magnitude of these parameters can be calculated.

"From small vehicle side slip angles, β , the velocity, V , along the x axis is equal to the resultant velocity."⁽⁹⁾
(i.e. $V_T \simeq V$ for calculation purposes) See Figure 2.

A typical vehicle may be chosen having the following properties. (4)

$$a = 4.81 \text{ FT.}$$

$$b = 5.02 \text{ FT.}$$

$$M = 144.9 \text{ SLUGS} = 4660 \text{ LBF}$$

$$I_Z = 3372 \text{ SLUG} \cdot \text{FT}^2$$

$$V = 70 \text{ MPH} = 103 \text{ FT/SEC}$$

$$R = 3,000 \text{ FT.}$$

The weight distribution is:

$$\frac{5.02}{4.81 + 5.02} \times 100 = 51\% \text{ on front}$$

$$\frac{4.81}{4.81 + 5.02} \times 100 = 49\% \text{ on rear}$$

The normal force on each front wheel is:

$$4660 \text{ LBF} \times .51 \times \frac{1}{2} = 1190 \text{ LBF}$$

on each rear wheel:

$$4660 \text{ LBF} \times .49 \times \frac{1}{2} = 1140 \text{ LBF}$$

It is desired to calculate the cornering coefficients C_1 and C_2 . From Figure 12, a plot of lateral force on each tire versus the slip angle for particular normal loads can be made. See Figure 13. Taking the slope of each curve the cornering coefficients can be found:

$$C_1 = \frac{\partial Y}{\partial \alpha} F_N \quad F_N = 1190 \text{ LBF}$$

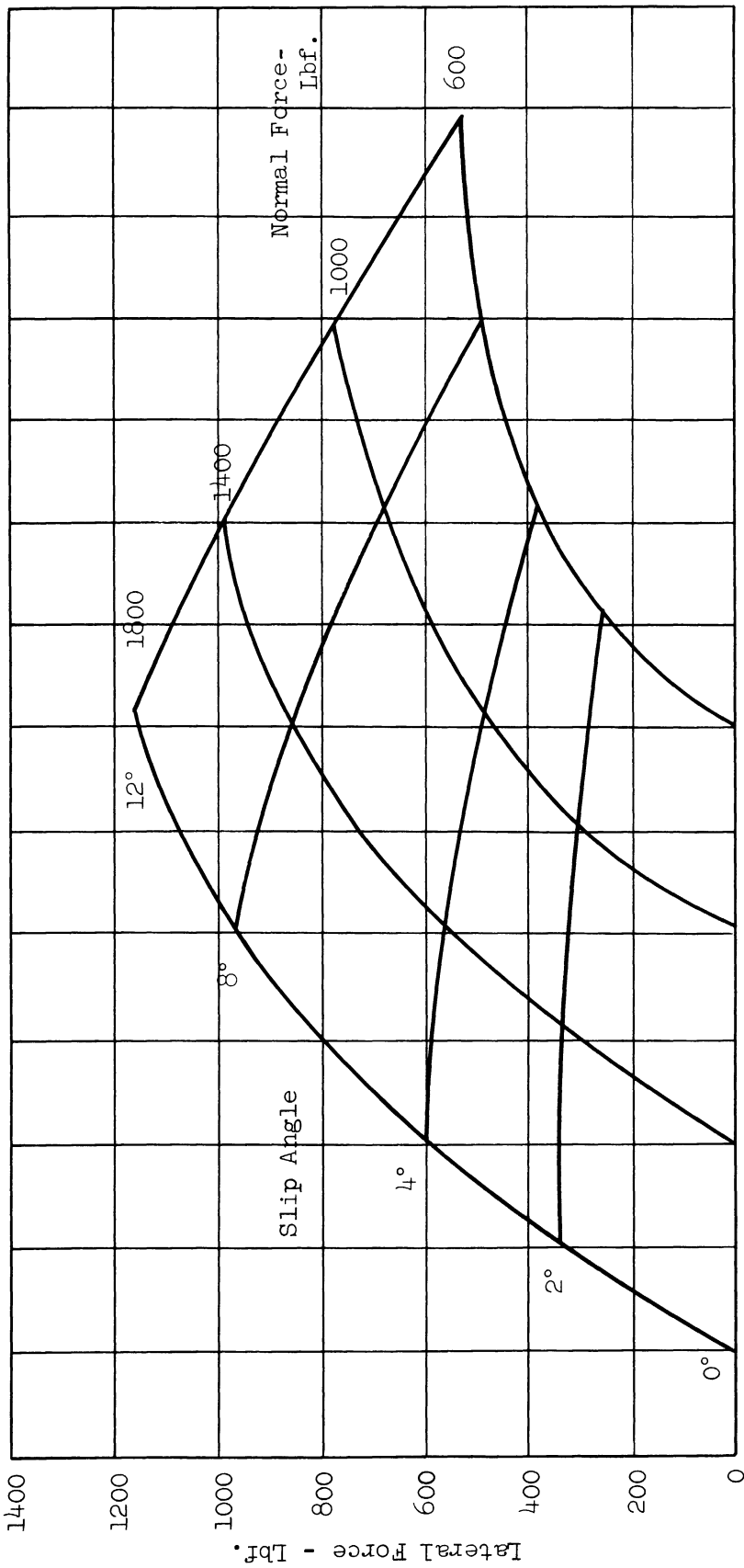


Figure 12. Lateral Force vs. Slip Angle and Normal Force "Generalized" for 7.60-15 Tires at 28 Psi

(From D. L. Nordeen - Reference 7)

Curve A: $F = 1190$ Lbf.

Curve B: $F_n = 1140$ Lbf.

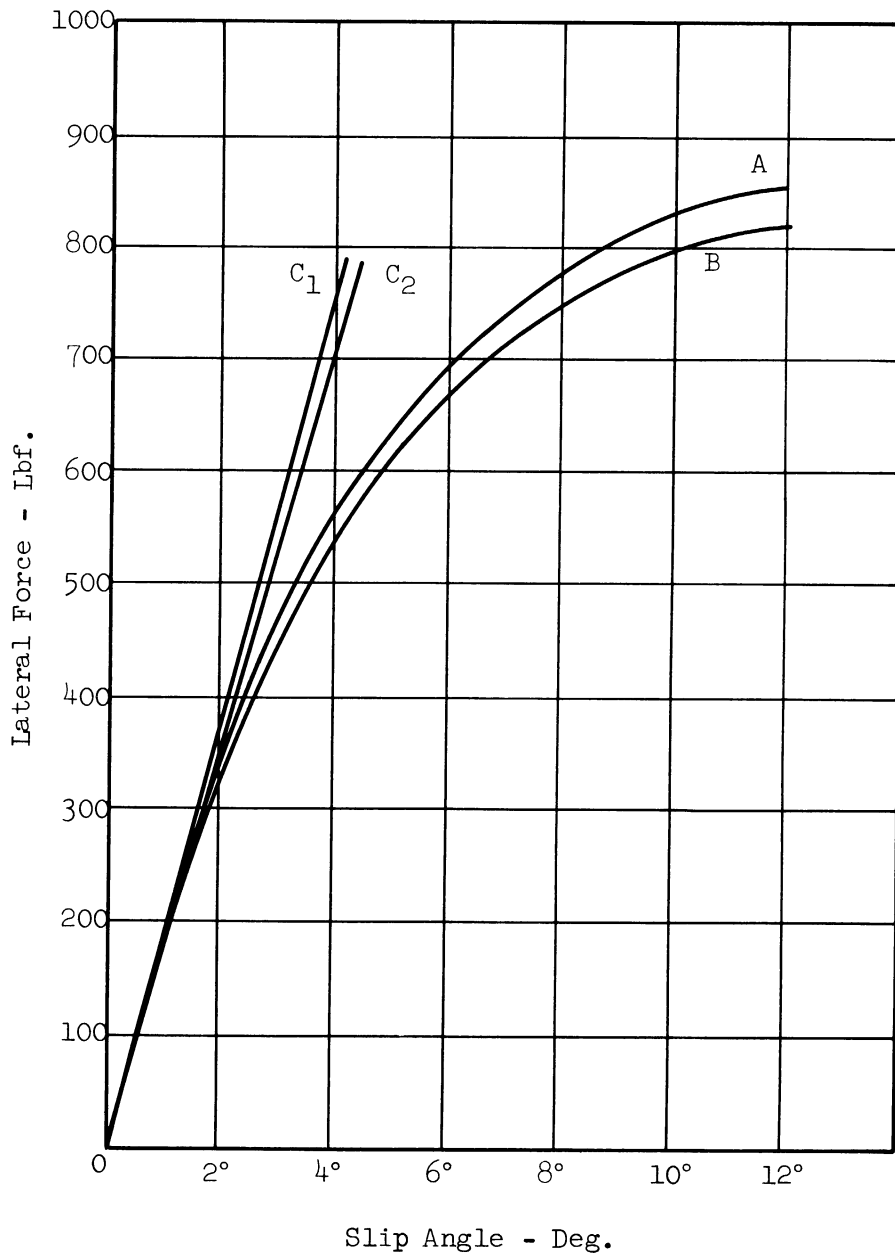


Figure 13. Lateral Force vs. Slip Angle and Normal Force

$$C_1 = 187.5 \frac{\text{LBF}}{\text{DEG}} \times \frac{57.2 \text{ DEG}}{\text{RAD}} = 10,700 \frac{\text{LBF}}{\text{RAD}}$$

$$C_2 = \frac{\partial Y}{\partial \alpha} F_N \quad F_N = 1140 \text{ LBF}$$

$$C = 180 \frac{\text{LBF}}{\text{DEG}} \times 57.2 \frac{\text{DEG}}{\text{RAD}} = 10,300 \frac{\text{LBF}}{\text{RAD}}$$

If the vehicle's path is circular, then the relation $V = rR$ is true. Rewriting the equation for steering angle, δ is:

$$\delta = \frac{a+b}{R} + \frac{1}{a+b} \left(\frac{a}{C_2} - \frac{b}{C_1} \right) \frac{MV^2}{R}$$

$$\delta = \frac{(4.82 + 5.02)}{3000} + \frac{1}{(4.82 + 5.02)} \left(\frac{4.82}{10,700} - \frac{5.02}{10,300} \right) \frac{(144.9)(103)^2}{3000}$$

$$\delta = .003103 \text{ RAD}$$

Solving for the side slip, the equation now reads

$$\beta = \frac{aC_1\delta - \frac{(C_1a^2 + C_2b^2)}{R}}{aC_1 - bC_2}$$

$$\beta = \frac{(4.82)(10,700)\delta - \frac{(10,700)(4.82)^2 + (10,300)(5.02)^2}{3000}}{(4.82)(10,700) - (5.02)(10,300)}$$

$$\beta = .00272 \text{ RAD}$$

Since β and δ are now known, the front slip angle, α^F , can be found from:

$$\alpha^F = \beta + \frac{ar}{v} - \delta, \text{ and } \frac{1}{R} = \frac{r}{V}$$

$$\alpha_F = .00272 + \frac{4.82}{3000} - .003103$$

$$\alpha_F = .00122 \text{ RAD}$$

Similarly, using the equation:

$$\alpha_R = \beta - \frac{br}{v}, \text{ and } \frac{1}{R} = \frac{r}{V}$$

$$\alpha_R = .00272 - \frac{5.02}{5000}$$

$$\alpha_R = .00105 \text{ RAD}$$

D. Conclusion

It can be seen that under the conditions presented in this problem, the front slip angle, α , is much smaller than the steering angle, δ , (i.e. $\delta > \alpha$). Thus, it is safe to assume that the front wheel is rolling in the same plane as it is fixed.

The rear slip angle is found very small and essentially equal to zero. Going back to the Ackermann principal of steering, it is found from these calculations and assumptions that the slip angles may be neglected; and, therefore, the perpendiculars to the wheels will meet at a common point if they are extended far enough.

It is interesting to determine from these calculations if a given vehicle is directionally stable. From the work of Segal, a vehicle will always be directionally stable (i.e. will understeer) if $C_1b > C_2a$. (10)

From the data used to calculate the slip angles, side slip, and steering angle, it is found that:

$$C_2^b - C_1^a = (10,300)(5.02) - (10,700)(4.82) = \\ + 250 \frac{\text{LBF} - \text{FT}}{\text{RAD}}$$

$$\therefore C_2^b > C_1^a$$

and the vehicle is shown to be directionally stable. Finally, it will be necessary to compare the oscillatory natural frequency, ω_n , of the vehicle to that of the control system.

$$\omega_n \text{ of the vehicle} = \frac{N_B}{I_z} - \frac{Y_r N_B}{M V I_z} + \frac{Y_E N_r}{M V I_z} \quad \text{Ref. (9)}$$

$$\omega_n = 1.398 \frac{\text{RAD}}{\text{SEC}}$$

At this time, an accurate description of ω_n for the overall control system has not been determined, other than that for the steering system. However, once the complete system has been specified, including actuators, servo mechanisms etc., the natural frequency must be found either numerically or experimentally and compared to ω_n outlines above. If necessary, compensation techniques should be used to insure that reinforcement does not occur.

III. SYSTEM DESIGN

A. Specifications

The following is a brief description of the sub-system assignments:

- a) Steering Control - The system must direct the vehicle along a specified path to a pre-determined destination without introducing any discomfort to the passengers because of large lateral accelerations or undue oscillations. The analysis should also include an analysis of the steady state and transient response of the system, as well as a complete stability check.
- b) Speed Control - The vehicle must be capable of maintaining relatively constant speeds, in accordance with the requirements of the spacing control, weather conditions, central control, etc..
- c) Spacing Control - It is necessary that the system maintain a safe distance between vehicles, being able to detect both moving and stationary obstructions in the highway.
- d) Mechanics - Given an error signal from the sensing systems, and understanding the effect of such vehicle parameters as slip, roll, etc. upon the operation of the vehicle, it is necessary to actuate and control the individual mechanisms of steering, braking, and accelerating.

In that economic feasibility is perhaps the most important factor that must be considered before any actual design or development can take place, it is necessary to consider a system which is capable of gradually merging with the present highway systems. In other words, it is desirable that the controlled vehicle operate satisfactorily in the presence of both controlled and noncontrolled vehicles while introducing no additional hazards to the existing system.

It was furthermore decided that the primary consideration of the study would be the flow of traffic along an intercity expressway, independent of entrance-exit congestion problems. The expressway is assumed to be a conventional divided highway, two lanes in each direction, carrying traffic at approximately seventy miles per hour.

The following system analysis includes both a statement of the proposed system and a brief analysis of many systems considered. Although several proposed methods of detection and control are desirable from a technical standpoint, prohibitive costs and/or present highway and vehicle construction may render such systems ineffective. However, unforeseen changes or technical advance in the near future may increase the acceptability of such systems, making their mention worthwhile.

With these specifications in mind, the specific subsystem designs can now be considered.

B. Steering

1. Introduction

Development of an automatic steering device reduces to the following:

- a) Determining a suitable reference for guidance
- b) Developing sensing devices to relate vehicle position the reference
- c) Developing actuation devices to reduce the error between the actual and desirable vehicle position
- d) Specifying power supplies

Also, it is desirable to know vehicle velocity, making it possible to adjust the steering for different speeds. In addition, the approximate transfer characteristics of vehicle performance should be known, and care should be taken to insure a comfortable ride.

Finally, a complete stability and overall performance analysis must be made, analogs and experimental vehicles should be developed, and the necessary refinements incorporated until suitable performance is achieved.

2. Design

The reference to be used for determining the path of the vehicle is a buried cable in the center of the lane, similar to that used by General Motors Research⁽¹¹⁾ and RCA Laboratories⁽¹²⁾. This cable is to be electrically excited and detectors (tuned antennas) can be used to determine the vehicle's position relative to the cable. The excitation

frequency of the cable will be low enough so that transmission of a detectable signal will not be a problem, i.e., the cable will be "electrically short" so that standing waves, reflection, etc., will not become a major problem.

Although a buried cable at first seems undesirable from economical viewpoint, it has been reported that such an installation might cost little more than the continual painting of the white lines over a period of years⁽¹³⁾. In fact, interest has been expressed by the highway engineers in developing such an instrument, specifically to aid in guidance of a high speed truck for painting the lane markings.

Having a suitable reference, there are several possible methods that can be used to actually "locate" the vehicle. One operating system developed by General Motors^(13,14) consists of two tuned coils mounted on either side of the vehicle's centerline, in a plane parallel to the buried cable and the centerline. (See Figure 14). The signals from the two coils are then compared, and a difference activates a steering servo so as to continually position the vehicle over the centerline, and consequently keep the error signal at zero.

While such a system is apparently functional, recent investigations⁽¹⁵⁾ suggest that the stability of the system could be greatly improved by adding an additional input signal and/or additional feed-back. Additional input signals could be proportional to the radius of curvature of the

centerline, proportional to the angle between the chassis and the centerline, or proportional to the angle between the front wheels and the centerline. Of these possibilities, the most promising seems to be a system utilizing an input proportional to the displacement of the automobile from the centerline, as mentioned above, and an input proportional to the angle between the front wheels and the centerline. (See Figure 14).

A brief investigation of the suggested improvements is carried out by D. Barrick in "Automatic Steering Techniques." (Reference 15). The analysis for the improved system can be developed as follows:

Consider the vehicle positioned in an xy coordinate system as shown in Figure 15.

We shall define α as the angle between the front wheels and the vehicle frame, and θ as the effective angle of the frame relative to the x axis. As described previously, this effective angle is not the same as the actual wheel angle. Since the control sensors will record the actual angles, a linear approximation will be used to convert such signals to effective values. For convenience, the following development will consider the effective wheel angle equal to the actual wheel angle. Again, it is understood that compensation will be necessary to improve this approximation.

- θ = angle of auto centerline relative to x axis
- α = effective wheel angle with respect to the auto
- γ = effective wheel angle with respect to the buried cable

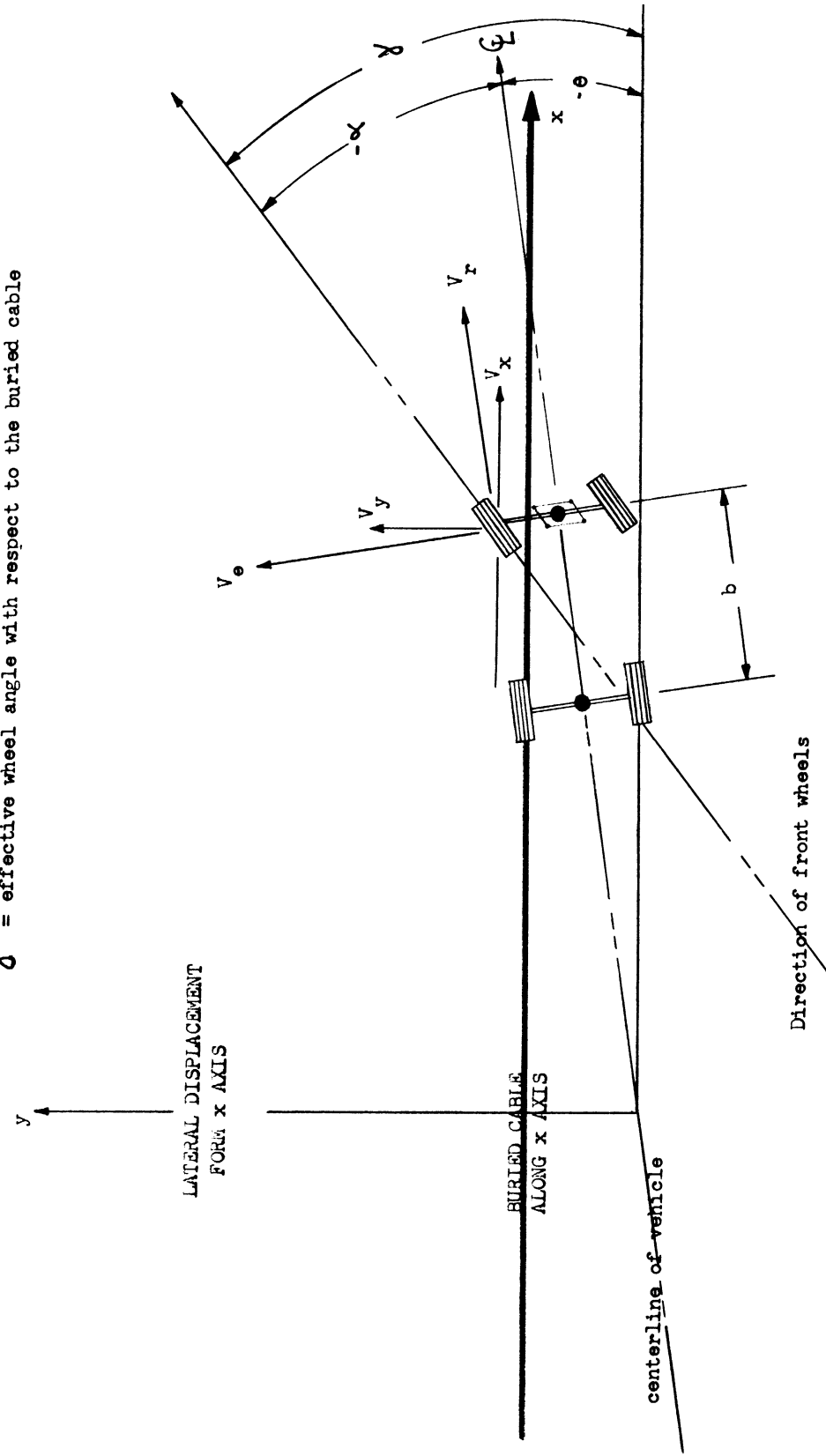


Figure 15. Description of Vehicle Position

(From D. Barrick - Reference 15)

We now wish to determine the position of the moving vehicle relative to the coordinate system as a function of α . To do this, it will be assumed that the vehicle pivots as shown in Figure 15 and as discussed before. The velocity of the vehicle in the x direction will be

$$V_x = V \cos (\theta + \alpha) = \frac{x}{t} \text{ for small } (\alpha + \theta)$$

and $V_y = V \sin (\theta + \alpha) = V(\theta + \alpha)$ for small $(\alpha + \theta)$

V = speed of vehicle.

From Figure 15, it is seen that the component causing θ to increase is V_θ (the velocity in the θ direction). Also, as assumed previously, the change in θ with respect to time can be approximated by

$$\frac{d\theta}{dt} = \frac{V_\theta}{b}$$

where b equals the wheel spacing and V_θ equals $V \sin \alpha \cong \alpha$. Therefore:

$$\frac{V\alpha}{b} = \frac{d\theta}{dt}$$

$$\theta = \frac{V\alpha}{bS}$$

furthermore, $Y = \int Y_y dt \cong \int V(\theta + \alpha) dt$ where Y equals the distance travelled in the y direction over a given period of time. Finally, our relationship between Y and α becomes $\frac{Y}{\alpha} = \frac{V}{S} \left(1 + \frac{V}{bS}\right)$.

In other words, given a wheel angle with respect to a vehicle b units long, we can determine the lateral position of the car. Therefore, the lateral error of the automobile from the center of the lane can be denoted as d and given by:

$$d = Y_{\text{reference}} - Y$$

where $Y_{\text{reference}}$ is the position of the center of the lane with respect to our xy coordinate system.

This distance d will be proportional to the error signal received from the tuned coils positioned on the vehicle chassis, equidistant from the vehicle's centerline.

The second reference measurement we wish to investigate is an input proportional to the angle between the vehicle's front wheels and the centerline. This measurement can be obtained by placing a 3rd coil in a plane perpendicular to the cable, supported so as to pivot with the front wheels; i.e., when the front wheels are turned 5 degrees to the left, the coil also rotates 5 degrees. Note that compensation for slippage can be electrical incorporated at this time if desired. Again referring to Figure 14, it is noted that the voltage induced in this coil will be zero so long as the coil is aligned with the cable. However, rotation of the wheels with respect to the cable produces a voltage which varies approximately linearly for small rotations. Actually, this signal voltage will vary slightly for any given rotation

as the vehicle moves away from the centerline. However, it is possible to minimize this error by proper choice of parameters. (Refer to Reference 15 for a more detailed analysis).

Referring to Figure 16, it is seen that the angle of the wheels, relative to the centerline, is equal to the angle between the centerline and the x axis, minus the angle of the wheels relative to the x axis. Or,

$$\gamma = \phi - \theta - \alpha \quad \text{See Figure 16}$$

where γ = angle between wheels and centerline

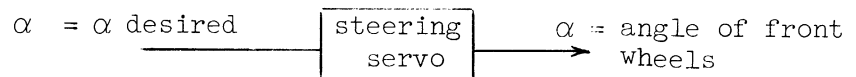
ϕ = angle between centerline and x axis

θ = angle between vehicle and centerline

α = angle between vehicle and the wheels.

The block diagram for this system can now be developed as follows:

Beginning with the steering servo (to be defined later), a signal proportional to the desired angle of the wheels is used to initiate a servo system which rotates the wheels to an angle α .



We now would like an expression for $\gamma = \phi - \theta - \alpha$

Remembering that $\theta = \frac{V\alpha}{BS}$

$$\alpha + \theta = \frac{V}{BS} + \alpha = \alpha \left(\frac{V}{BS} + 1 \right)$$

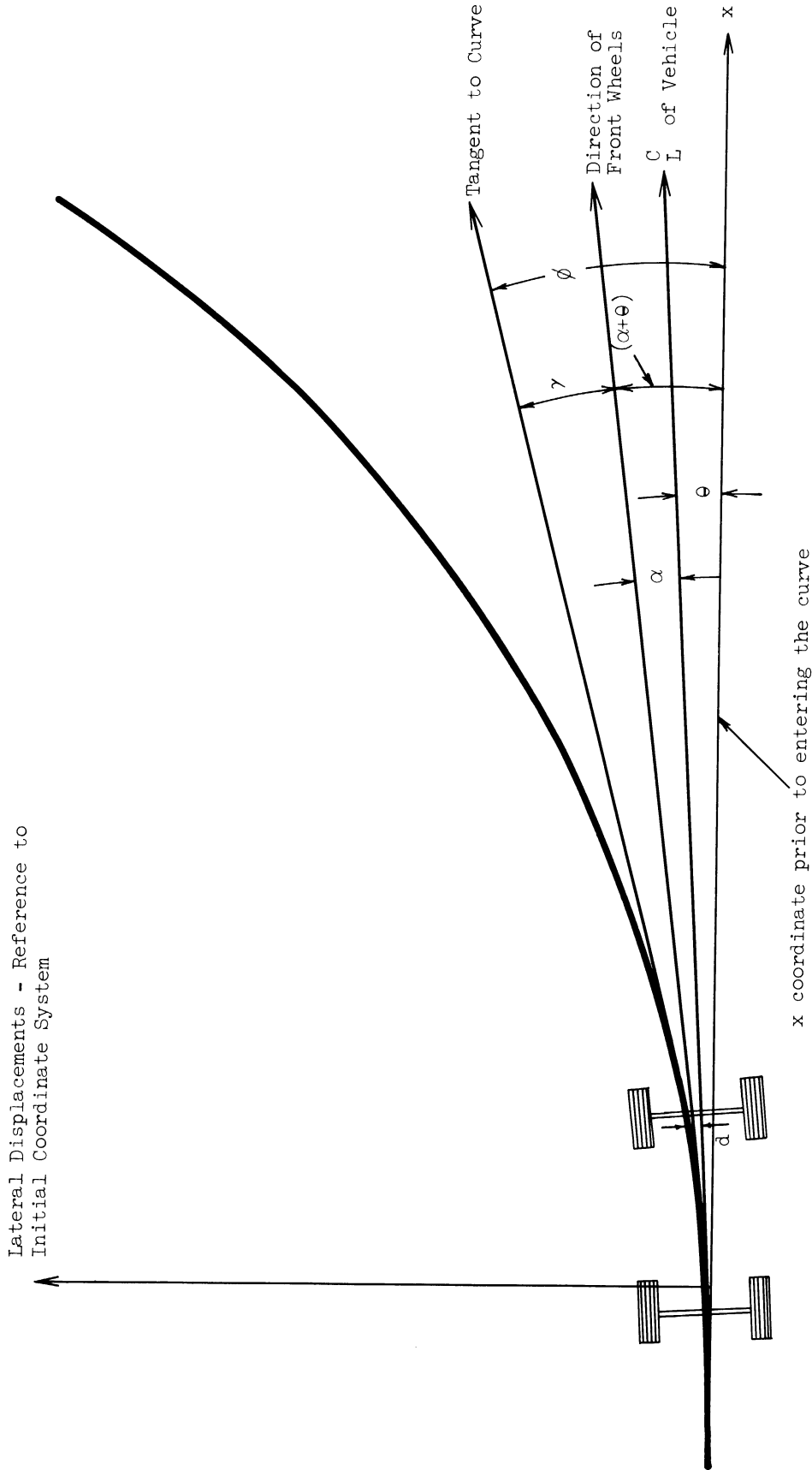
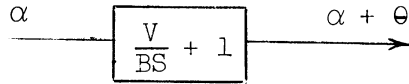
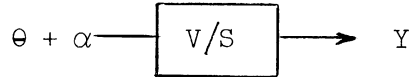


Figure 16. Description of Vehicle Position Upon Entering a Curve (From D. Barrick - Reference 15)

Therefore



Now Y , the actual lateral position of the vehicle, can be found using $Y = \int Y_y dt \approx \int V(\theta + \alpha) dt$
 $= \frac{V}{S} (\theta + \alpha)$



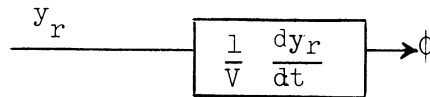
In order to describe $\gamma = \phi - \theta - \alpha$, it is necessary that we have an expression for ϕ . This expression is obtained as follows:

ϕ = angle between the centerline and the x coordinate for small angles

$$\frac{dy_r}{dx} = \text{TAN } \phi = \frac{\text{SIN } \phi}{\text{COS } \phi} \approx \phi$$

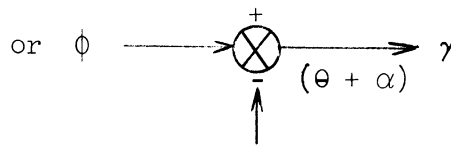
also, $x = vt$

$$\phi = \frac{1}{v} \frac{dy_r}{dt} = \left(\frac{S}{V}\right) y_r$$

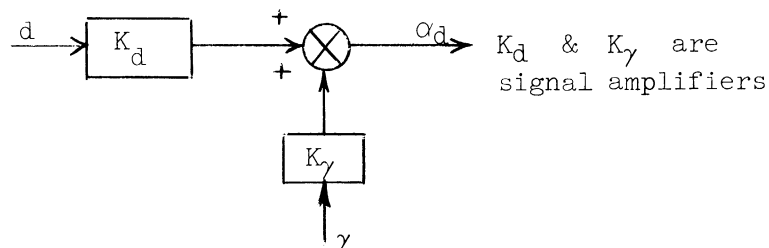


From here, it follows that

$$\gamma = \phi - \theta - \alpha$$



Finally, we need only find an expression for α_d to complete our loop. To do so, we begin with $d = y_r - y$, where d will be proportional to the error voltage obtained from the pair of tuned coils positioned over the centerline. Given this error voltage, we desire to displace the front wheels by an angle α_d . However, we also wish to make use of our input signal, giving the present angle of the front wheels with respect to the centerline. We therefore make the desired α_d a function of both lateral displacement and present wheel angle, with respect to the buried cable.



As of yet, no mention has been made of the steering servo motor. As might be expected, it is both desirable and practical to make use of present, commercially available power steering equipment. For the sake of convenience it will be assumed that the transfer function for the servo system can be described by a linear, second order system.

$$\frac{\alpha}{\alpha_d} = \frac{\omega_o^2}{s^2 + 2\zeta \omega_o s + \omega_o^2}$$

where the undamped natural frequency of the servo equals 20 radians/sec and the damping factor $\zeta = .5$ (See Ref. 15).

It will be seen later that this is not a completely valid assumption, in that our steering servo will be electro-hydraulic in nature, and described by a much more complicated transfer function.

In addition, no attempt has been made to determine the dynamic characteristics of each component in this system (i.e., suspension, weight distribution, etc.). However, such a feedback control system tends to wash out the effect of small changes in the vehicle's parameters, leaving the steering performance of such a vehicle fairly consistent.⁽¹³⁾

3. Stability Analysis

Keeping these limitations in mind, the flow chart for our system is shown in Figure 17. The transfer function for this system is:

$$\frac{Y}{Y_r} = \frac{\omega_o^2 V (K_d + K_\gamma S/V) (V + bS)}{bs^2 (s^2 + 2\zeta\omega_o S + \omega_o^2) + K_\gamma \omega_o^2 bs^2 + \omega_o^2 V (K_\gamma + K_d b) S + K_d \omega_o^2 v^2}$$

The root locus for the above transfer function, plotted as a function (K_γ) for $K_d = 0.1$, is shown in Figure 18⁽¹⁵⁾. This locus was plotted for the following values:

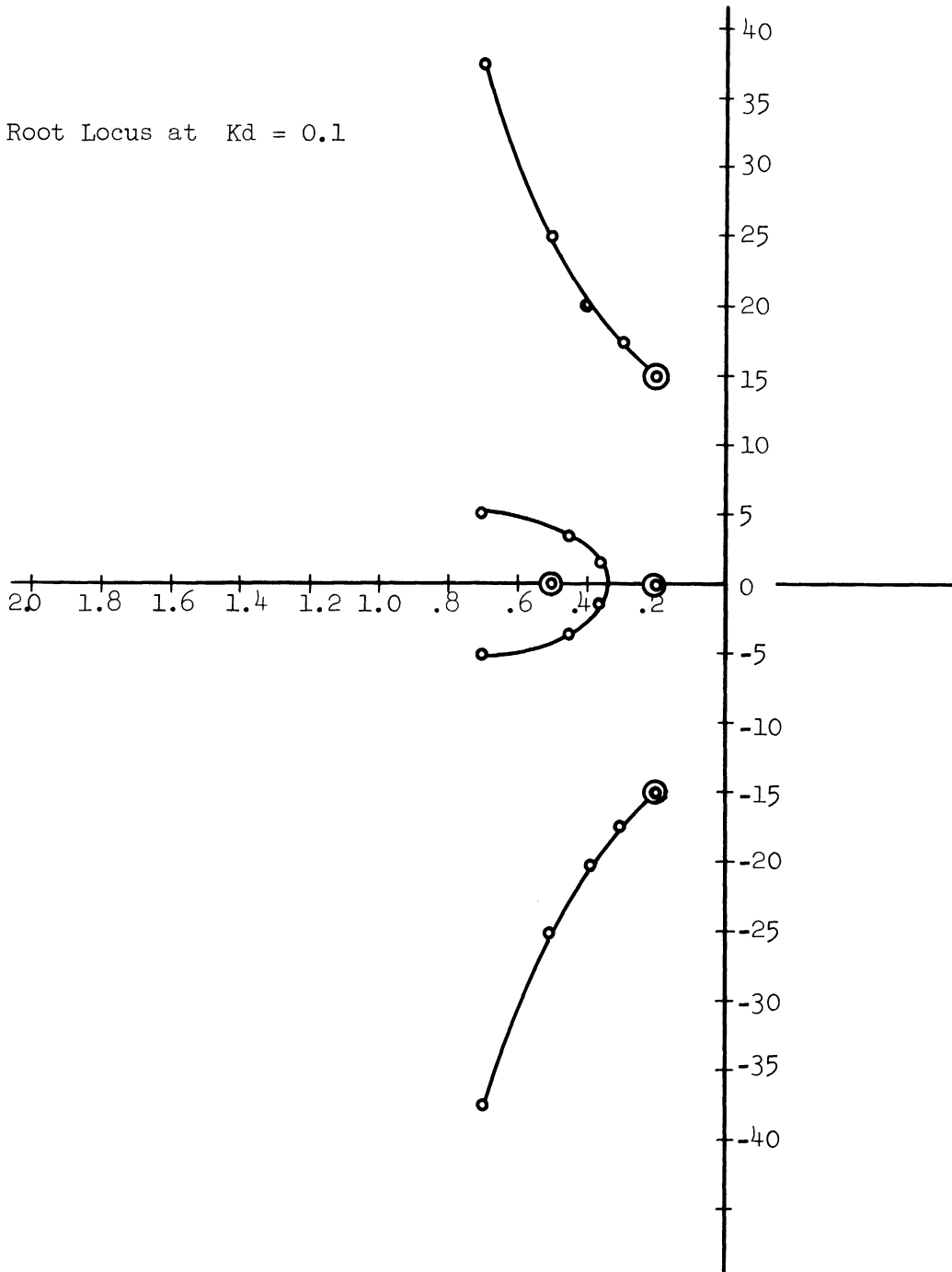
$V = \text{velocity} = 100' / \text{sec} \approx 70 \text{ m.p.h.}$

$v = \text{distance between axles} = 20 \text{ ft.}$

$\zeta = .5$

$\omega_o = 20 \text{ radians/ft.}$

Root Locus at $K_d = 0.1$



Transfer Function:

$$\frac{Y}{Y_R} = \frac{\omega_0^2 V(K_d + K_\gamma \frac{S}{V})(V + bS)}{bS^2(S^2 + 2\rho\omega_0 S + \omega_0^2) + K_\gamma \omega_0^2 bS^2 + \omega_0^2 V(K_\gamma + K_d b)S + K_d \omega^2 V^2}$$

Figure 18. Root Locus at $K_d = 0.1$

It is noted that this system will never go unstable for positive K_γ . This is a great improvement over many present systems, which are found to be very sensitive to variations in K . The block diagram for an experimental, operational vehicle developed by General Motors is shown in Figure 19. This system uses a reference system identical to the one described earlier (i.e.--a buried cable), and uses for positioning a single pair of tuned coils which produce an error signal proportional to the vehicle's displacement from the reference.

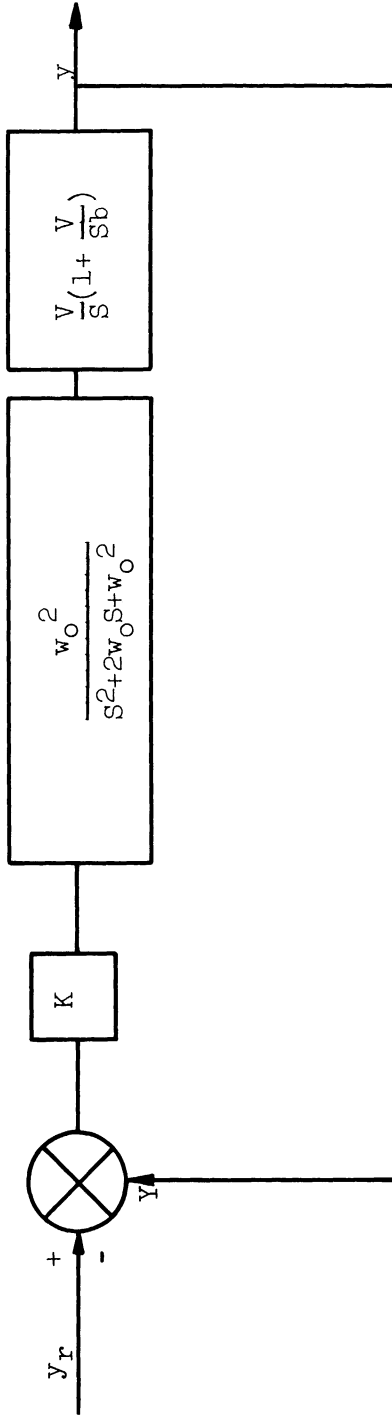
The transfer function for this simplified system is

$$\frac{y}{y_r} = \frac{K_d \omega_0 V (bs + V)}{bs^2 (s^2 + 2\zeta \omega_0 s + \omega_0^2) + K \omega_0^2 (V)(bs + V)}$$

and the root locus for this system is shown in Figure 20. Notice that this system can go unstable for positive K_d , thus making a much less desirable system, from this standpoint, than the system described above, however, we must consider that the reduced cost of such a simplified system might be sufficiently large to justify its use in a somewhat modified form.

4. System Error Analysis

It is interesting to investigate the steady state response of such a vehicle as it enters a long continuous curve of radius r_c . This is, of course, one of the critical design criteria of the system. For such a path, the angle of



Transfer Function:

$$\frac{y}{y_r} = \frac{K_d w_0^2 V (bs+V)}{bs^2 (s^2 + 2pw_0 s + w_0^2) + K_d w_0^2 V (bs+V)}$$

Figure 19. Block Diagram for Experimental System Presently Used by General Motors and RCA Laboratories

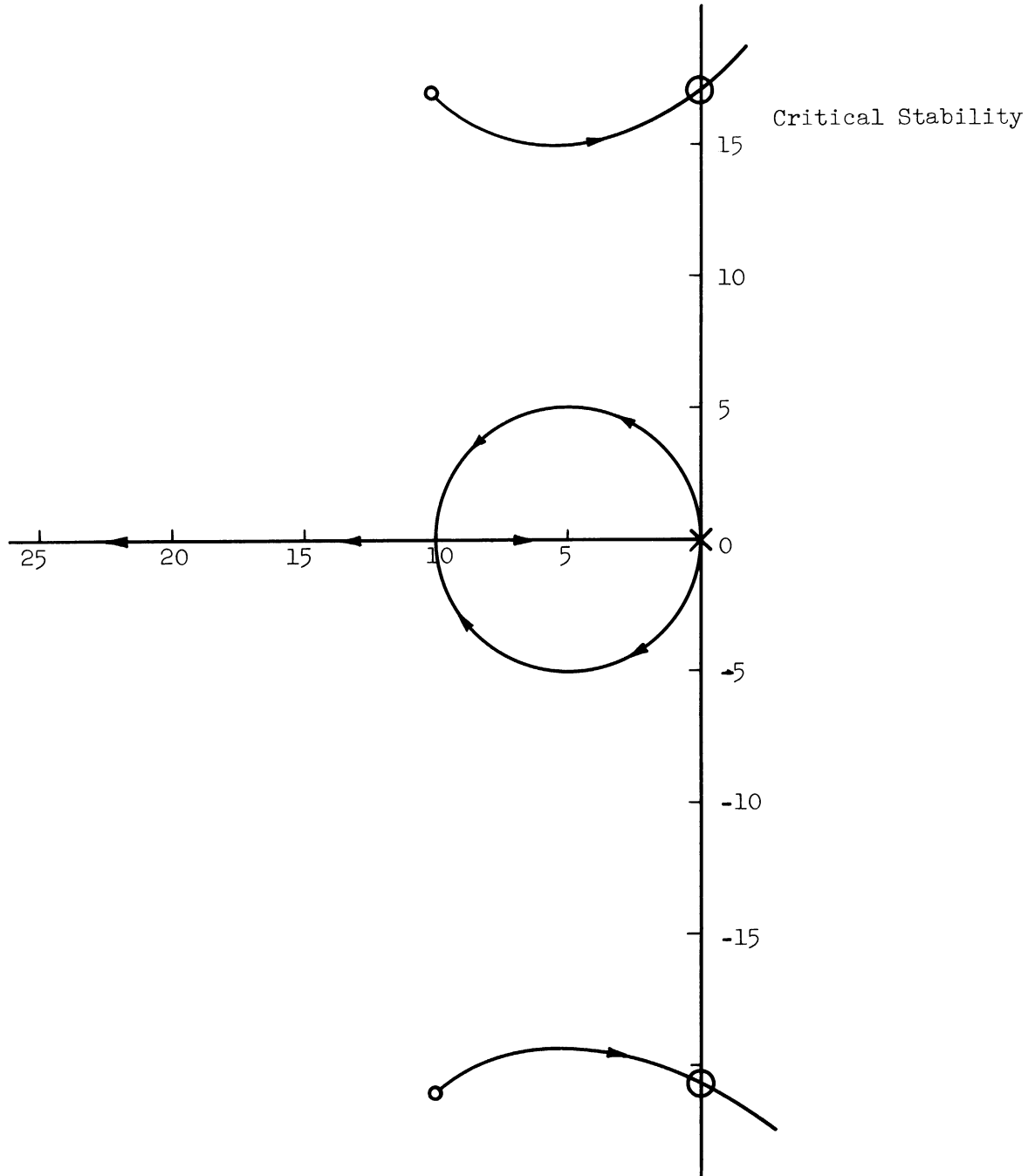


Figure 20. Root Locus for Experimental System Described in Figure (From D. Barrick - Reference 15)

the front wheels relative to the centerline must settle to zero in a steady state condition. Consequently, α_d will equal α . Looking at the block diagram (Figure 17), it is found that $\alpha_d = K_d d + K_\gamma \gamma$,

$$\text{and} \quad \alpha_d = K_d d + 0$$

For a curve of known radius r_c , where $r_c \gg b$ (approx. length of vehicle), $\sin \alpha = \alpha = b/r$. Therefore,

$$K_d d + K_\gamma 0 = \alpha_d = b/r$$

For example, considering a curve of $r_c = 150$ ft. and a vehicle with $b = 20$ ft., we find that $K_d d = 20/150$. For $K_d = .1$, $d = 1-1/3$ ft. outside of the cable. By adjusting as desired.

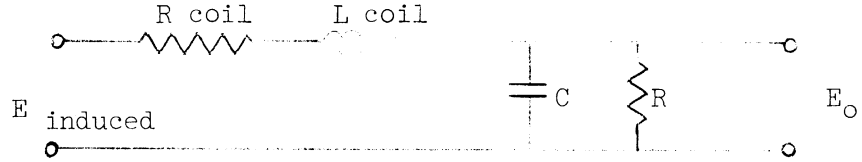
Now, consider a sinusoidal highway. Here it is possible to adjust for peak accelerations, limiting the oscillations and resultant lateral displacements to any desired value, such as $G/3$ at 70 m.p.h. as suggested previously. It is noticed that increasing K_γ greatly reduces lateral accelerations without impairing stability and it can be shown that $K_\gamma = 1$ is the most desirable⁽¹³⁾. K_γ actually has no effect upon either increasing or reducing the actual displacement; instead, K_γ effects only the rate at which steady state is attained.

5. Component Description and Design

The main detection devices are the three detection coils tuned to the frequency of the buried cable. As it is desirable to obtain as high an output voltage as possible, a

high-Q (Q equals the energy stored/energy dissipated per cycle) ferrite material should be used as a core for the coil. The detection coils can be represented as follows:

(See Reference 13)



The transfer function for the detector is:

$$\begin{aligned} \frac{E_o}{E_1} &= \frac{1/LC}{s^2 + \left(\frac{RR_c C + L}{R + L}\right) \left(\frac{R + R_c}{RLC}\right) s + \frac{R + R_c}{RLC}} \\ &= \frac{1}{LCs^2 + \left(\frac{RR_c C + L}{R}\right) s + 1} \\ &= \frac{1/LC}{s^2 + \frac{RR_c C + L}{RLC} s + \frac{1}{LC}} \end{aligned}$$

Therefore, ω_o , the natural frequency of the detector equals $\frac{1}{LC}$, and $2\zeta\omega_o = \frac{RR_c C + L}{RLC}$,

$$\text{so } \zeta = \frac{RR_c + L}{2R \sqrt{LC}},$$

$$\text{also } \tau = \frac{2LCR}{RR_c C + L},$$

and the bandwidth = $\frac{\zeta\omega_b}{\pi}$ for $\zeta^2 \ll 1.0$

It is now possible to choose the parameters desired by substituting in values for R, L, C, etc.. (Reference 13)

Figure 21 shows the output voltage as a function of coil position for a coil such as that described above, and Figure 22 shows the error voltage for two coils spaced one foot apart as their position over the cable is varied.

Steering Servo

The detailed analysis of the actuation and power of the steering system will be discussed in detail later in the paper. In short, it is desired to convert the amplified detection signals into mechanical outputs as efficiently as possible.

Figure 23 schematically describes the system including input to the actuators.

6. Conclusion

Fundamentally, we have discussed the possibility of automatically steering a highway vehicle through the influence of an electrically excited, buried cable. With this reference, we are combining a signal proportional to the vehicle's distance from the centerline and a signal proportional to the angle of the front wheels, with respect to the cable. Having proposed a suitable system, the block diagram was reviewed and the transfer function of the vehicle's lateral displacement, with respect to the cable was derived.

By assuming reasonable values for the many system parameters, a root-locus plot was investigated to determine the stability of the network. Having found the system stable for

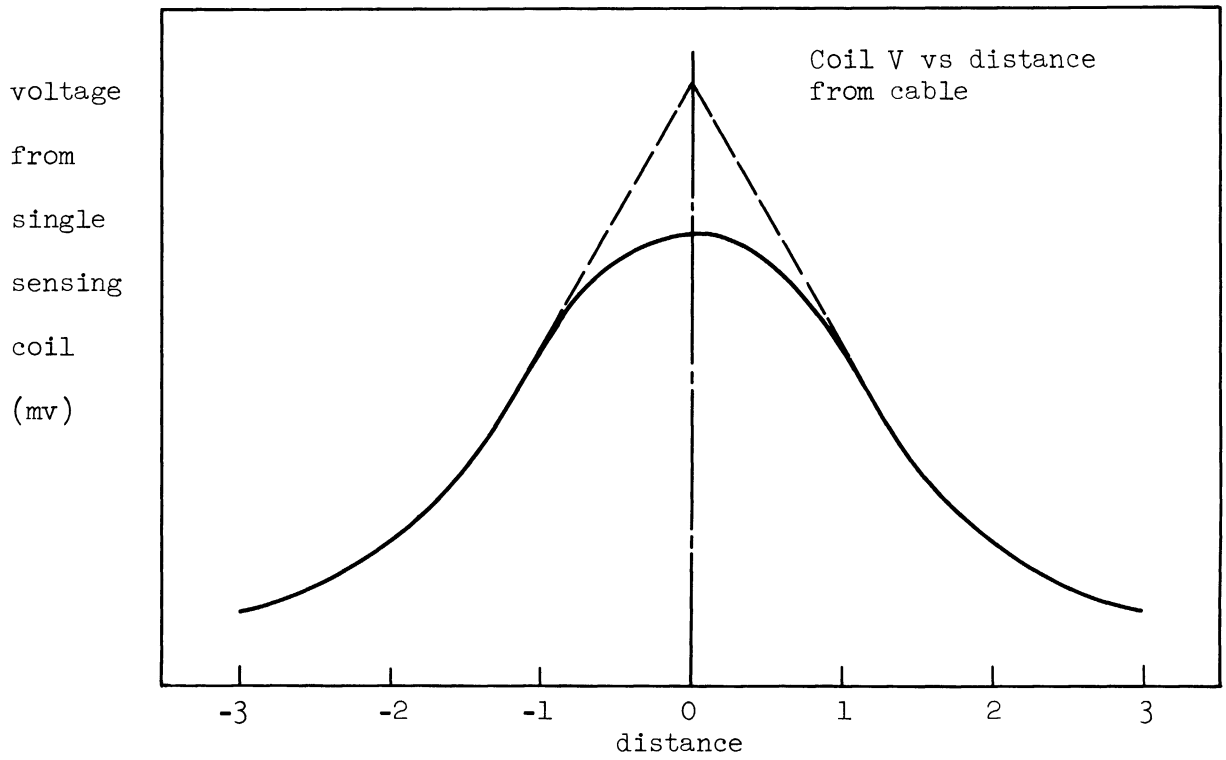


Figure 21. Coil voltage vs distance from cable

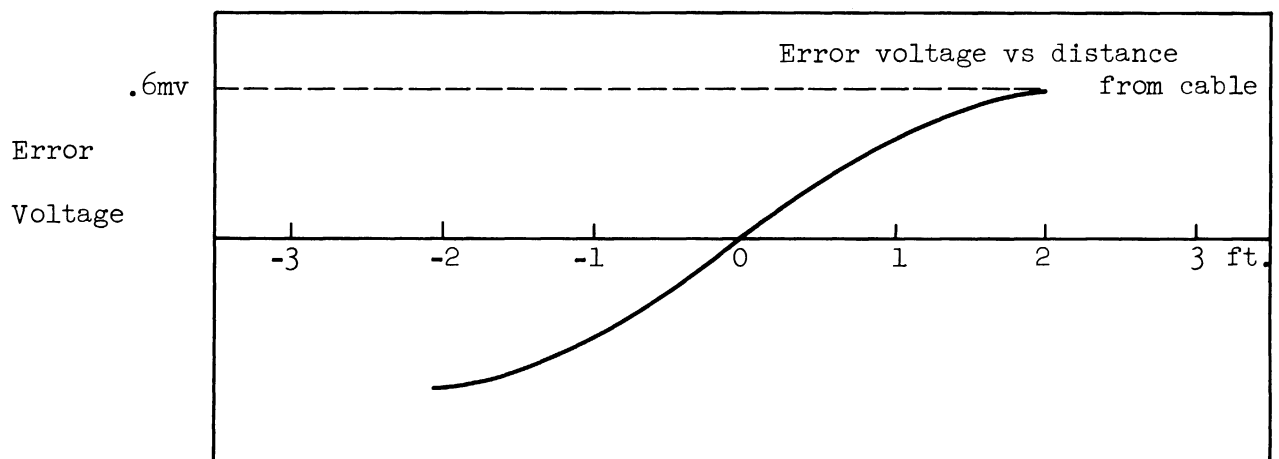


Figure 22. Error voltage vs Distance from Cable (From D. Barrick-Reference 15)

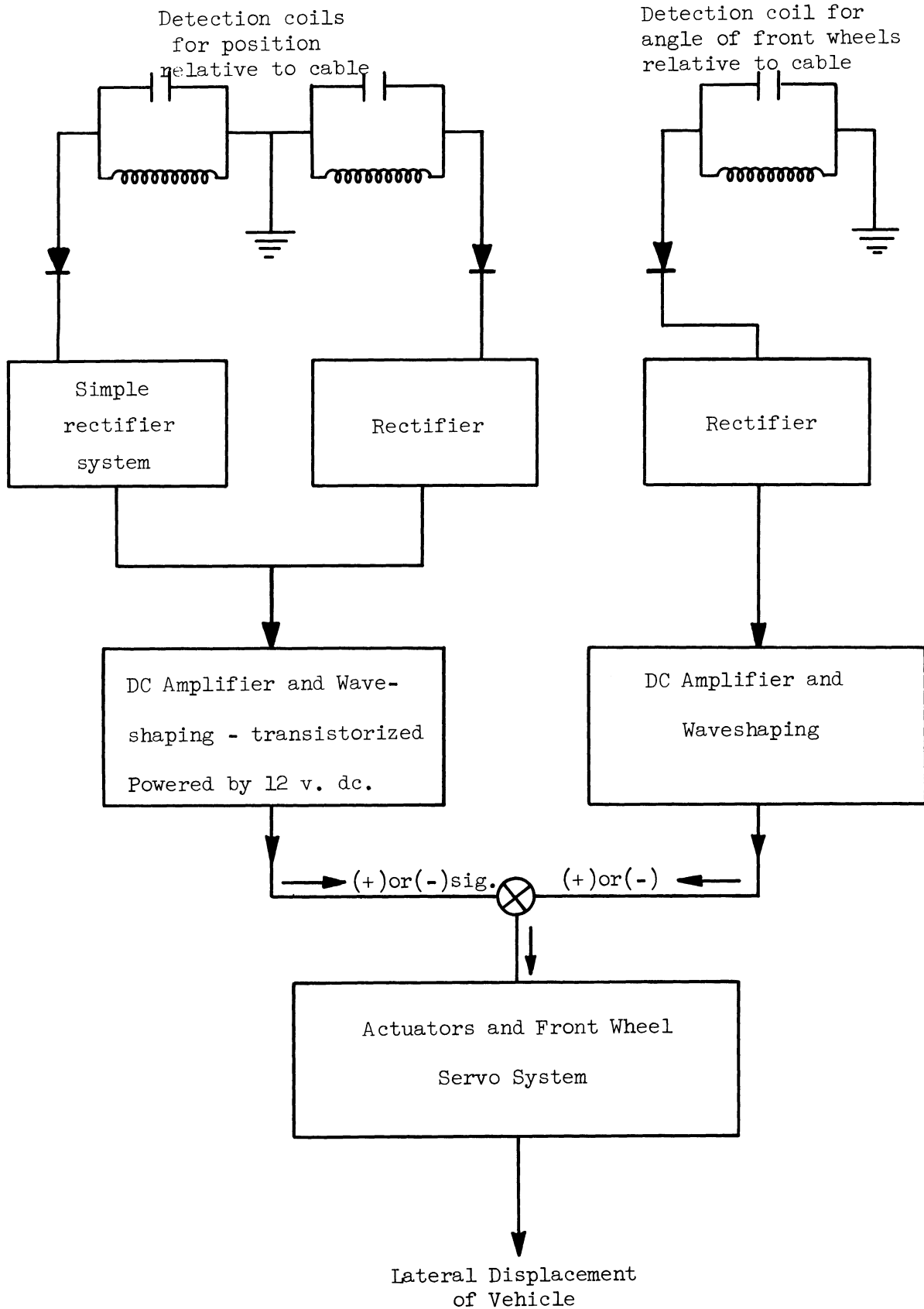


Figure 23. Signal Detection

all values of positive gain at 100 ft/sec, it is noted that velocity appears only on the right side of the transfer equation, and consequently, the system will be stable for all lower velocities.

Similarly, the lateral accelerations is limited to $1/3$ G at 70 m.p.h. For a comfortable ride, a peak lateral acceleration of $1/3$ G is permissible. Actual tests have shown that a driver may experience lateral accelerations up to 1G for a short period of time, but that the lateral acceleration should not exceed $G/2$ if skidding is to be avoided⁽¹³⁾. Since lateral acceleration varies as $a = \frac{V^2}{r_c}$, it will never exceed $1/3$ G at speeds less than 100 ft/sec.

From a preliminary design viewpoint, this system shows promising potential. However, to obtain a optimum description of performance, a complete analysis of the system's time response, including Bode diagrams, Nyquist plots, etc., can be used to determine the complete operational parameters of such a feedback unit. If necessary, compensation techniques can be used to improve these parameters. Should this automatic steering still seem satisfactory, an analog system can be developed and the system's response and performance reviewed as a function of various inputs. Finally, either a scaled model or a complete prototype can be developed and further examined. This discussion begins the fundamental investigation that provides the initial foundation for further development.

C. Speed Control

1. Introduction

The automatic speed control system discussed below will be responsible for maintaining the controlled vehicle at a constant speed, independent of upgrades or downgrades, curves in the highway, or weather conditions, i.e. headwind or tailwind. A system to be discussed later, the spacing system, will detect obstacles on the highway and will initiate any necessary corrective action, overriding the automatic speed control system as described shortly.

Each controlled vehicle on an automatic highway must have knowledge of two parameters in order to maintain its velocity. These two parameters are:

- 1) a velocity command signal, received from the highway, which indicates the speed at which the vehicle should be traveling:
- 2) a signal indicating the vehicle's actual speed. The command signal allows external speed alteration of all controlled vehicles, as may be necessitated by adverse road conditions (water or snow) or traffic congestion.

It should be noted that the second parameter, the velocity of the system vehicle, must be known very precisely so as to keep all traffic moving uniformly, and thereby reduce the possibility of oscillations in the spacing control system.

Finally, since easy conversion of existing highways is desirable, the system selected for velocity control must be capable of installation with minimum difficulty-- in other words, it must not require more than a narrow slot in the highway, or perhaps a series of small, reasonably space holes.

2. Proposed Systems

Presently, there is a commercially available automatic speed control manufactured by A. C. Spark Division of General Motors.⁽²⁰⁾ With this system, called Electro-Cruise, the desired speed is set manually by the driver, the actual speed is measured by the speedometer (flexible cable, magnetic drag cup type) and the error signal operates a pneumatic actuator which in turn regulates the throttle setting. In this system, the only braking utilized is the braking power of the engine, as the mechanical brakes are not automatically controlled. Although this system functions well in its intended use, its application to a completely automatic system is limited in that the control speed must be manually adjusted and because the actual speed measurement obtained from the speedometer does not give the desired accuracy due to such uncontrollable variables as tire pressure, load, and slippage.

Other speed indicator systems considered include the following:

- a) Tachometer: A system utilizing a commercially tachometer to measure accurate shaft speeds was found economically feasible. However, as mentioned above, the correlation between shaft speed and the vehicle's translational speed is too inaccurate for our purposes.
- b) Ultrasonics: A system involving ultrasonic generators in an application of the Doppler Effect was discarded due to variations in temperature, air pressure, etc.
- c) Visible light, utilizing photocells: This system was found desirably inexpensive and dependable under perfect highway conditions. However, numerous road and weather conditions render such a system highly undependable.
- d) Discontinuous shielded cable: This system, designed to give an effective pulse signal as a vehicle passed overhead, involved critical attenuation problems, installation difficulties, etc.
- e) Crisscrossed wire: A system similar to General Motor's Auto-Control,⁽¹³⁾ involving a crisscross wire producing a field with a series of nulls along the highway, was rejected because it required a relatively wide slot (much wider than that cut by a diamond saw) in the highway and thus a very expensive and difficult installation.

3. Design Proposal

A system consisting of permanent magnets placed along the highway was proposed for the speed control signal. As

the vehicle passes over the magnet it senses the presence of the "marker" by receiving a pulse in a pickup coil. The time interval between successive pulses corresponds to the time interval between successive markers and hence is a measure of the average velocity of the vehicle over the road section between the two markers. Measurement of actual speed in this manner eliminates errors caused by wheel slippage or variations in effective wheel radius.

For the reasons mentioned above, it is desirable to have the command speed signal originate from the highway. One solution was proposed by General Motors⁽¹³⁾. It involves burying a cable in the ground alongside the highway, carrying a radio frequency voltage modulated by a low frequency corresponding to a speed command. The cable can be divided into sections several hundred yards long each, thus permitting different speed commands at different points of the highway. A minor departure from the G.M. system (made for the sake of convenience as will be later apparent) is to make the modulating signal a width modulated pulse train rather than a sinusoid.

4. Analysis of Permanent Magnet Signaling System

Before discussing the device which compares the command speed and the actual speed, let us consider a detailed description of the markers and the pickup coil.

The permanent magnet system was selected for use because of its relative simplicity and economic feasibility. The markers in the highway will be placed in pairs spaced two feet apart in the direction of travel with a distance of twenty feet between pairs, as indicated in Figure 24. (The reason for this spacing will become apparent when the detection system is discussed.)

From Faraday's Law, the electromotive force induced in each turn of the pickup coil the time-changing magnetic field is given by:

$$E = - \frac{d\phi_B}{dt} = - \frac{d\phi_B}{dX} V = - \frac{\Delta\phi_B}{\Delta X} V ,$$

where E is the electromotive force, ϕ_B is the magnetic flux through the coil, and V is the velocity of the car.

Dropping the minus sign and solving for $\Delta\phi_B$:

$$\Delta\phi_B = \frac{E\Delta x}{V}$$

But,

$$\Delta\phi_B = A_e \Delta B ,$$

since A_e is constant.

Then:

$$\Delta B = \frac{E\Delta x}{A_e V} .$$

The variable A_e appearing here is the effective not the actual area of the coil. Steady-state analysis of the vehicles lateral displacement from the

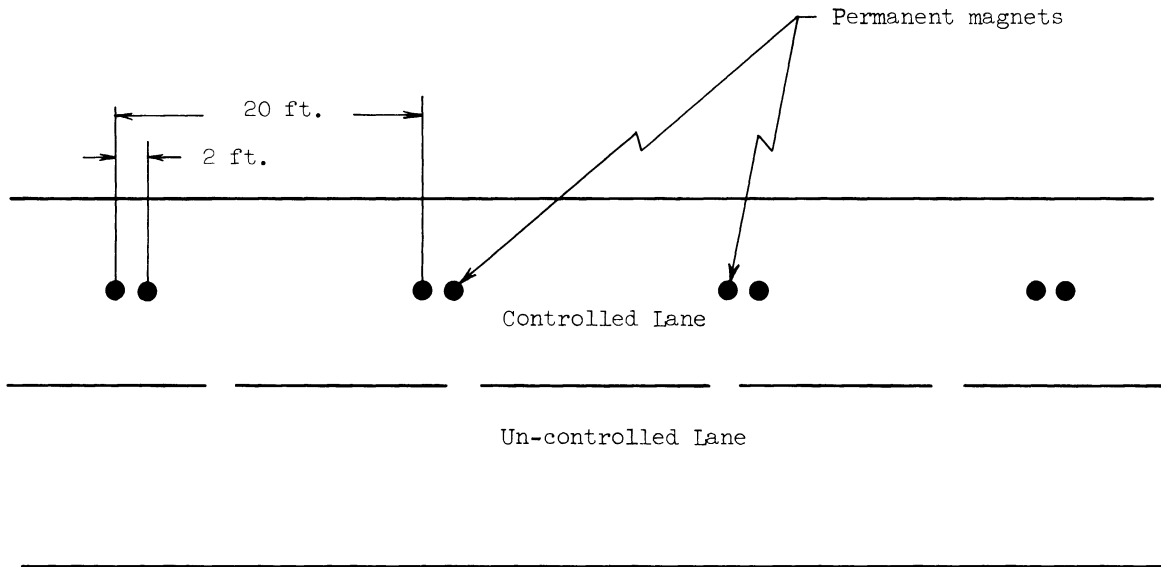


Figure 24a. Positioning of Magnets in Highway

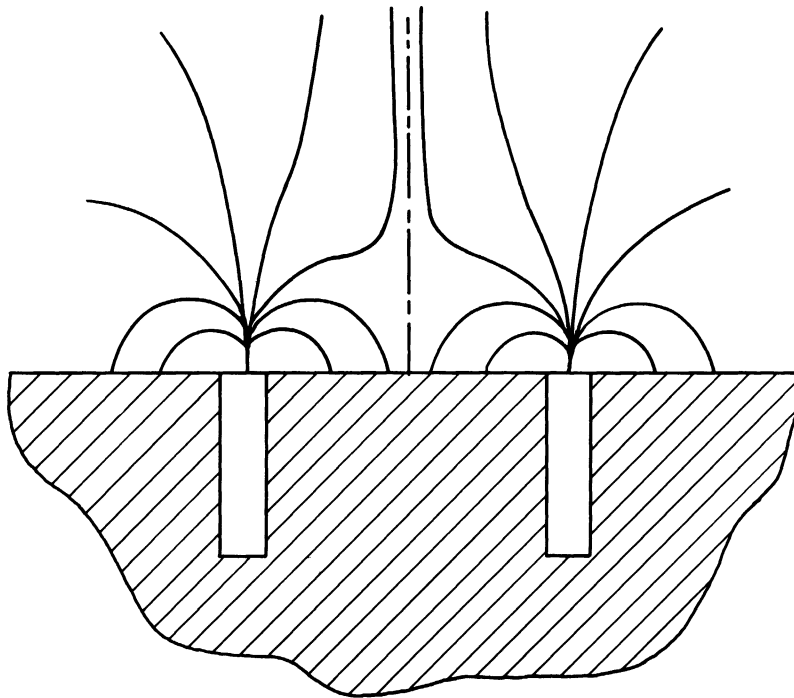


Figure 24b. Flux from One Pair of Magnets

center of the highway on a curve indicates that the vehicle will drift approximately one foot from the control strip (see steering analysis). Therefore, it is necessary to make the coil about three feet in width (see Figure 25). However, in the above calculations it is assumed that B is constant over the area of the coil, which is not the case for such a large width, so it is clearly necessary to estimate the effective area. Returning to the equation for ΔB , if Δx is chosen as the distance between the zero and maximum values of B through the coil (see Figure 26), then $\Delta B = B_m$, where B_m is the maximum value of flux possible. Therefore

$$B_m = \frac{E\Delta x}{A_e V} .$$

If the magnetic potential field is assumed to be spherical and if $B_m/8$ is very small, Δx may be approximated as $d\sqrt{3}$ where d is the vertical distance from the magnet to the coil. Furthermore, $A_e = (2d + w)$ where w is the width of the coil (see Figure 25). Then:

$$B_m = \frac{Ed\sqrt{3}}{2dwV} = \frac{E\sqrt{3}}{2wV} .$$

Assuming that the Emf needed for acceptable signal detection is 10mv per turn of the coil, that the velocity of the car is 60 mph, and that the width of the coil is 10cm, then from the above equation the maximum B field needed is 34 gauss.

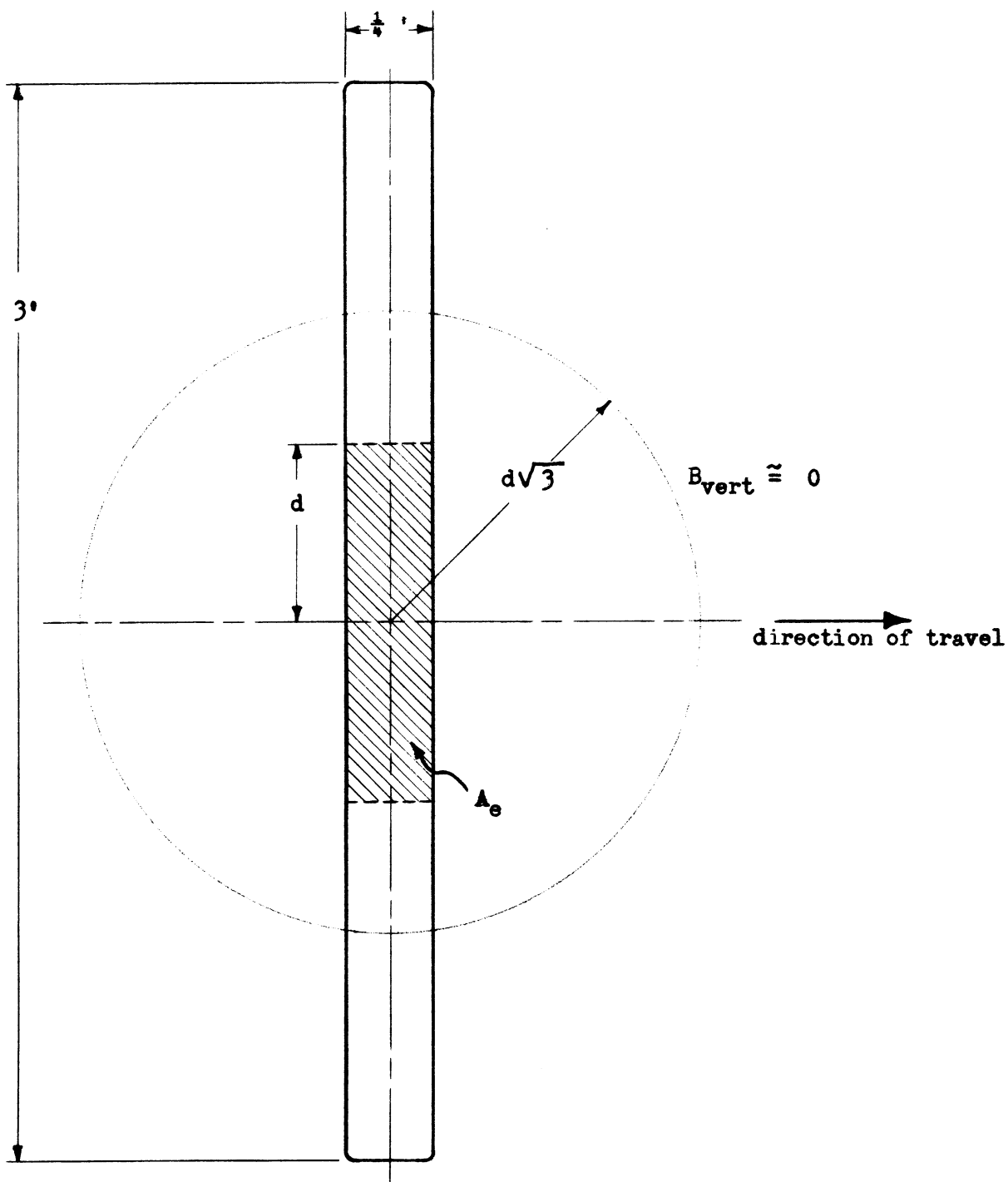


Figure 25. Speed Control Detection Antenna

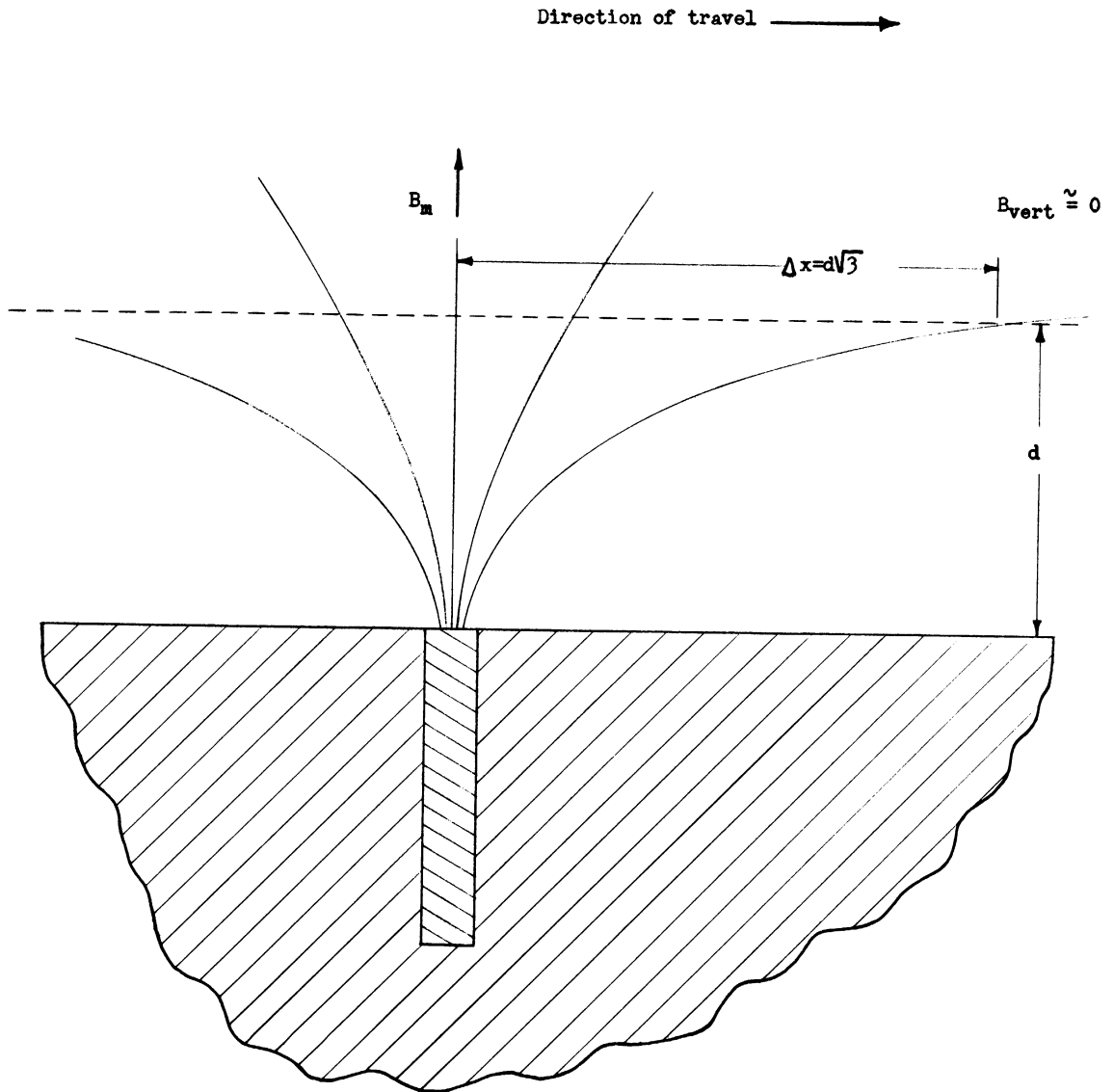


Figure 26. Magnetic Field Parameters

In order to calculate the size of the magnet required to produce this field, it is necessary to use the magnetic dipole equation:

$$B = \frac{\mu_0 \mu}{2\pi r^3} \quad \text{for } r \gg l/2$$

where B is the magnetic flux density at a point on the axis of the dipole at a distance r from its center, μ is the magnetic dipole moment, and l is the length of the magnet, But $\mu = KV$ where K is the equivalent sheet current density and V is the volume of the magnet. Furthermore, the value of B at the surface of the magnet, B_0 , is given by the equation:

$$B_0 = \mu_0 K/2 \quad \text{for } R \ll l$$

where R is the radius of the magnet. Therefore:

$$B/B_0 = V/\pi r^3 \quad 2r \gg l \gg R$$

Since $r = (l/2 + d)$ where d is the distance from the magnet to the loop and $r \gg l/2$, then $r = d$.

Substituting $r = d$ and $B = B_m$:

$$V = \pi d^3 B_m / B_0 \quad 2d \gg l \gg R$$

Assuming that $d = 15$ cm (6 in) and that $B_0 = 10^4$ gauss (using an Alnico magnet) then the volume is 36 cm³. Assuming the density to be that of Alnico (0.264 lb/in³), the mass of the magnet is found to be 0.61 lbs. However, this figure

is based upon the assumption that $2d \gg l \gg R$. A better estimate is about 1 lb.

It should be clear at this point that these calculations were made for a velocity of 60 mph and that if the system is to work at lower speeds the magnet size will have to be increased. For instance, if 30 mph is the desired lower limit for operation, the magnet size will have to be doubled to 2 lb.

Since Alnico magnets cost roughly \$1 per lb and since it is desired to place two magnets in the road for every 22 ft. (for reasons to be discussed in a later section), the cost of this system, not including installation will be approximately \$960 per mile.

5. Error Detection Device

a) General

The device which compares these two signals and produces an error signal output operates essentially as follows. The input pulses from the highway markers are first refined by a Schmitt Trigger Circuit and then fed into an Eccles-Jordan bistable multivibrator which produces as output a pulse whose duration is equal to the time interval between two successive markers. These pulses are then fed into a pulse width demodulator which produces a DC voltage output proportional to the vehicle's average velocity. Similarly, the command signal (width modulated pulse train) is fed to another demodulator which produces a DC level corresponding to the command speed.

The two voltages (velocities) are compared and the difference is the error signal which is fed to the actuator.

b) Detailed Operation

Figure 27 is a sketch of the voltage induced in the pickup coil as a function of time for a given velocity. This voltage is the input to a Schmitt trigger circuit (Figure 28); the output is shown in Figure 29. This output is then clamped by the circuit shown in Figure 31. This series of triggering pulses is made the input to the multivibrator and clamping circuit (Figure 32) and the output is, as shown in Figure 33, a pulse of duration T_1 , where T_1 is the time it takes the vehicle to travel two feet.

The shaped pulses are then fed into a pulse width demodulator (PWD) which recovers the velocity information as a DC voltage whose level varies linearly with velocity. To better demonstrate the operation of this circuit, a laboratory model for a PWD operating under the conditions of the ACHV system was built and tested. Figure 34 shows the demodulator (which requires only 3 transistors, 6 resistors, and 3 capacitors at a total cost of less than \$5 for components) and Figure 35 shows the input-output characteristics of the demodulator.

The pulse width demodulator operates by integrating the incoming pulse at a constant rate for the duration of the pulse and then holding that voltage level on a capacitor until the next pulse arrives, at which point the capacitor is

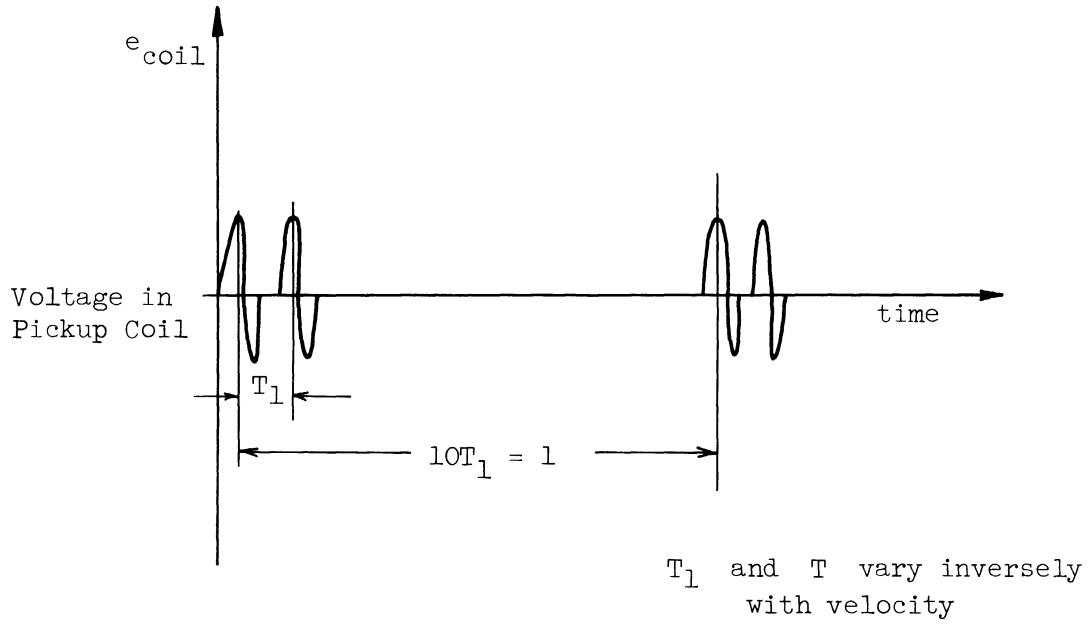


Figure 27. Waveform in Speed Pickup Coil

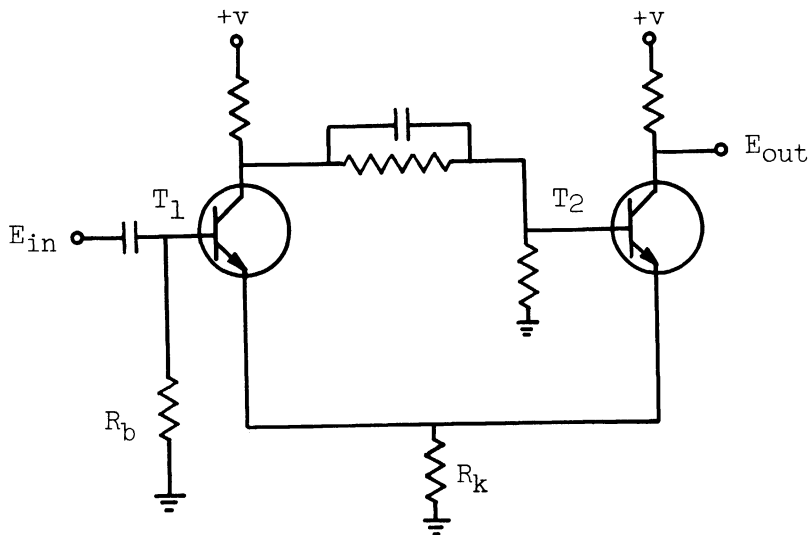


Figure 28. Schmitt Trigger Circuit

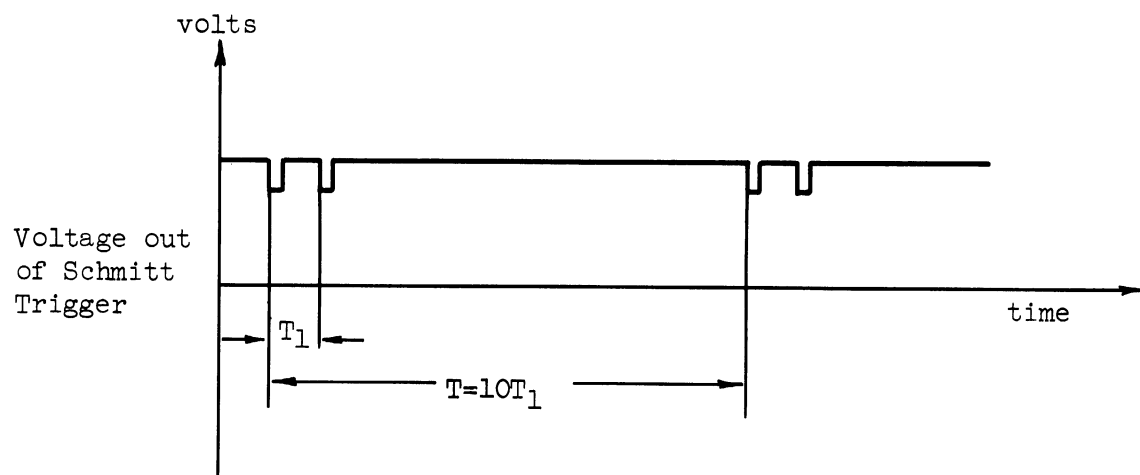


Figure 29. Output of Schmitt Trigger

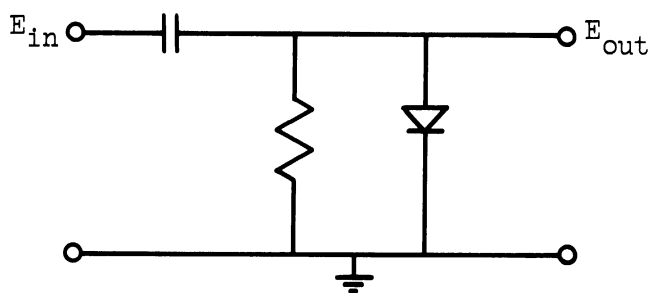


Figure 30. Clamper Circuit

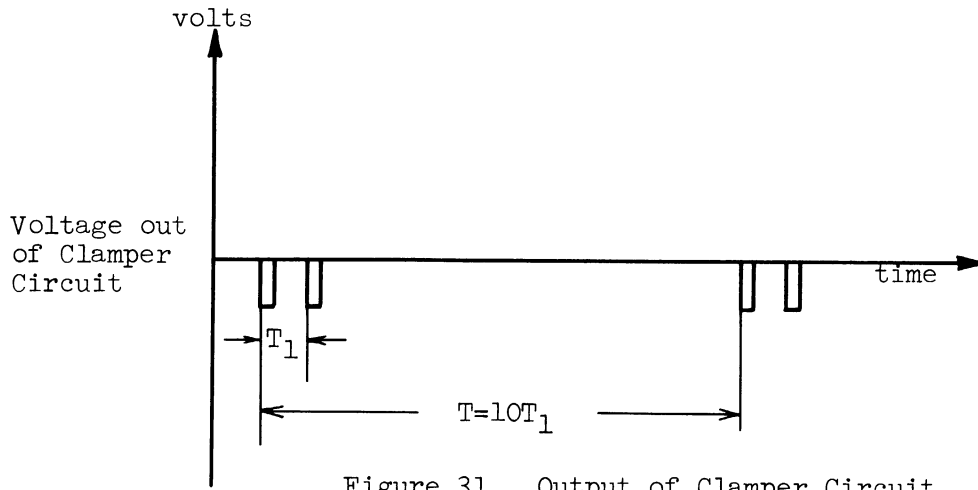


Figure 31. Output of Clamper Circuit

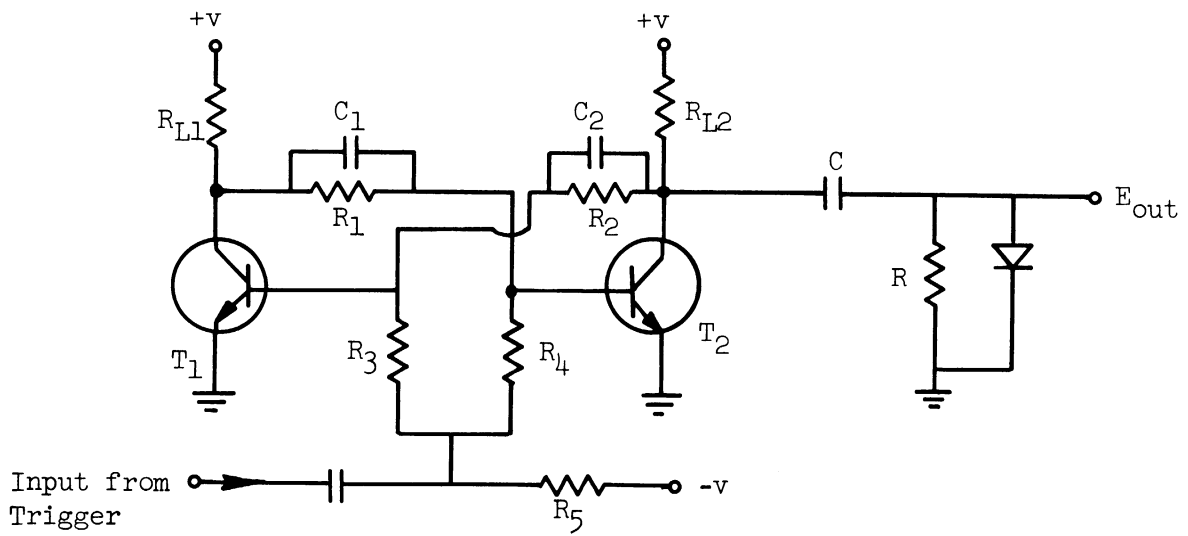


Figure 32. Flip-Flop and Clamper Circuit

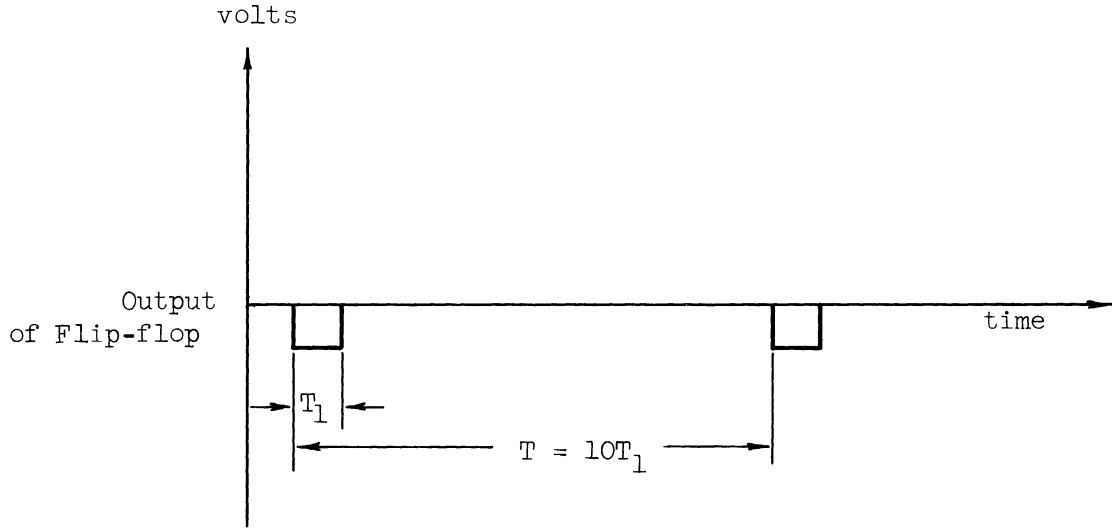


Figure 33. Output of Flip-Flop Circuit

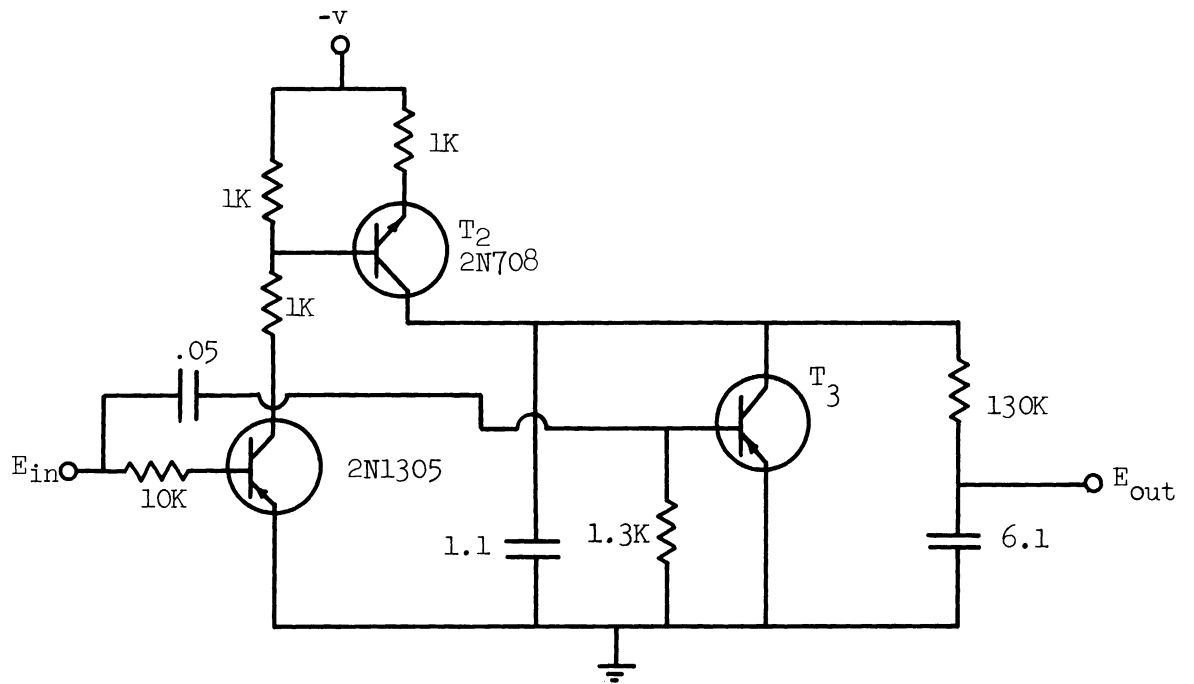


Figure 34. Pulse Width Demodulator

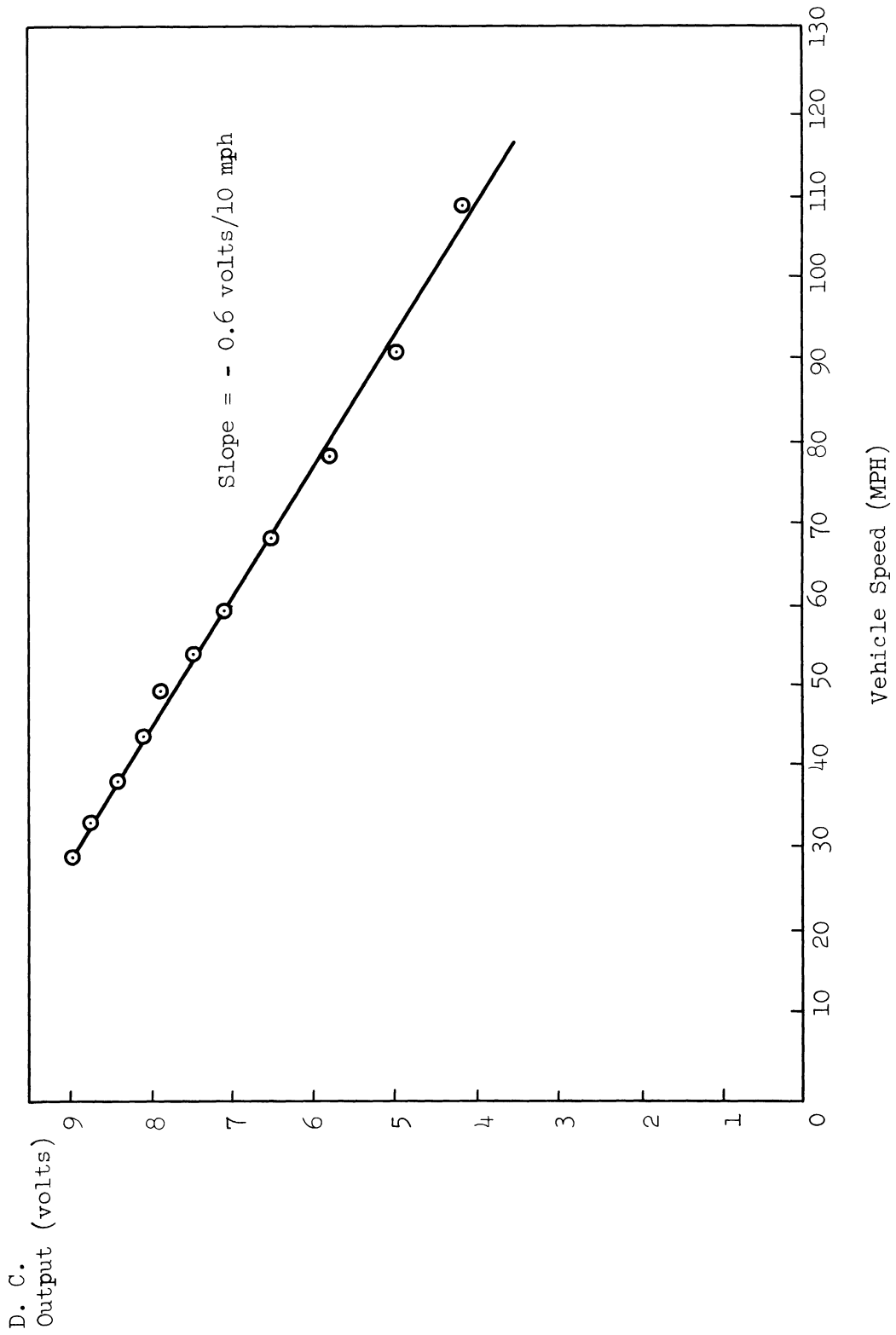


Figure 35. Input-Output Characteristic of Demodulator

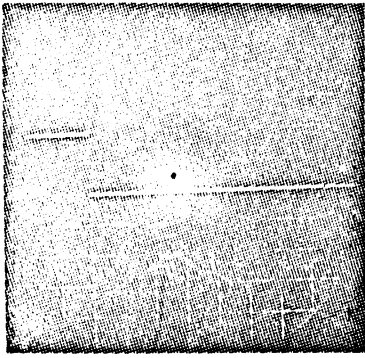
quickly discharged to a value near zero volts and integration of the second pulse begins. In more detail, the operation is as follows:

An input pulse of 5 volts and negative polarity causes transistor T1 to saturate which biases transistor T2 in such a way as to cause T2 to act as a constant current source. T2 charges capacitor C2 at a constant rate (since $\frac{de}{dt} = \frac{I}{C2} = \text{const.}$) The charging (integration) continues until the input returns to zero, at which time T1 ceases to conduct the therefore causes T2 to shut off. C2 holds the voltage constant at that level as long as the output current drain is small.

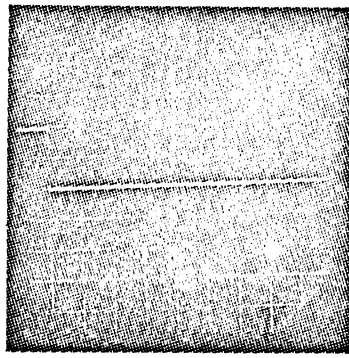
The combination $R_1 C_1$ acts as a differentiator, applying a negative pulse to the base of transistor T3 at the time that an input pulse arrives and a positive pulse to the base of T3 when the input drops to zero. The positive pulse has no effect on T3, but the negative pulse (which coincides with the leading edge of the input pulse) causes T3 to momentarily short capacitor C2, thus returning C2 to ground potential.

An RC filter is placed across C2 to extract the DC level from the capacitor and reject the relatively rapid voltage changes on the capacitor due to discharging and charging. Figure 36 illustrates the operation of the circuit as observed in the laboratory. The PWD Circuit is similar to the circuit designed by Knowlton.⁽²¹⁾

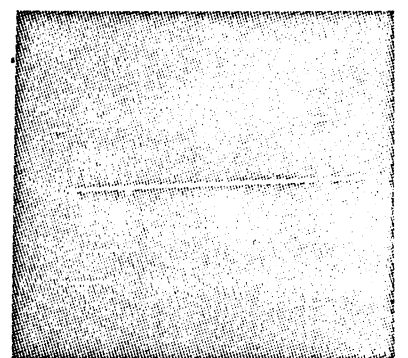
Figures 37a and 37b are the over-all block diagram and schematic representation of the total speed control comparator system.



1a

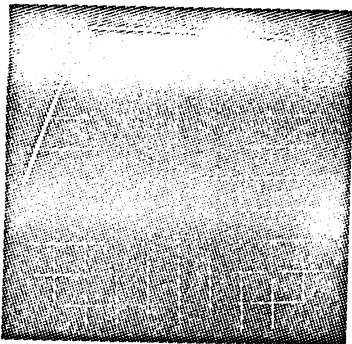


2a

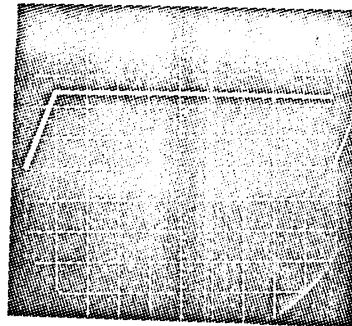


3a

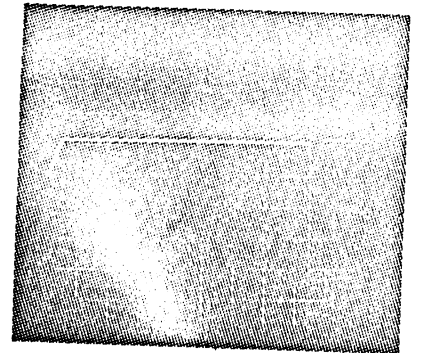
Input Pulses whose width corresponds to 20, 40, and 80 miles per hour, respectively.



1b

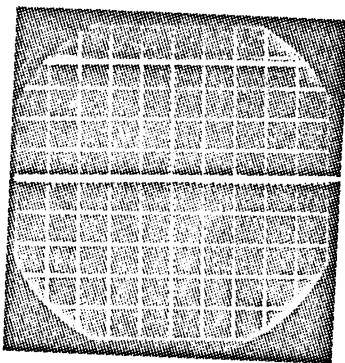


2b

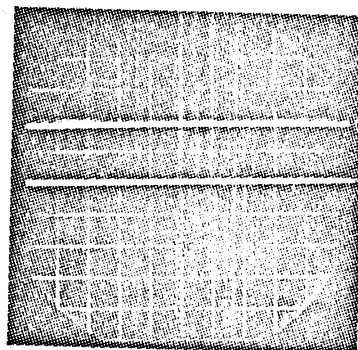


3b

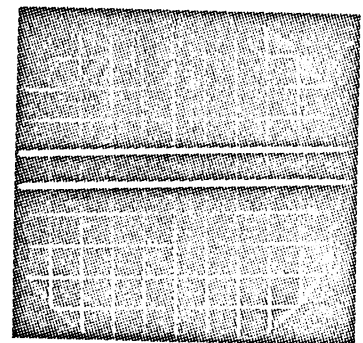
Output on charging capacitor equal to the time integral of the respective inputs.



1c



2c



3c

Output of the PWD after filtering for the above inputs.

Figure 36

Photographs of Pulse Width Demodulator in operation in laboratory

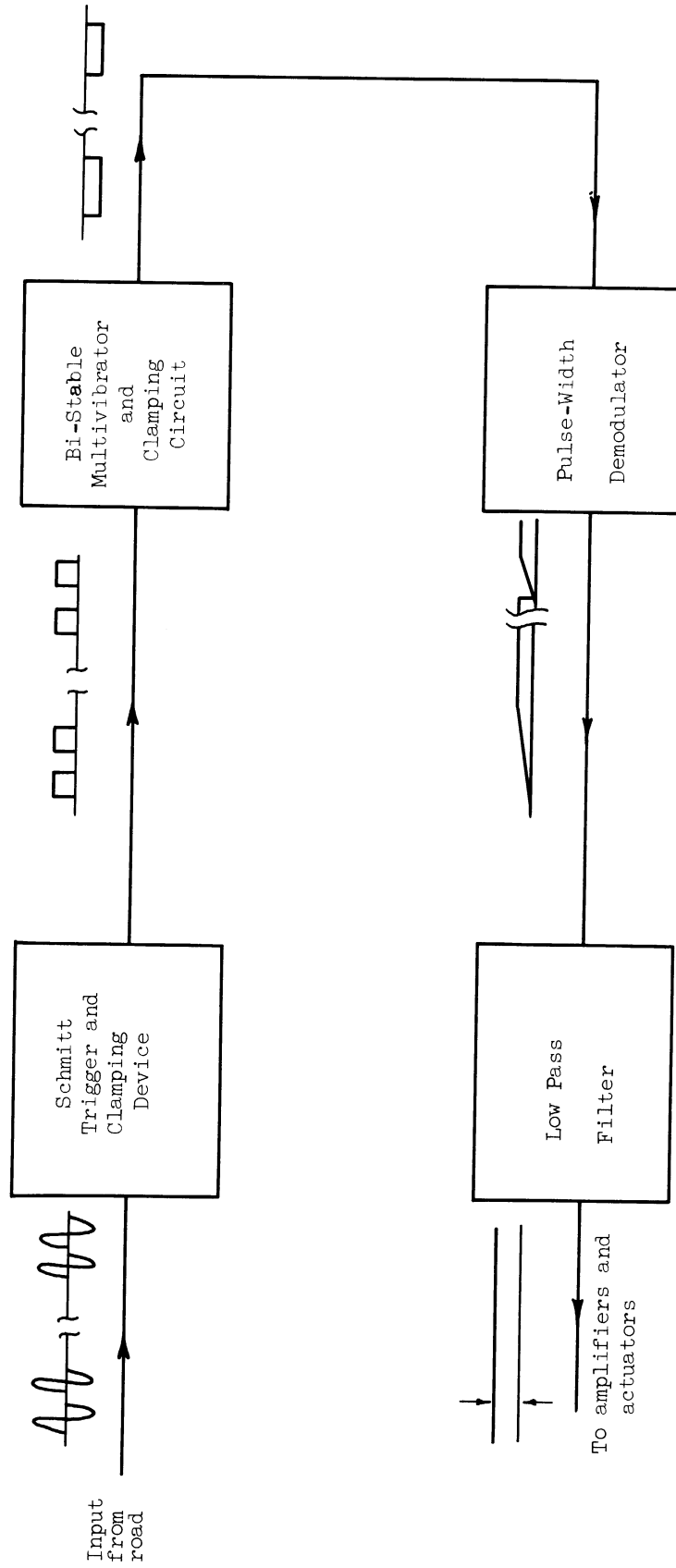


Figure 37a. Block Diagram of Speed Control

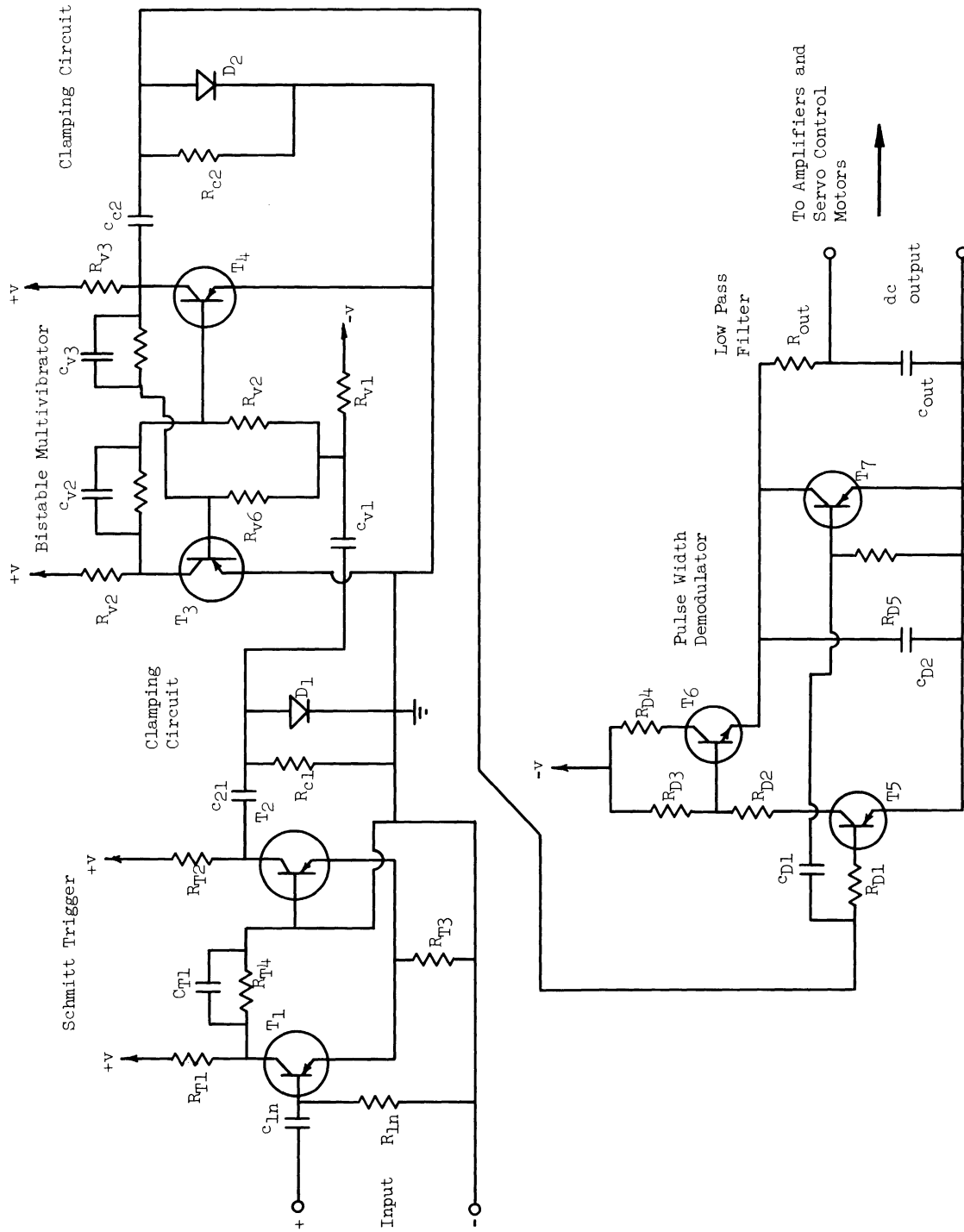


Figure 37b. Schematic Diagram of Speed Control Comparator System

D. Spacing Control

1. Introduction

The problem of spacing is that of maintaining a "safe distance" between vehicles on the highway at all times, a "safe distance" being defined as a distance great enough to prevent a spacing of zero between any two vehicles at all times. In other words, a vehicle should always be able to compensate for any disturbance in the flow of traffic (e.g., accidents, vehicles moving in and out of lanes, sudden stops, etc.)

Certain assumptions will be made at this time to establish boundaries around which the sub-system can be designed. Some of the assumptions serve to re-emphasize the scope of this particular project within the total system, while others are merely a priori decisions on the implementation of the sub-system.

It is felt that a suitable control must satisfy the following conditions:

- a) It must be compatible with existing traffic and highway conditions and construction techniques.
- b) It must be capable of being introduced gradually over a period of years and must, therefore, allow for the presence of unequipped vehicles on the highway.
- c) It should be inherently failsafe and exhibit good reliability.
- d) All costs, but in particular those which will be absorbed directly by the consumer upon purchasing an equipped car, must be kept at a minimum.

As mentioned previously, a system such as this should not require more than a slight modification of existing highways nor should it warrant any large-scale alteration of present construction techniques. Developing a system which must be readily acceptable to state and federal authorities as well as the consumer, demands high compatibility. Also, it is inconceivable that the number of equipped vehicles will grow so rapidly that any highway could be limited to only automatically controlled vehicles.

Since consideration is with limited-access, intercity four-lane highways, it would also be very undesirable to limit unequipped vehicles (of which there will be many) to one lane in each direction, leaving the remaining lanes for controlled traffic. Therefore, it is necessary to have controlled and non-controlled vehicles not only on the same highway, but in the same lane. This is where much of the difficulty arises in designing a spacing control; for it demands that any detection device be independent of whether or not the vehicle is a controlled vehicle.

This restricts one to passive detectors in which nothing more than the mere presence of a vehicle (moving or stationary) is required for detection. In addition, because there will be this interplay of equipped and nonequipped vehicles, the presence of controlled vehicles should not increase the danger to uncontrolled vehicles.

Although the total system can succeed only with financial support from the government, it will be assumed that this

support will not include any equipment connected directly to the vehicle. Therefore, in an attempt to keep consumer costs low, an effort is made to keep the necessary equipment in the vehicle at a minimum. This stipulation dictates, among other things, that an obstacle detection device primarily external to the controlled vehicle is preferable.

The spacing problem can be divided into three areas:

- a) Detection
- b) Relay of information to the trailing vehicle
- c) Reception and utilization of this information by an equipped vehicle to determine a proper course to action.

2. Detection

If a vehicle is to maintain a safe distance between itself and any obstacle in its path, it must have a means of detecting the obstacle any where on the lane in which it is traveling. The speeds involved in the types of highways under consideration (60-70 mph) are great enough in themselves to warrant relatively few detection devices to accurately predict the position of a vehicle in a given section of highway. Since, however, one must be concerned with all possible situations (e.g. a stopped vehicle) a system in which there is complete coverage is required.

In choosing a detection device, consideration should be given to:

- coverage
- ease of installation

- required maintenance
- cost
- reliability
- complexity of associated monitoring equipment

An investigation of existing methods of vehicle detection discloses that a loop (or loops) of wire buried in the roadway is, at present, the most popular. Both General Motors Corporation and the Radio Corporation of America have designed a spacing control utilizing this detection technique.^(11,12)

Although both of the systems do solve the problem, they are both relatively complex, particularly in the electronic monitoring devices used. Therefore, a complete analysis of the problem was initiated in an attempt to find a more acceptable spacing system. The following is a list of the areas considered:⁽⁴⁹⁾

- Mechanical devices
- Magnetic devices
- Radar
- Photoelectric cells
- Ultrasonics
- Infra-Red
- Strain Gages
- Loop Detectors

a) Mechanical Devices

The most obvious of the mechanical devices are the pneumatic tubes presently employed as counters. However, they have the dubious honor of offering perhaps the greatest

disadvantages of any method investigated. Those presently in use are tempermental, unreliable, exceedingly prone to breakage and, from the psychological standpoint, very annoying to the driver as the vehicle passes over the sensors.

Proceeding further, one must consider the possibility of an actual pressure sensitive switch or treadle in the roadway. Such devices are presently used to activate stoplights at intersections. It was found, however, that the high installation and maintenance costs and the number required per section of highway made this consideration quite undesirable. To achieve anything near continuous coverage there would have to be a "switch" on the order of one every few feet; this is certainly economically unfeasible. Considering commercially available units, it was found that the size alone (typically 100" x 14" x 7")⁽⁵⁰⁾ makes installation quite an undertaking, involving a large modification of the highway. For the most part, they also can not detect vehicles travelling **in excess** of 60 mph.

b. Magnetic Devices

These devices operate on the principle that all vehicles contain magnetic materials and are therefore capable of changing the field surrounding the detection element. The systems investigated are often difficult to install, involving wholesale excavation of the highway, since they are roughly the size of the above mentioned treadle. They are also highly directional, thus limiting the area of coverage

per unit. Their ~~greatest~~ disadvantage is that such a device can only detect motion of the vehicle. This immediately excludes magnetic vehicle detectors from any further consideration, since, as stated, it was agreed that stationary vehicles should be detectable also.

c. Radar

Certainly, radar could provide the most positive indication of the presence of an object. It has the pronounced advantage of being able to detect non-metallic objects (e.g. persons or animals walking on road), and give complete coverage of the highway. One small disadvantage is that all the necessary equipment must be placed over or at least very near the highway, perhaps on mounting posts along the shoulder. This, in addition to being exposed to the weather, places the equipment in jeopardy of physical damage. Ideal as the system may initially seem, it has one insurmountable drawback-cost. Many systems are currently available for use as traffic counters and speed detectors. A typical unit, available from Automatic Signal Corp. of Oakpark, Illinois, mounted overhead, costs \$900-1000 per installation. This is 3-5 times the cost of some other methods to be discussed.

d. Photoelectric Cells

Photoelectric cells have been used with a great deal of success as traffic counters and as spacers and safety devices in industry. Photo cells, however, have been discarded for several reasons. First, they require poles placed

along the roadside (Figure 38, object A). Second, to detect vehicles in one lane of a multilane highway would require embedding the light source in the road. (Figure 38, object B) This could then be obstructed by snow, ice, or dirt. Third, maintenance would be difficult and obstruct traffic. Fourth, precise aiming of the light source is required during installation. Fifth, there is difficulty in calibration due to extraneous light sources. Sixth, the photoelectric cells must be placed extremely close together to insure complete coverage.

e. Ultrasonics

This method of detection is very similar to radar and, indeed, the advantages and disadvantages are much the same. One additional problem encountered, however, is that the area of coverage from a single transducer is very small. Therefore, obtaining continuous coverage of a lane would be difficult. Again, the cost is very prohibitive. General Railway Signal Co. manufactures a suitable system (again as a traffic counter) which sells for about \$900 per installation. The transducer is mounted overhead on a metal framework. When one considers the great number of these required, the corresponding number of mounting structures themselves is undesirable. These reasons, coupled with the difficulty in adjustment and unreliability, necessitated the elimination of ultrasonics as a detection device for our purposes.

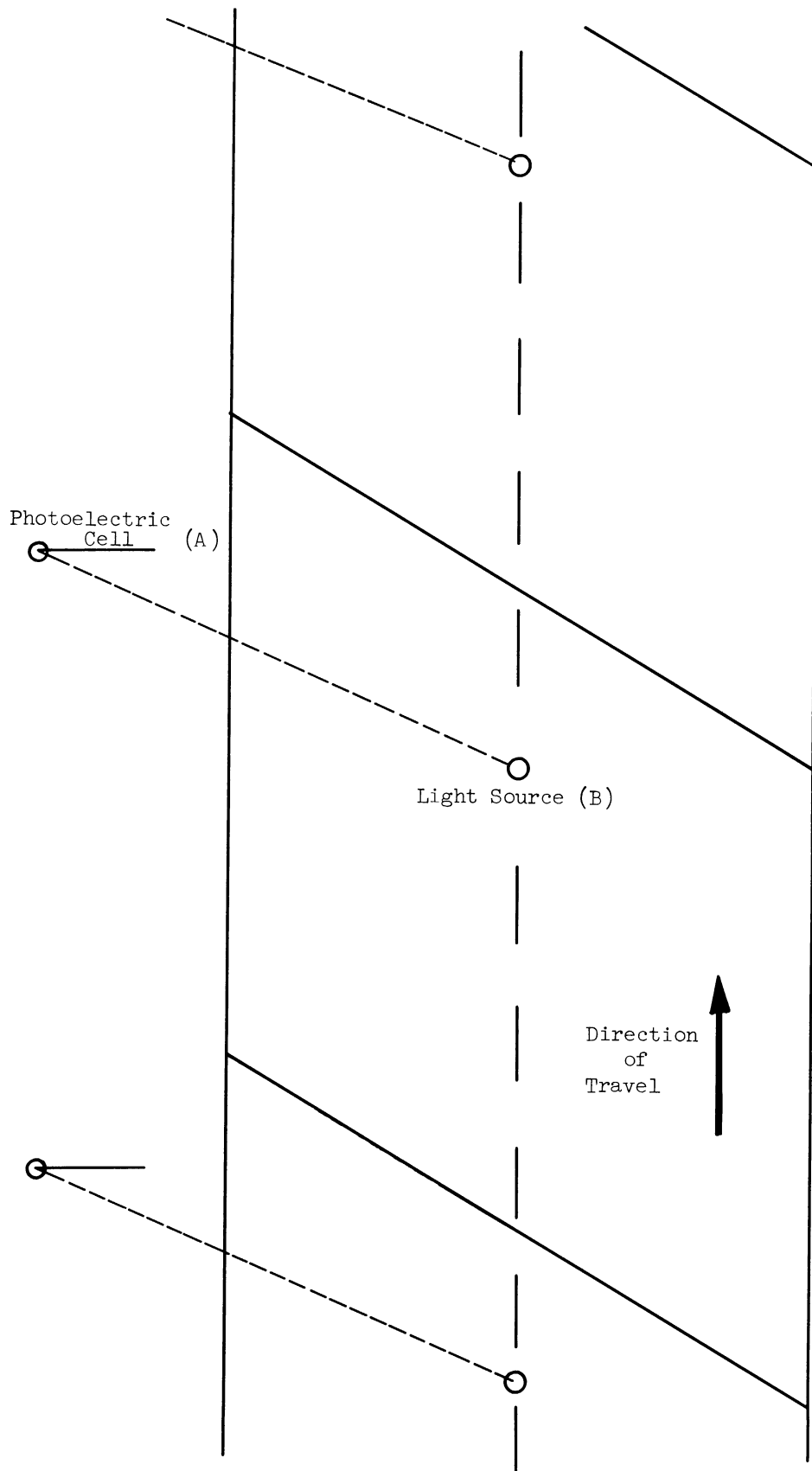


Figure 38. Photoelectric Detection Unit

f. Infra-Red

As a detection instrument, this type of device was used by traffic officials in the early 1950's and has since come into disuse.⁽²²⁾ The main difficulty arises due to problems of ambient light which can be overcome only at the expense of costly electronics with associated reliability problems. This method shares installation problems with radar and ultrasonics; that is, the necessity of some type of mounting framework along the roadside.

g. Strain Gages

Using a strain sensor to detect the presence of a vehicle on a section of highway seems unique. Presently, most highways are designed as an elastic beam on an elastic support (Westergaard theory)⁽²³⁾. Because this design theory is used in the construction of highways, a strain gage seems to be the perfect answer for an inexpensive vehicle presence detector. Two different uses of strain gages as presence detectors are detailed below.

The original idea was to see if the strain gages could be attached to the re-inforcement bars already present in the highway. After obtaining information as to the functions of re-enforcement bars, the idea was discarded because the re-enforcement bars are also used to distribute the load from one lane to the other. This would cause the strain sensors to be activated by a vehicle present in the lane not being covered by ACHV, thereby giving false obstacle reports to the vehicles under control.

Should this Automatically Controlled Highway Vehicle System ever be introduced on a highway in which the lanes are independently re-enforced, a strain sensing presence detection system has some unique advantages, viz:

- A. Installation can be made in the slot used for the steering cable. The pavement does not have to be disturbed as is necessary with the loop detection system.
- B. Strain gages can be obtained commercially with resistances of 3000 ohms.⁽²⁴⁾ These gages used in a balanced bridge arrangement (Figure 39) with a 110 volt a.c. supply could be used to operate a relay directly, eliminating the electronic devices necessary with a loop detector.
- C. The balance bridge arrangement (Figure 39) has a failsafe property inherent in its design. The full bridge has four elements; should one element fail the full bridge could be switched to a half bridge automatically and operate normally until the inoperative element was replaced.⁽²⁵⁾ The open circuit caused by an element's failure could trigger a warning device in a central control station in order to initiate repair action.
- D. The strain sensors give coverage over a large area; hence they could be placed at intervals to give continuous coverage.
- E. Strain sensors do not wear out from use.⁽²⁵⁾ Therefore they would be a permanent installation.
- F. The detection system in Figure 39 would be very inexpensive compared to a loop detection system. Commercial loop detection systems run from \$200 to \$300 apiece while the approximate cost

of strain gage detection system is \$25.

strain gages	\$3.00 each	\$12.00
relays	1.00	5.00
resistors	1.00	2.00
wire	6.00	6.00
		<hr/>
TOTAL		\$25.00

G. The strain sensing device could be used with the same roadside transmitters as the loop detectors presently used, making it possible to use both strain gage and loop detectors in the same system.

To avoid the problem caused by the distributing effect of the the re-enforcement bars, it was suggested to embed in the highway an independent beam with the strain gages on the beam. (Figure 40). The beam's maximum deflection could be set at 1/16 of an inch, thereby being un-noticable to the passengers in vehicles passing over it. For ease of construction, the beams could be kept narrow, three to four inches wide and covering about 90% of the width of the ACHV lane. These units could be mass produced.

This idea was also discarded because it required cutting into the highway in order to position the beams. See Figure 40. Also it would be difficult to adjust the surface of the beam flush to the surface of the road. There would be a substantial increase in cost due to manufacturing the beams, and this system would not offer complete coverage of the ACHV lane.

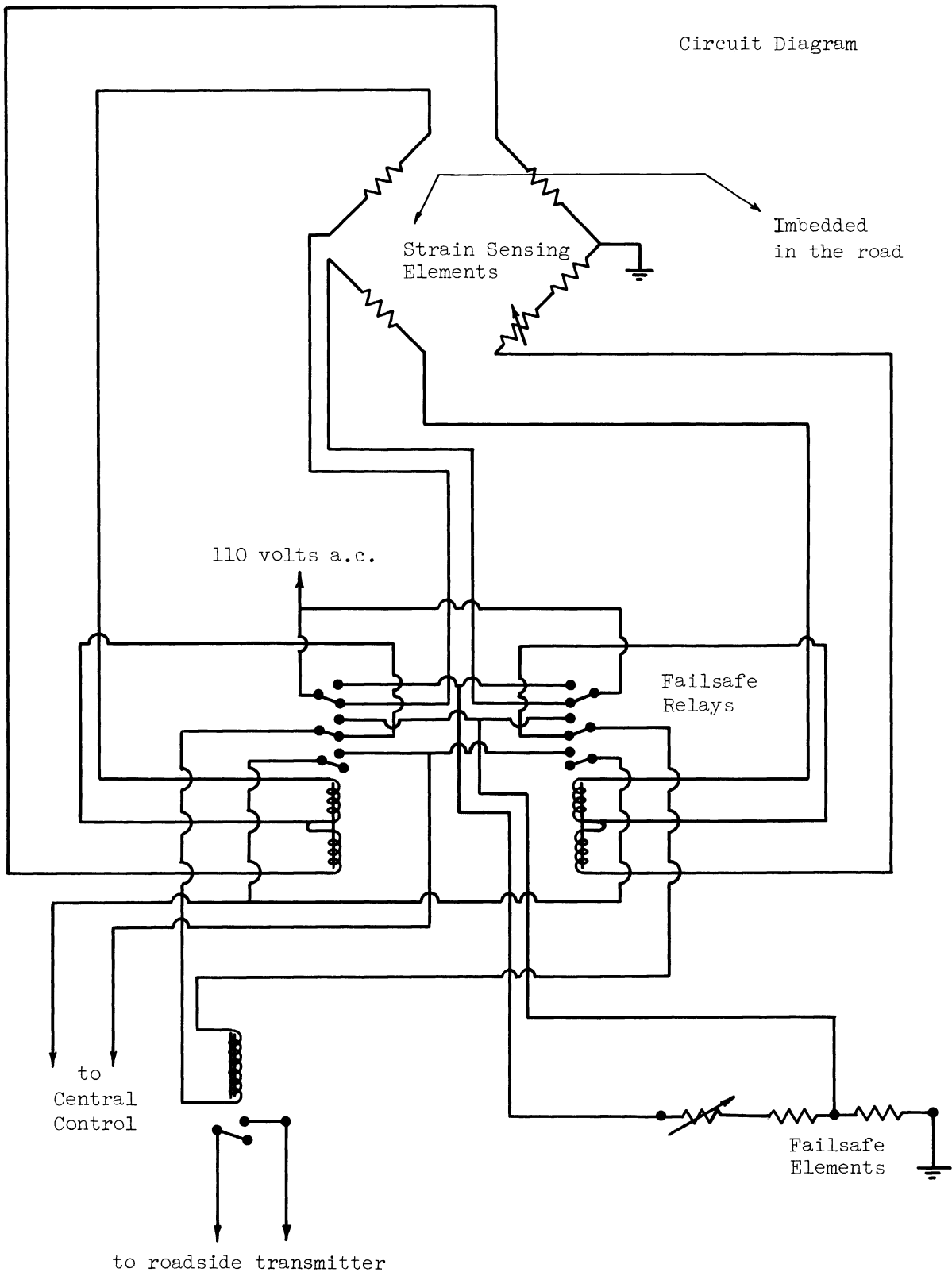
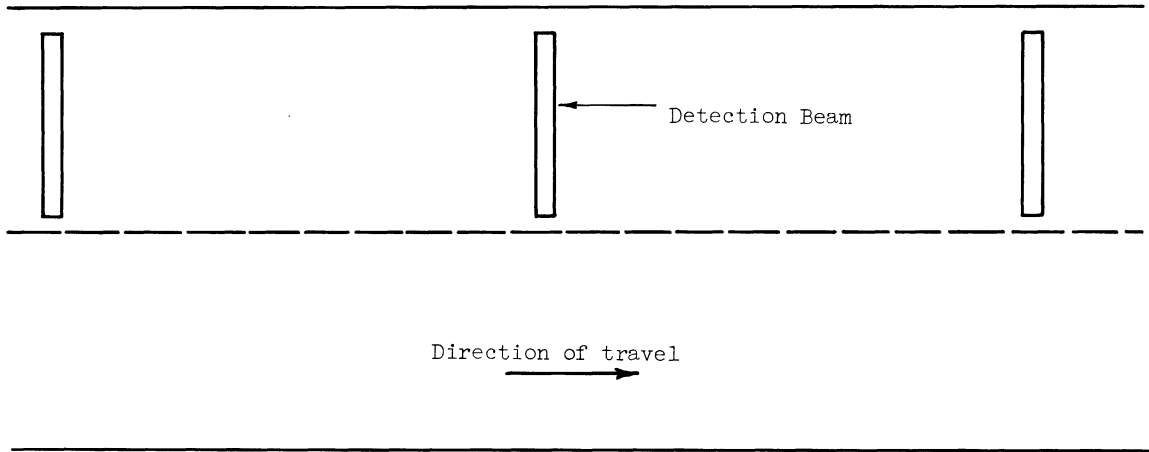
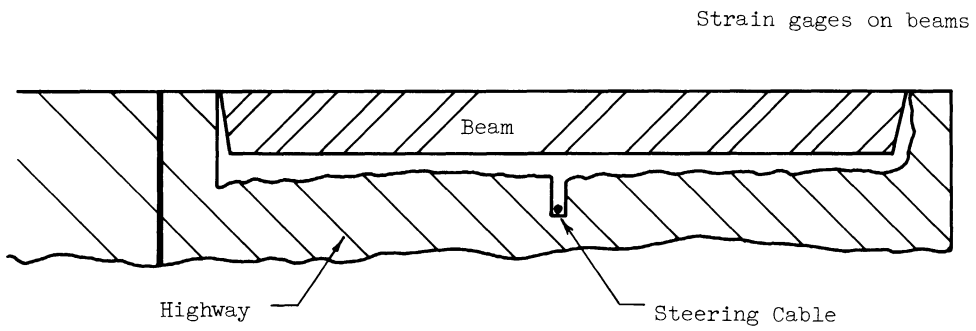


Figure 39. Strain Sensor Presence Detector



A. Top View



B. Cross Section View

Figure 40. Beam Detection Unit

The first strain gage system discussed satisfies all of the design requirements of this project, except for the problem of transverse loading across the lanes. That is, disregarding transverse loadings, it is compatible with existing highways, applicable to limited access highways utilizing only one lane, requires a minimum amount of time and cost for installation, and offers a maximum amount of safety to those using ACHV. It is noted that this system offers great promise if it is to be used where the highway is designed with the lanes independently re-enforced.

Having investigated all the current means of traffic detection, and having attempted to perfect a new device, it is found that all methods considered have certain deficiencies which make them incompatible with the requirements for the detection device set forth. Realizing that compromises do have to be made, it is felt that some of the requirements of continuous coverage, inherent high reliability, and compatibility with existing highway construction techniques must be reduced. With this in mind, the loop detector is again considered.

h. Loop Detectors

In addition to the detectors and associated electronics developed by RCA and GM, it is found that adequate devices are in fact on the commercial market and are being used more and more extensively by traffic departments for providing information on vehicle speeds and densities. Two such detectors are:

-Link Presence Detector, model HLS-1; manufactured by General Precision, Inc. (See Figure 41a)

-TACDET-CP Vehicle Detector, manufactured by
Fischer and Porter Company.

The operation of both these loop detectors is much the same. A rectangular loop of wire, varying in size from roughly 6' x 6' to 10' x 100' is placed in the highway so that cars will pass directly over it. The loop is part of a tuned circuit, and the presence of a metallic object over the loop changes the inductance and, therefore, the phase of the voltage in the loop. It is this change in voltage phase that is detected.

The output of the detector is a relay closure during the time the vehicle is over the loop. The sensitivity is such that the detector will be actuated when 1'-2' of a car is in the loop. ⁽²⁴⁾ Should a vehicle stop within the loop, the detector will maintain an indication of the vehicle's presence for any preset period of time, after which the vehicle will be ignored. The purpose of this feature in the commercial units is to discount parked cars. For our purposes, the detector would maintain the indication of the vehicle's presence (i.e. a closed relay) until it passed out of the loop.

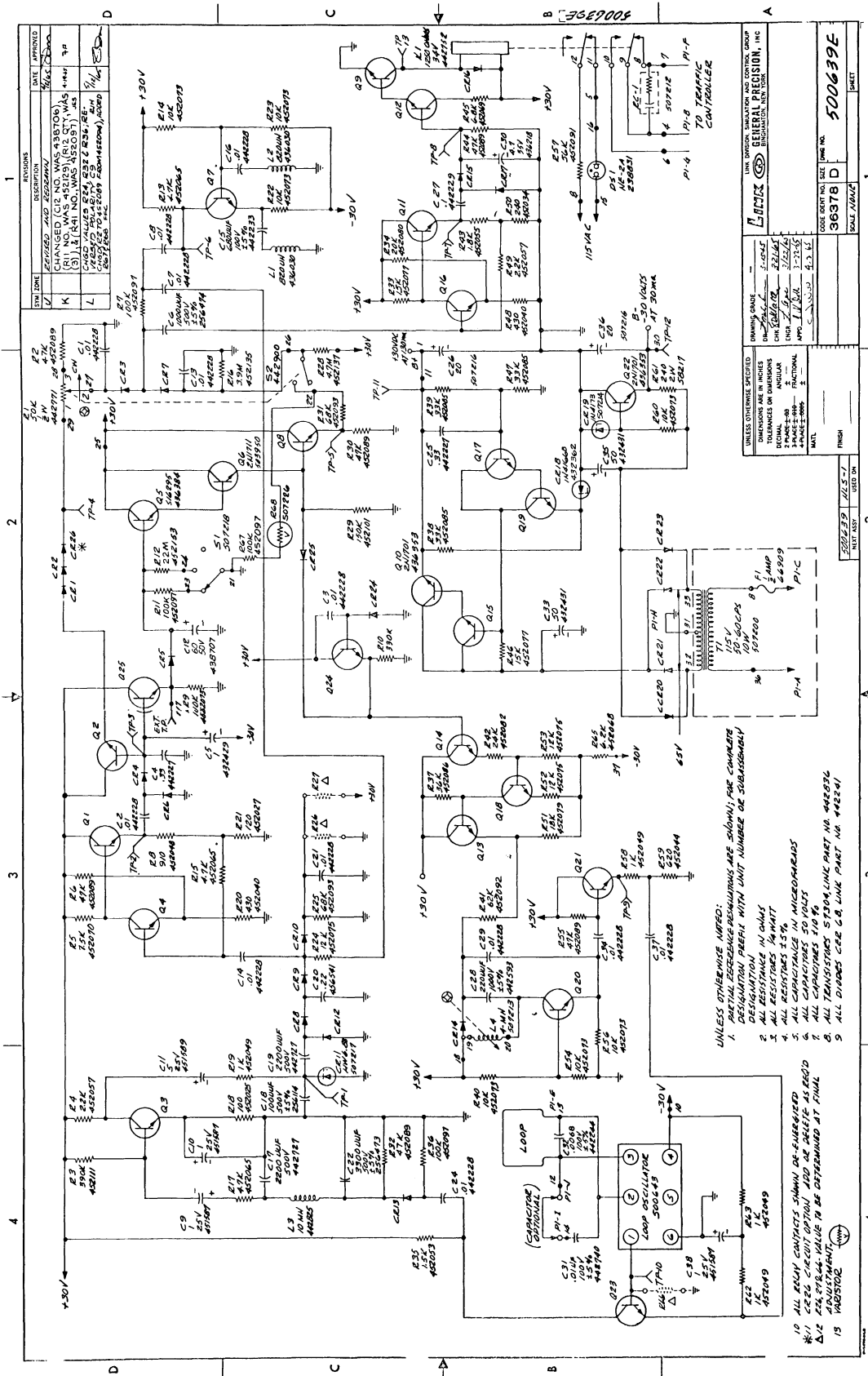
As mentioned before, the loop detector has its disadvantages also. It will only detect fairly large metallic objects. Therefore, such obstacles as animals and people walking on the highway will remain unnoticed. The electronic monitoring equipment associated with a loop detector

is quite complex and therefore, expensive (exact costs will be given later in the report.) Nevertheless, it is estimated that such a detector will cost approximately two-thirds of that of some other systems of comparable ability investigated; namely, ultrasonics and radar. It will also be seen that the number of installations required per mile to obtain the desired coverage is considerably less than many of the lower priced methods investigated.

The advantages which resulted in the selection of the loop detector are quite definite. As just implied, considering the sized of loops possible, continuous coverage can easily be realized with a relativity few number of installations per mile. The installation itself is extremely simple, involving little modification to the highway while using a well established procedure. Once in the highway, the loop requires no maintenance and is extremely resistant to any type of failure.

Installation

The general design plan calls for the detection loop to be placed at the extreme right and left sides of the ACHV lane. The loops would be spaced 8ft. apart, being 42ft. in length (See Figure 41b). This gives an effective loop length of 50ft. The detectors can be placed anywhere along the median side of the road in the vicinity of the loop, the most economical position being along side the transmitter, thus allowing the same power line to supply



UNLESS OTHERWISE SPECIFIED	UNLESS OTHERWISE SPECIFIED
TOLERANCES ON DIMENSIONS	UNLESS OTHERWISE SPECIFIED
1 FRACTIONS	UNLESS OTHERWISE SPECIFIED
2 DECIMALS	UNLESS OTHERWISE SPECIFIED
3 ANGLES	UNLESS OTHERWISE SPECIFIED
4 ROUNDED TO NEAREST 0.001	UNLESS OTHERWISE SPECIFIED
5 UNLESS OTHERWISE SPECIFIED	UNLESS OTHERWISE SPECIFIED
6 UNLESS OTHERWISE SPECIFIED	UNLESS OTHERWISE SPECIFIED
7 UNLESS OTHERWISE SPECIFIED	UNLESS OTHERWISE SPECIFIED
8 UNLESS OTHERWISE SPECIFIED	UNLESS OTHERWISE SPECIFIED
9 UNLESS OTHERWISE SPECIFIED	UNLESS OTHERWISE SPECIFIED
10 UNLESS OTHERWISE SPECIFIED	UNLESS OTHERWISE SPECIFIED
11 UNLESS OTHERWISE SPECIFIED	UNLESS OTHERWISE SPECIFIED
12 UNLESS OTHERWISE SPECIFIED	UNLESS OTHERWISE SPECIFIED
13 UNLESS OTHERWISE SPECIFIED	UNLESS OTHERWISE SPECIFIED
14 UNLESS OTHERWISE SPECIFIED	UNLESS OTHERWISE SPECIFIED
15 UNLESS OTHERWISE SPECIFIED	UNLESS OTHERWISE SPECIFIED

UNLESS OTHERWISE NOTED:

- PARTIAL RESISTANCE DESIGNATIONS ARE SHOWN; FOR COMPLETE DESIGNATION PREFIX WITH UNIT NUMBER OR SUFFIX
- ALL RESISTANCES IN OHMS
- ALL RESISTANCES IN M-HM
- ALL RESISTANCES IN MICROHM
- ALL CAPACITANCES IN P.F.
- ALL CAPACITANCES IN MICROF
- ALL CAPACITANCES IN MICROF
- ALL CAPACITANCES IN MICROF
- ALL DIMENSIONS ARE IN INCHES
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- ALL DIMENSIONS ARE IN INCHES

10 ALL RELAY CONTACTS SHOWN DE-SERIALIZED
 *1 C222 CIRCUIT OPTION, ADD OR DELETE AS REQ'D
 Δ12 C224, S1644, VALUE TO BE DETERMINED AT FINAL
 13 1A252102

500639E
 36378 D
 500639E
 SCALE: 1/8" = 1"

41a. Schematic Diagram Presence Detector

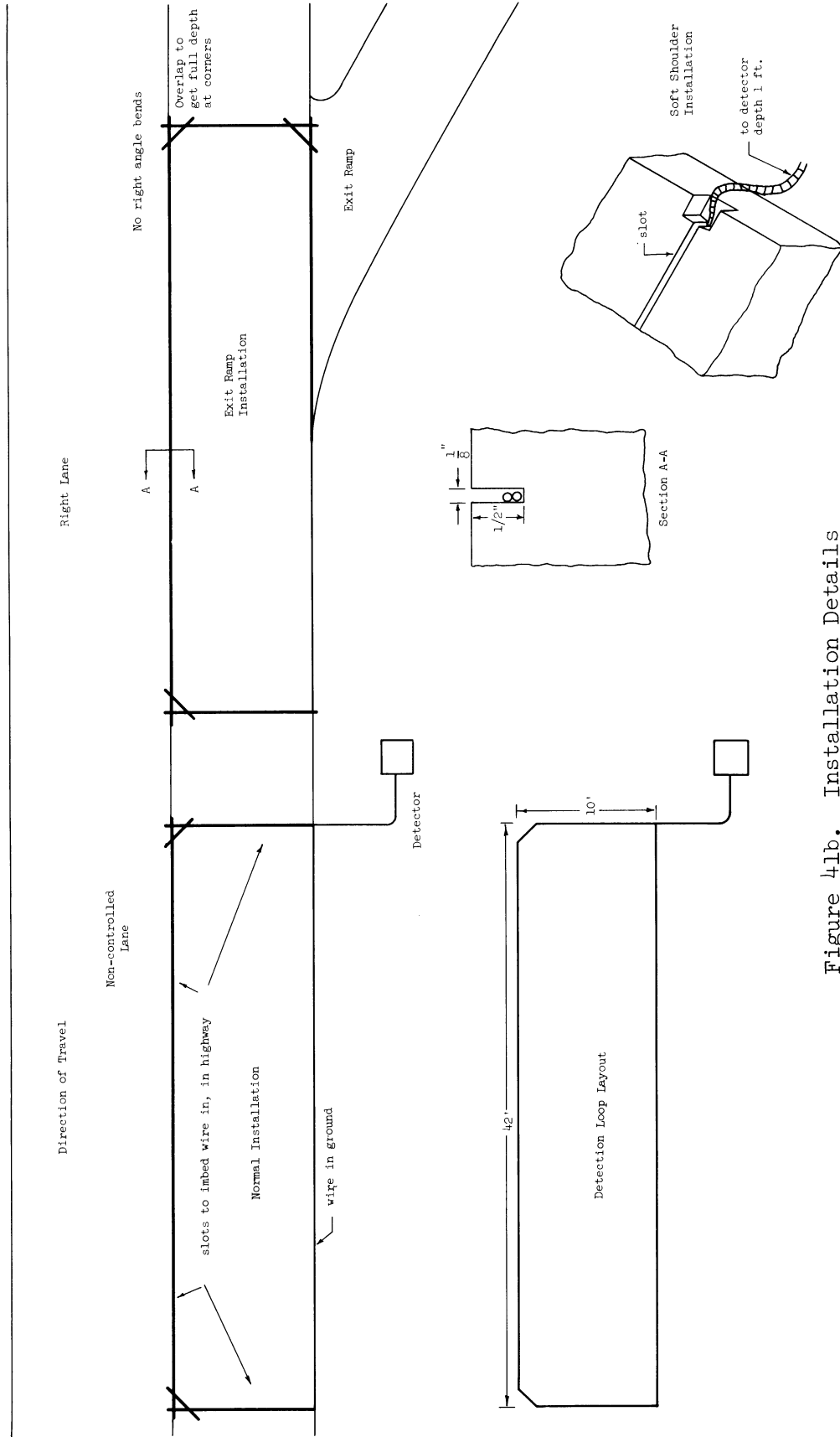


Figure 4lb. Installation Details

both transmitter and detector. If transmitters and detectors were placed at alternate ends of each loop they could be placed in one housing.

Keeping the loops as far above metal re-enforcement as possible is important. (51) To imbed the loops, a narrow, shallow slot is cut in the road surface with a diamond or abrasive saw. In this installation, only three sides of the loop need be imbedded in the highway; as the fourth is being placed in the shoulder along the edge of the road (See Figure 4lb). The slot is filled with a highway grout after installation of the wire. In areas where there are exits and entrances a fourth cut will have to be made for the median side of the loop, and a fifth cut will be necessary to accomodate the detector leading wire (See Figure 4lb). The slots will be $1/2$ to $3/4$ inches in depth, depending upon wire size. The width of the slot will be about $1/8$ of an inch, again depending on wire size. A two component resin that will not soften in hot weather should be used to fill the slots.

The loop should be made of one continuous length of wire if possible. If not, all splices should be soldered and waterproofed. Care should be taken not to coil any part of the lead-in wire.

The wire should be pressed into the slots with wooden instruments so as not to damage the insulation.

Loop Specifications

Size	10 ft by 42 ft
Spacing	8 ft
No. of turns in Loop	2
Slot Depth	1/2 inch
Slot width	1/8 inch
Grout	2 Compound type resin
Type of wire	# 14TW

Lead Specifications

Type of wire ⁽⁵²⁾	#14-2UF
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Detector Specifications

Either ⁽⁵²⁾	Link model HLS-1
or	Tacdet

Thus, a means of detecting the presence of a vehicle has described and its installation explained. This is only the first of the three phases of the overall spacing problem. Next is a consideration of how an obstacle's presence on the highway is to be relayed to upcoming vehicles.

3. Relay of Information

a. Introduction

The first decision is how far down the highway it is necessary to transmit this information as to the presence of an obstacle. For reasons of economy it should be no further than that required for safety. At 75 mph, it takes 253 feet to stop a vehicle at a deceleration of 24 feet

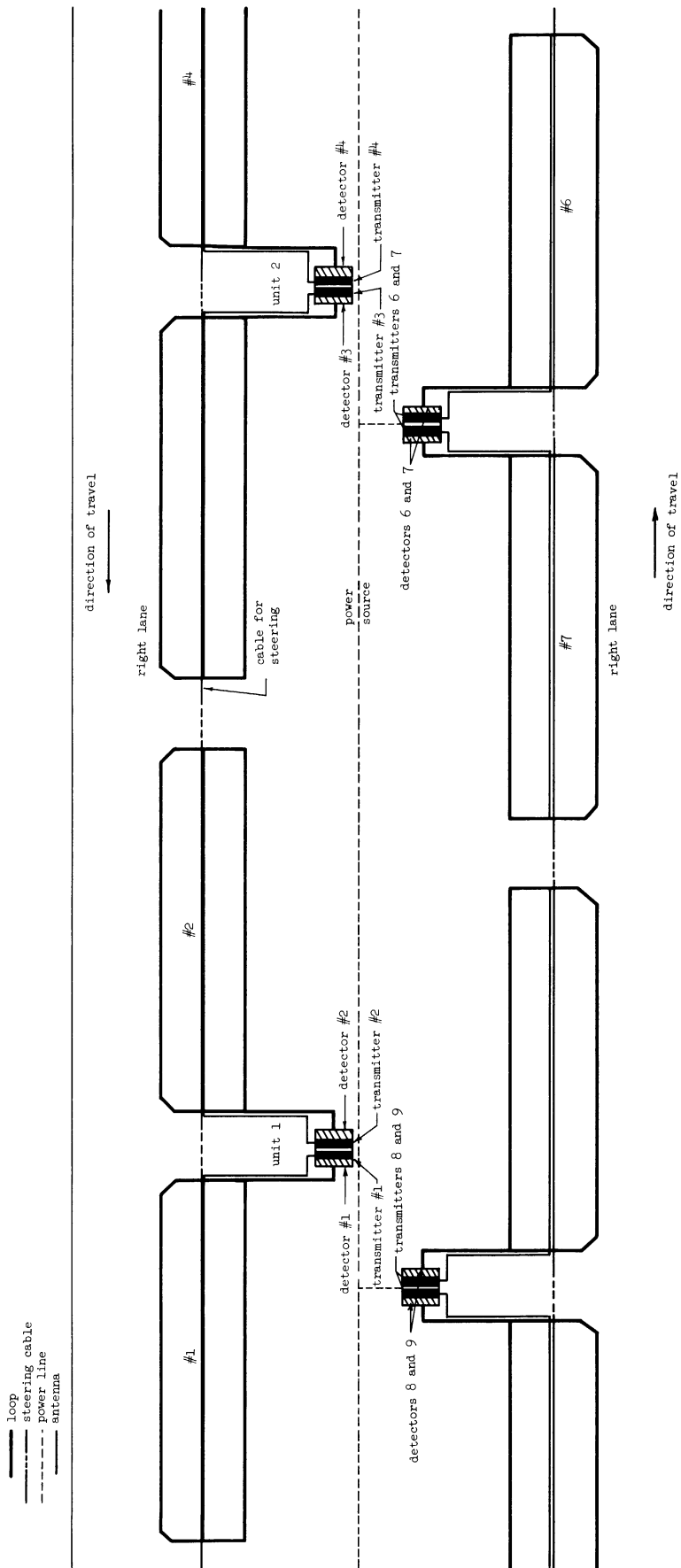


Figure 42. Basic Layout of Spacing System

NUMBER OF LOOPS per mile	LENGTH OF LOOPS in feet
264	20
211	25
176	30
151	35
132	40
106	50

LENGTH OF LOOP	CAUSES INCREASE IN
increase	ease of installation
decrease	reliability and safety
decrease	cost of installation
increase	uncertainty of position
decrease	speed calculation accuracy

Figure 43. Variation in Some Loop Parameters

per second⁽¹²⁾, about the maximum deceleration possible by internal means. (Refer to Figure 44) This does not include driver reaction time, which could conceivably double the distance. However, the automatic system will have a much reduced reaction time. Using 300 ft. as the recommended spacing the upcoming vehicle will be able to stop before striking any stationary vehicle. The speed allowed under various weather conditions will be such to allow the vehicle to stop within 300 feet. This command speed is predetermined at a centralized control center.

At first glance, it appears that this large a spacing is not necessary. Indeed, the rule of thumb is to allow one car length for every 10 mph you are traveling. This is acceptable,

assuming that all cars are moving relatively close to the same speed. Certainly, a lead vehicle requires approximately as much distance as the trailing vehicle to decelerate equivalently. But what happens in an accident; the vehicle is decelerated by other than internal means and may come to rest within a very short distance. In this case, the "rule of thumb" does not provide for an adequate stopping distance. Furthermore, statistics show that the majority of accidents on high speed expressways are rear-end collisions. From this standpoint the proposed system shows definite advantages in terms of safety.

Demanding such a large minimum spacing has the effect of reducing the density of cars. However, it also means that a higher average speed can be maintained safely, which results in an increased flow rate. The increased distance between vehicles also means that there will be much more room for unequipped vehicles to safely pull in and out of the controlled lane. Furthermore, the disturbance caused by this merging will be less and the traffic will flow more smoothly.

In conclusion, 300' is the distance which this system tries to maintain between vehicles. Any obstacle will be observed (via the transmission system to be discussed) by any equipped vehicle within the 300' controlled spacing interval (CSI). Beyond this, the road appears clear to the upcoming vehicle.

As previously mentioned, our system was designed to accommodate both equipped and nonequipped vehicles, allowing the nonequipped vehicles in the outside lanes to pull into the

INITIAL SPEED

NEGATIVE ACCELERATION

		to zero at 24 fps ²		to 50% V at 10 fps ²		to 50% V at 24 fps ²	
MPH	FPS	t	s	t	s	t	s
7.5	11	0.46	5.1	0.38	3.14	0.23	1.9
15	22	0.92	10	1.1	18.1	0.46	7.6
22.5	33	1.38	23	1.65	43.4	0.69	11.1
30	44	1.83	40	2.20	72.6	0.92	30.3
45	66	2.75	91	3.30	167	1.38	68.1
50	73.5	3.06	112	3.67	201	1.53	84.4
55	81.5	3.39	138	4.07	248	1.69	98.5
60	88	3.66	162	4.40	290	1.84	121
65	95.5	3.97	188	4.77	332	1.99	142
70	102.5	4.27	219	5.14	395	2.15	165
75	110	4.59	253	5.50	454	2.30	190
90	130	5.42	353	6.50	668	2.72	265

		to 25% V at 10 fps ²		to 10% V at 6 fps ²		to 10% V at 2 fps ²	
MPH	FPS	t	s	t	s	t	s
7.5	11	0.28	2.7	0.18	1.78	0.55	5.8
15	22	0.55	10.6	0.37	7.25	1.10	23.0
22.5	33	0.83	24.0	0.57	16.9	1.65	51.6
30	44	1.10	42.3	0.73	28.9	2.20	92
45	66	1.65	95.0	1.10	65.5	3.30	207
50	73.5	1.84	118	1.22	80.7	3.67	256
55	81.5	2.04	145	1.36	99.5	4.08	316
60	88	2.20	169	1.46	116	4.40	368
65	95.5	2.39	199	1.59	137	4.78	434
70	102.5	2.56	230	1.71	158	5.12	498
75	110	2.75	265	1.83	181	5.50	575
90	130	3.25	370	2.17	254	6.50	804

t - time in seconds
s - distance in feet to respond

Figure 44. Braking Distances

controlled lane for passing. Clearly then, an ACHV may not always enter this CSI at its extreme end. (Consider what would happen if a vehicle pulled into the controlled lane 100 feet ahead of an equipped vehicle). The trailing vehicle must, therefore, know not only that it is within 300 feet of an obstacle, but also how close it actually is.

Again, the road is considered divided into blocks, or more specifically, the CSI created by the lead vehicle is divided into distinct sections. For reason of economy and applicability, the number of blocks should be kept to a minimum. All logic points toward making these the same length as the detection blocks i.e. 50 feet.

b. Component Description

Associated with each detection block is a transmitter, its antenna running down the center of the lane with the steering cable. The antenna extends the length of the detection block; therefore, the field of each antenna is such that the transmitter services only that one block. The transmitters are similar to those used by hobbyists for radio controlled models. They are called tone transmitters and broadcast a continuous carrier in the 27 megacycle range, upon which any one of a different number of tones may be imposed (in this case, from 400 cycles per second to 600 cycles per second). A 6-channel transmitter, such as the Model SL-6, manufactured by the Citizen-Ship Radio Corp. (See Figure 45) is used in this system.

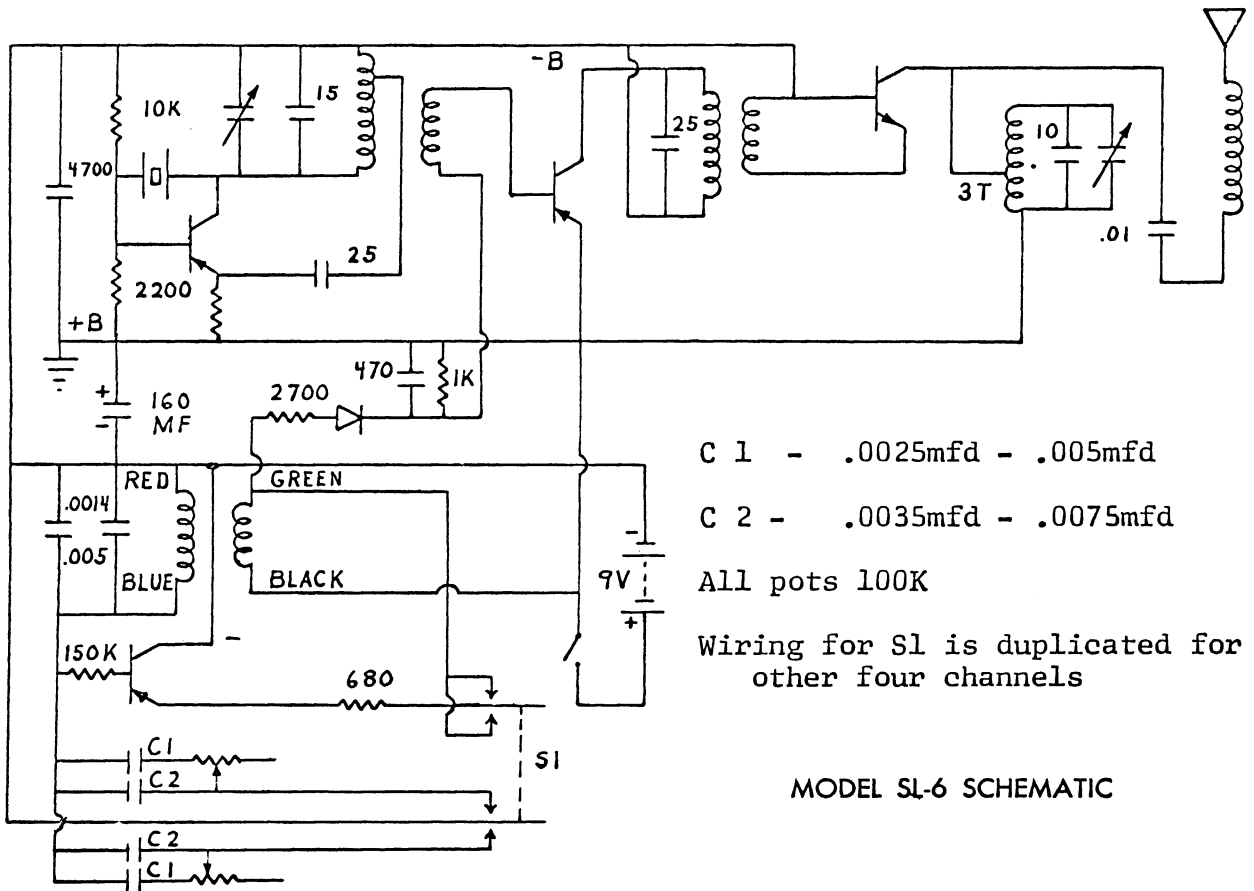


Figure 45. Six Channel Transmitter for Detection Block

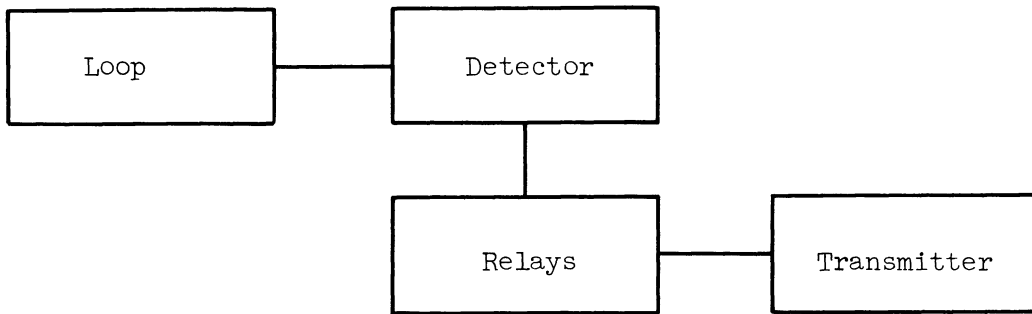


Figure 46a. Block Diagram of Presence Detection System

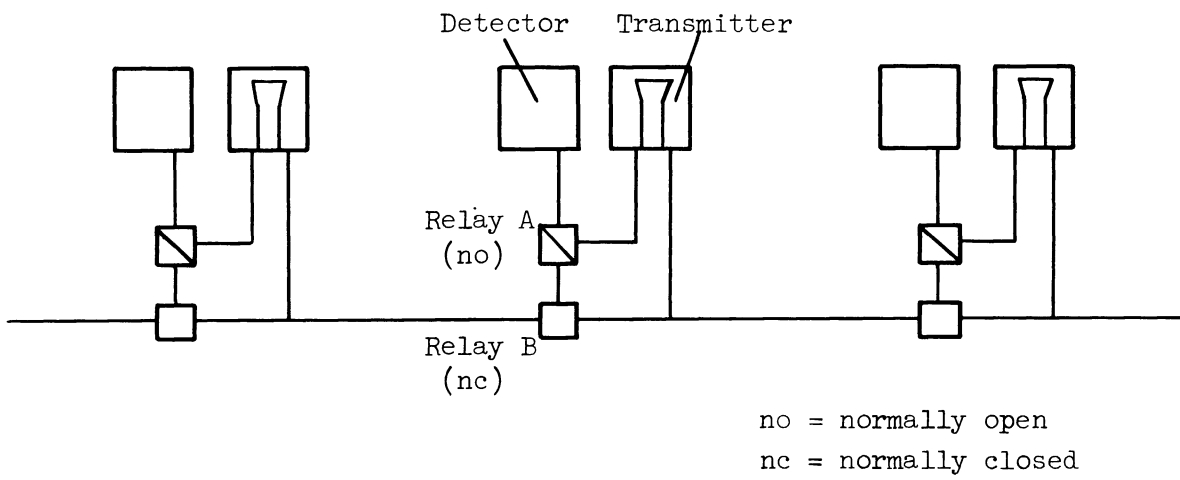


Figure 46b. Interconnection Diagram

A car passing over a detector will actuate a relay that will turn on the transmitter in the trailing block (not the one occupied by the vehicle) to a broadcast a specific tone; the next block, a different tone, and so on, in a definite sequence for the six blocks (i.e. 300 feet) immediately behind the lead vehicle. When the vehicle passes into the next block, the immediately succeeding blocks again will be activated. Therefore, a controlled vehicle within 300 feet of the lead vehicle may determine the relative spacing by the tone of the carrier. The detector itself merely performs the task of switching the various transmitters on and off. Referring to Figure 46 and 47, it is seen how this is accomplished. The relay marked A turns on the six transmitters that form the controlled spacing interval behind each car. The relays marked B disconnect all other lines going to each of these six transmitters when relay A turns on. This eliminates all signals except the one from the car directly in front of the ACHV. It is important to note that there is no overlapping of control zones. The CSI of one vehicle extends only as far back as the first obstacle behind it, which in turn originates its own CSI.

Detection and Transmission System

Cost Analysis

Leadin Wire	20' at \$0.023 per ft.	\$.50
Loop	104' at \$0.023 per ft.	2.40
Detector	\$100.00 per unit	100.00

Transmitter	\$74.95 (retail)	\$	34.00
Relays (2)	\$ 3.55 (retail)		3.75
Power Lines	50' at 0.05 per ft.		2.50
interconnection lines	775' at \$0.01 per ft.		7.75
Saw cuts	20' in concrete at \$0.10/ft.		2.00
	42' in expander at \$.05/ft.		2.10
	84' in ground at \$.05/ft.		4.20
Epoxy Sealer	\$8.00/gal. (retail)		5.00
Labor	Operate Saw	2 hours	
	Insert Loop and Seal	1 hour	
	Set up road signs and direct traffic	1 1/7 hour	
	Connect detector, trans- mitter, and relays	2 hours	
	Put in Power lines	1/2 hour	
	Put transmitter inter- connects	2 hours	
		<hr/>	
		9 hours	
	9 hours at \$3.00/hour	27.00	27.00
Housing for detector, transmitter, and relays			25.00
			<hr/>
			\$216.20

In large quantities approximately 225/installation

105.5 x 225 = \$23,630/mile

4. Receiving System

a. Introduction

The primary concern of an equipped vehicle is to know if any obstacle is in its path and, if so, how far away it is. To insure smooth and appropriate responses for all situations, however, it is necessary to also know how fast the vehicle is approaching the obstacle. In the case of two vehicles, it is necessary for the trailing vehicle to know both the spacing and relative velocity.

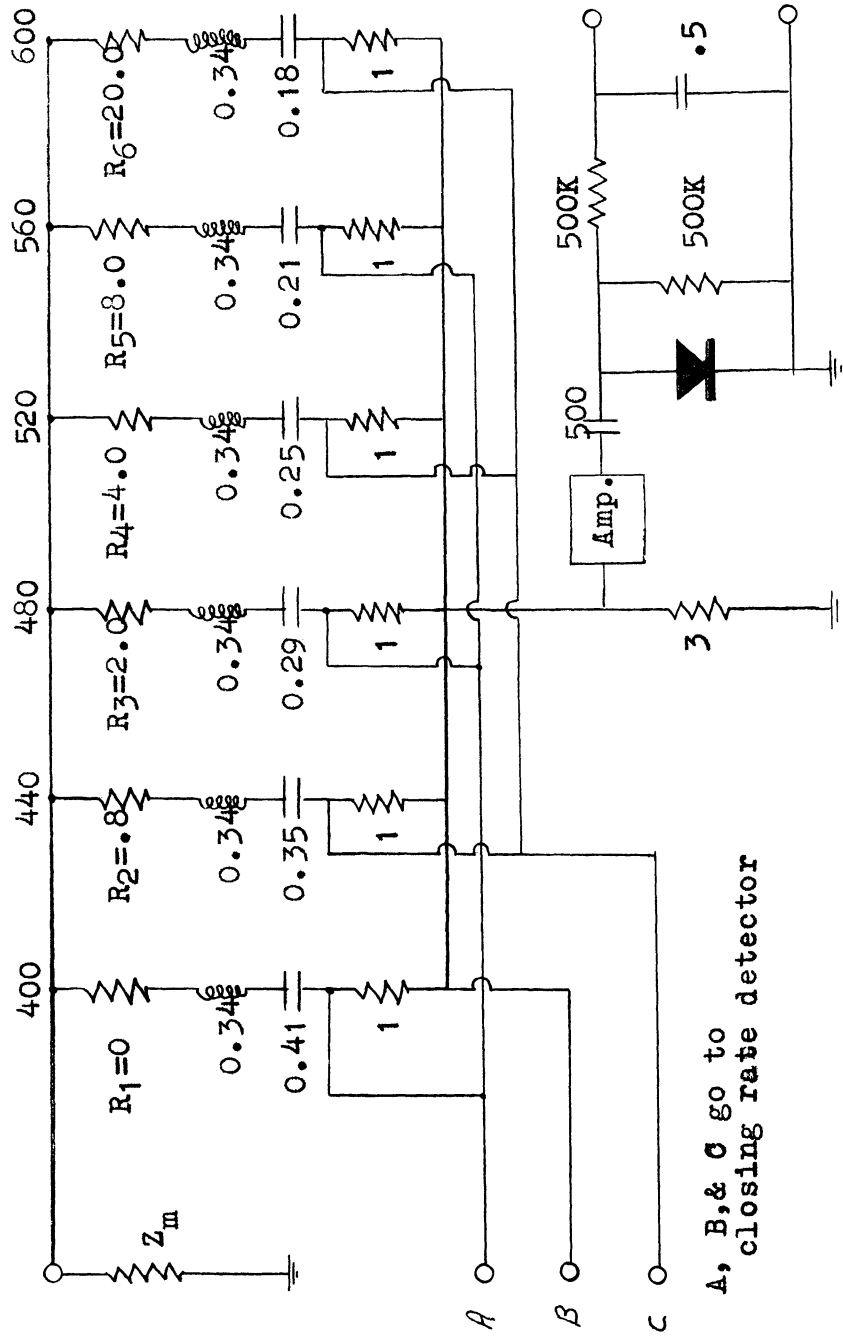
The receiving system then has three functions. One, it receives the spacing information from the detection system. Two, it transforms this into the relative velocity of the two vehicles involved. Three, it utilizes the combination of separation distance and relative velocity in finally determining the desired degree of braking.

b. Receiver

The receiver used in this system is a six-channel unit similar to the transmitter described earlier. A typical example of the type needed is the Model RL-6 made by the Citizen-Ship Radio Corp. (See Schematic, Figure 48). Reception is through an antenna mounted on the bottom of the vehicle.

1. Spacing Signal

Information as to the position of the vehicle is carried in six different channels of the receiver. Each different frequency corresponds to a distance (See Table below), after conversion to a corresponding dc voltage.



A, B, & C go to closing rate detector

Figure 48. Six Channel Receiver

(See Figure 48).

Channel	Frequency (cps)	Spacing	
		Min	Max
1	600	300	350
2	560	250	300
3	520	200	250
4	480	150	200
5	440	100	150
6	400	50	100

Each of the six LC networks in Figure 48 is tuned to resonate at one of the information frequencies. Conductance in any network results in a voltage across the 3 ohm resistor, the relative value of which is determined by the voltage divider composed of the 3 ohm resistor and $R_1, R_2, R_3, R_4, R_5, R_6$. This output in turn is amplified to obtain the required dc level to control braking after rectification with a peak above average rectifier. For the voltage divider shown in Figure 48, the output voltages are in the ratios 1:2:3:4:5:6.

The Q of each of the LC networks is about 45. This gives a Δf of approximately 12 cps centered at each of the six channel frequencies. This gives good selectivity, but also allows for some drift in the information frequencies.

2. Determination of Closing Rate

The closing rate of two vehicles is determined by a RC network (See Figure 49). The capacitor is charged to 12 volts and allowed to discharge through a resistor for

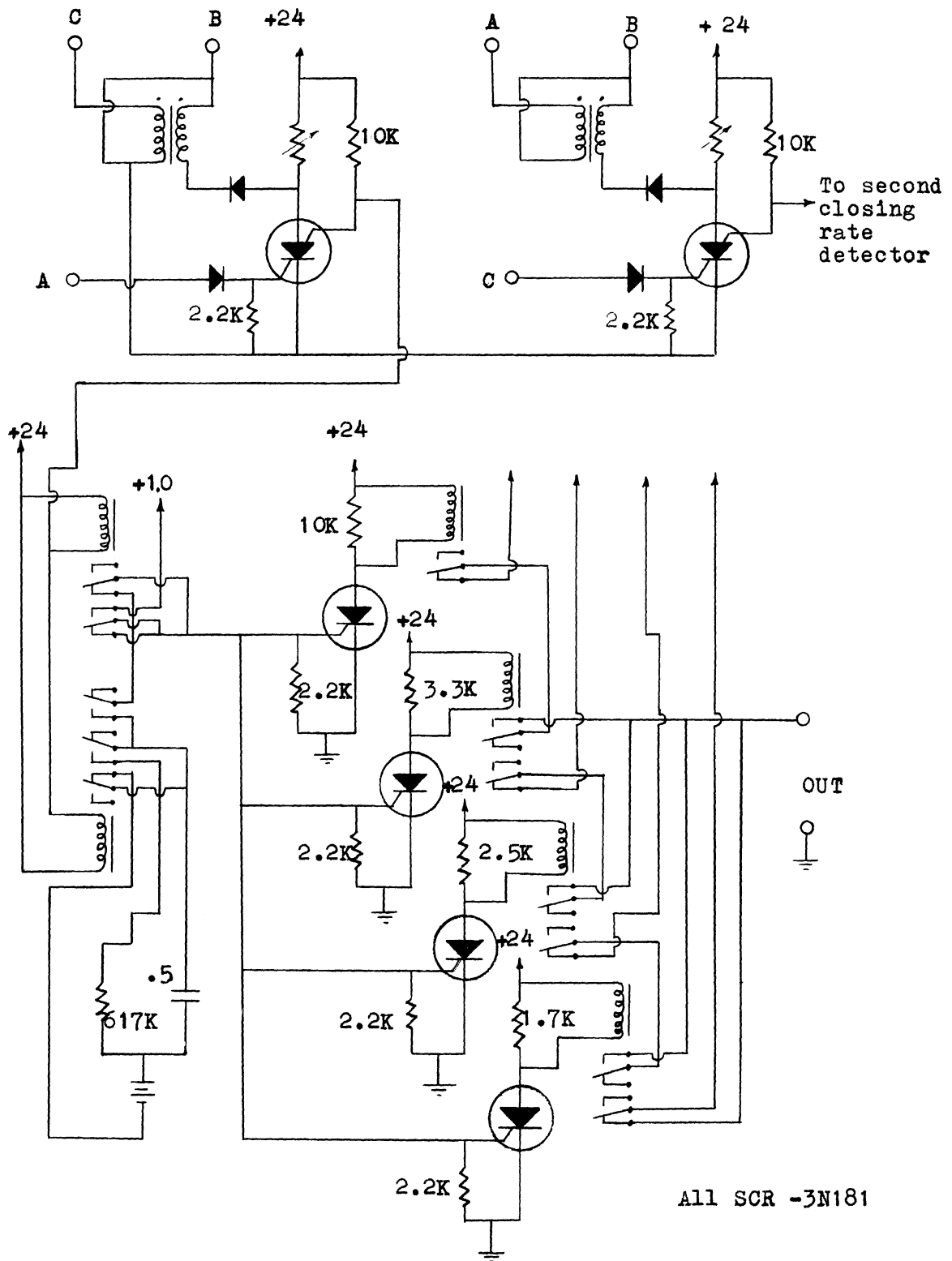


Figure 49. Relative Velocity Detector

a certain period of time, the time being that between successive frequency changes, which is the time required for the spacing between two vehicles to change by 50 feet. It is, in effect then, an indication of the average relative velocity between the two vehicles. The silicon controlled switches and relays in Figure 49 serve to start discharge, stop discharge, reset all elements to initial values, and give desired output.

Any desired dc level may be obtained for any specific range of relative velocities. It is desirable to accurately determine relative velocity. However each additional refinement involves the addition of one more silicon controlled switch, relay and associated circuitry, with the accompanying cost increase. For our purposes satisfactory information is obtained using five distinct ranges.

3. Derivation of Braking Signal

The separation and relative velocity are known in terms of dc levels. Actually, only ranges of relative velocity and separation are known. This presents the greatest obstacle in attempting to derive a braking pattern which incorporates safety and a reasonable degree of passenger comfort, further complicated by the fact that only distinct degrees of braking may be realized.

For every value of spacing and relative velocity there is a unique value of deceleration required to prevent a collision. The 300 foot controlled spacing interval allows enough space

for the upcoming vehicle to stop, provided maximum deceleration is applied within 50 feet after entering the controlled spacing zone.

A summary of deceleration rates for different spacings and relative velocities is given in Figure 50. Realizing that on a dry pavement, the maximum deceleration a vehicle can develop internally is about 24 feet per second squared, Figure 50 indicates the numerical limits of spacing and relative velocity beyond which braking alone cannot prevent a collision. What any system must do is consider combinations of spacing and relative velocities (with their associated uncertainty) and produce an output that is the appropriate deceleration for each situation. The actual mechanism of converting the values for spacing and relative velocity into a deceleration signal must also be kept as uncomplicated as possible.

Utilizing the information of Figure 50, a compromise system has been designed, attempting to combine such factors as low cost, adaptability to largest possible variety of situations, and high passenger comfort.

The operation of the system is as follows:

- (1) output voltages of 1, 2, ... 6 volts dc are assigned to spacing distances as follows
- | | |
|----------|---------|
| 50 feet | 6 volts |
| 100 feet | 5 volts |
| 150 feet | 4 volts |

<u>Separation</u> (Feet)	<u>Relative Velocity</u> (m.p.h.)	<u>Required Deceleration</u> (ft/sec ²)
50	10	2.15
50	20	8.6
50	30	19.3
50	40	34.4
50	50	53.8
50	60	77.5
100	10	1.08
100	20	4.28
100	30	9.65
100	40	17.2
100	50	26.9
100	60	38.75
150	10	0.71
150	20	2.85
150	30	6.43
150	40	11.5
150	50	17.9
150	60	25.8
200	10	0.53
200	20	2.14
200	30	4.82
200	40	8.60
200	50	13.45
200	60	19.4
250	10	0.43
250	20	1.71
250	30	3.86
250	40	6.85
250	50	10.76
250	60	15.5
300	10	0.36
300	20	1.43
300	30	3.22
300	40	5.74
300	50	8.95
300	60	12.90

Figure 50. Required Deceleration Rates.

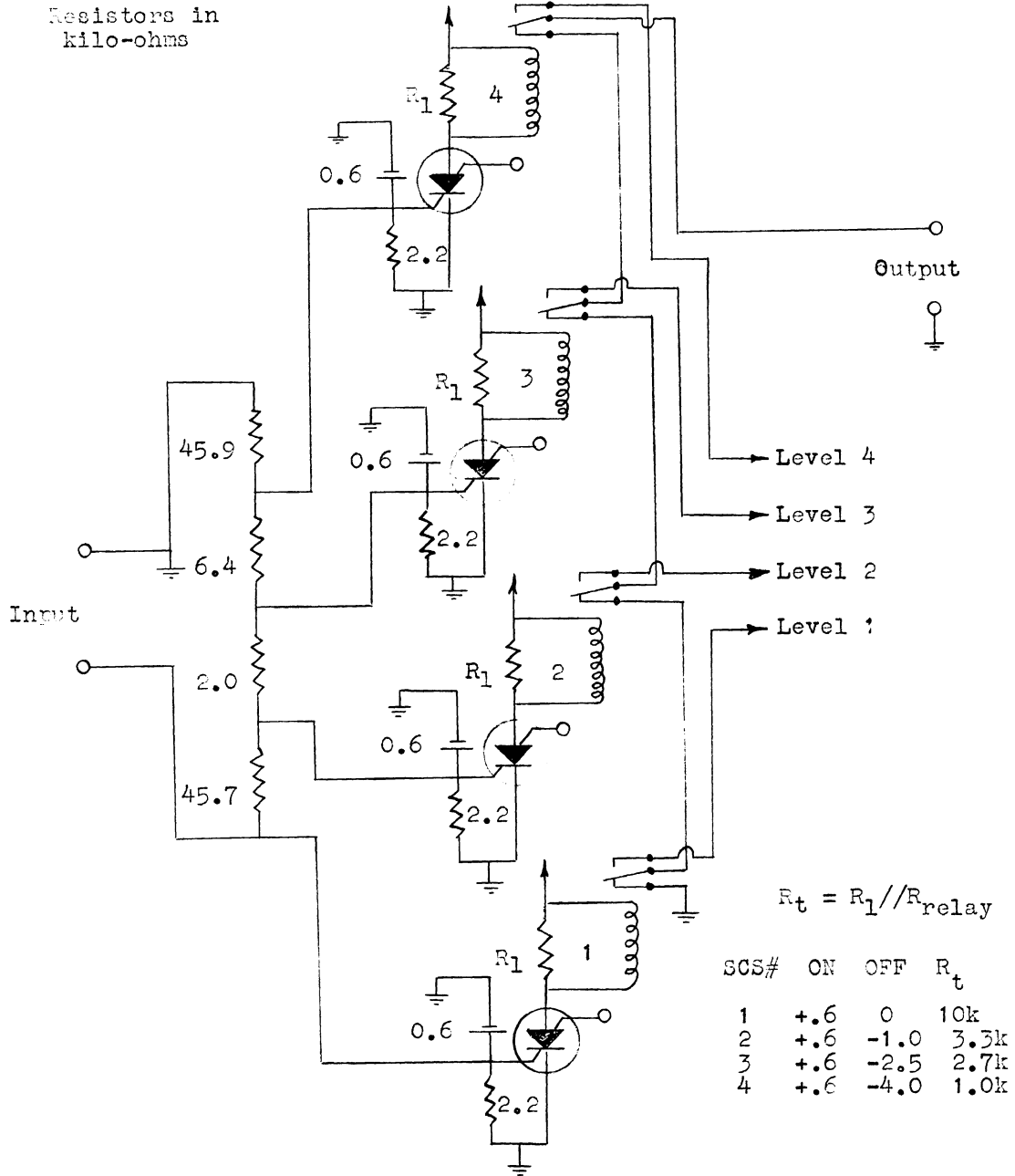


Figure 51. Braking Level Computer

200 feet	3 volts
250 feet	2 volts
300 feet	1 volt

(2) output voltages are assigned to these ranges of ranges of relative velocities (See Figure 51)

- 50 V_r
- 37 $V_r - 50$
- 30 $V_r - 37$
- 20 $V_r - 30$
- 8 $V_r - 20$
- $V_r - 8$

It may be mentioned that it is the ratio of the values given that is of importance, and so long as this ratio is maintained, the result remains the same.

In this particular solution, we have allowed for a relative velocity of up to 60 mph for a vehicle pulling into the controlled lane less than 300 feet away. This indeed is one of the more extreme cases that could possibly result. Ordinarily, the relative velocity will be only a few mph. The system does have this extended capability, however.

The trailing car will receive a braking signal of a specific degree whenever it is in the 300 foot controlled spacing zone of the lead vehicle. In other words, cars will seek to maintain the desired spacing of 300 feet no matter what the velocity.

This section on automatic spacing control has mentioned only braking. As now envisioned, the spacing control operates merely as an override on the speed control mechanism. When a car is receiving no spacing signal (i.e., is greater than 300 feet from the nearest obstacle), the speed control will seek to maintain the command speed as set by a centralized control headquarters. This requires nothing more than operation of the throttle. Entrance into a controlled spacing zone will require only braking, and any action, from decompression braking to a panic stop, entails a release of the throttle. Once out of the controlled spacing zone, the speed command again takes over.

Receiving System Cost Analysis

Receiver	54.95 (retail)		26.00
Filter for dc braking control			
	11 Resistors (precision) \pm 5%	1.50	
	6 Inductors (precision) \pm 2%	1.50	
	6 Capacitors (precision) \pm 2%	1.50	
	3 Resistors \pm 10%	.15	
	2 Capacitors \pm 10%	.30	
	1 Diode	.75	
	Labor	3.00	
		<u>8.70</u>	<u>8.70</u>
			34.70

per installation about \$35.00

D.5. Conclusion

Various systems for detecting the presence of an obstacle have been presented. The strain gage system was found very promising, and a detailed analysis of its potential was completed. However, due to the construction of present highways, the system will not be used as part of the over-all design presentation. Instead, a loop detection device was analyzed, and its installation specified. Having done this, the transmission and reception of the detection information was discussed, including an analysis of necessary components.

E. Servo-Mechanism Control

1. Introduction

Given an electrical input, as described in the preceding sections, corresponding to velocity, effective wheel angles, lateral displacement, spacing, etc., it is necessary to convert this signal into an appropriate output, i.e., braking accelerating, turning. The response produced must be as required by the individual system specifications, and it must be as efficient and economical as possible.

For the purposes of this system, the conversion of the electrical signals into mechanical work can be accomplished using:

1. Electrohydraulic servo-systems
2. Electric servo-motors
3. Solenoids

2. Electrohydraulic Servo-Mechanisms

Electrohydraulic servo-mechanisms have three basic components:

1. An actuator
2. A valve system
3. A solenoid or torque motor to move the valve.

Actuators are available with either lateral or radial movements. High torques and/or large forces can be achieved with relatively small units (refer to section on rotary actuators).

There are three types of valves used either as a single or a two stage unit; they are

1. Spool valve
2. Flapper valve
3. Jet pipe.

Since it will be shown that it is desirable to use a combination of the above units, the operation of each will be discussed individually, and finally a combined system will be described.

a. The Spool Valve

The spool valve acquires its name from the piston-like member that resembles the spool upon which sewing thread is wound. The raised portions of the spool, L_1 , L_c , and L_r , are called lands. L_1 and L_a open and close the exit ports #2 and #3 respectively. See Figure 52. The center land controls the inlet pressure flow rate (Q). If moved to the right, orifice

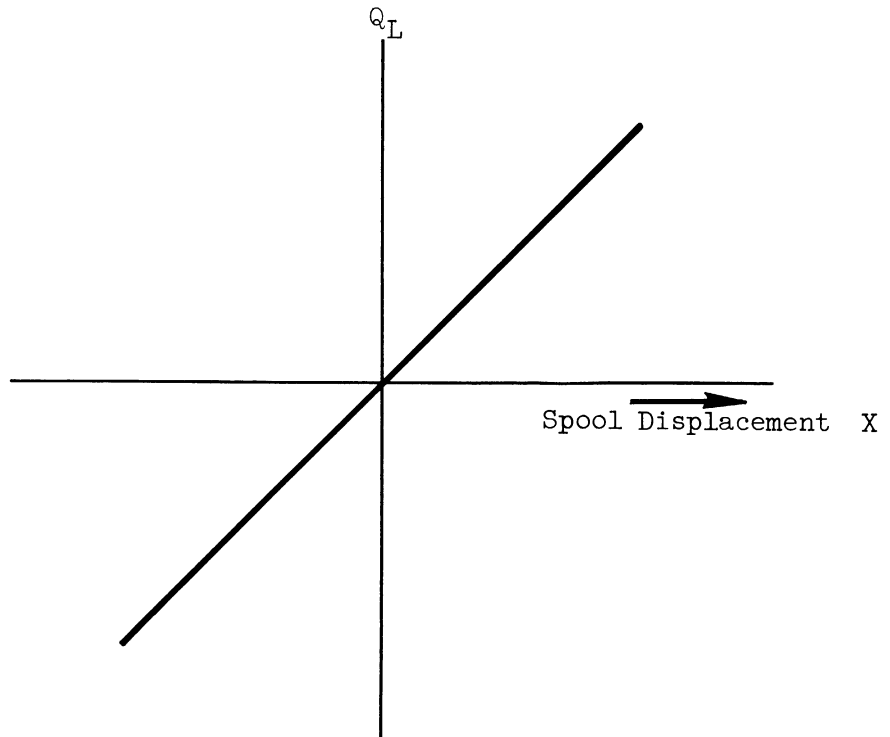
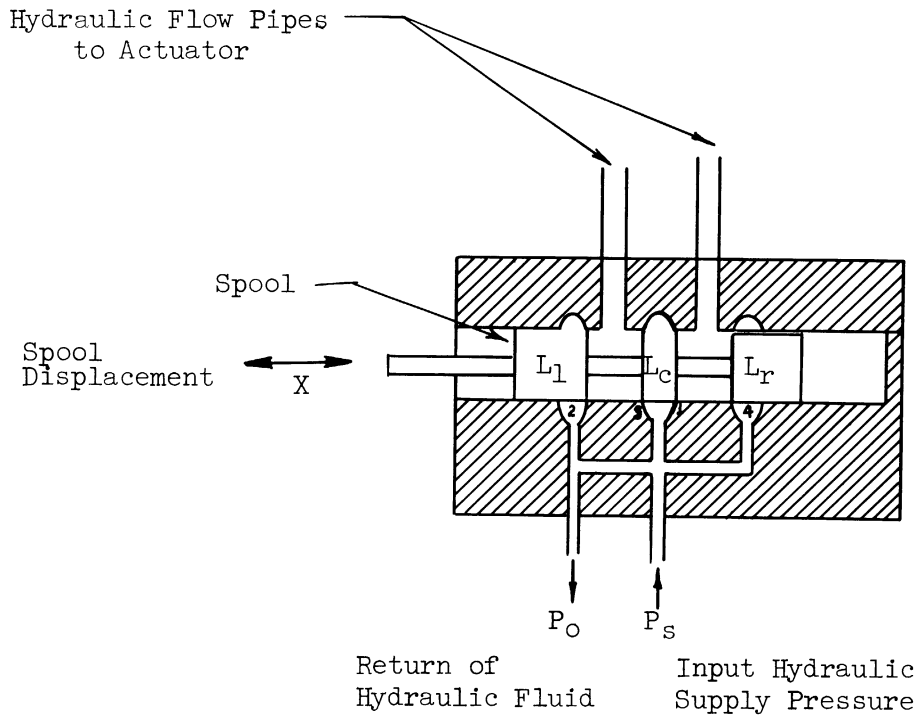


Figure 52. Spool Valve and Its Flow Characteristics

three is opened; if to the left, orifice one is opened.

$Q \triangleq$ rate of flow

$$Q = xC_1 \sqrt{\Delta P_1} = xC_3 \sqrt{\Delta P_2} \quad (1)$$

C_1 and C_3 are coefficients for the two orifices.

$P_V \triangleq$ total pressure drop across the valve

$$P_V = \Delta P_1 - \Delta P_2 = \frac{Q^2}{x^2 C_1^2} - \frac{Q^2}{x^2 C_2^2} \quad (2)$$

$$P_V = \frac{Q^2}{x^2} \frac{(C_2^2 + C_1^2)}{C_1^2 C_2^2} \quad (3)$$

due to symmetry conditions, $C_1 = C_2 = C_0$

$$P_V = \frac{2Q^2}{x^2 C_0^2}$$

$$P_V = P_S - P_L$$

$$P_S - P_L = \frac{2Q^2}{x^2 C_0^2} \quad (4)$$

Q = total flow, which must equal the flow through the land. Therefore, $Q = Q_L$

$$Q_L = xC_0 \sqrt{P_S - P_L} \quad (5)$$

b. The Flapper Valve

The flapper valve employs two orifices and two nozzles, with the flapper positioned between the nozzles.

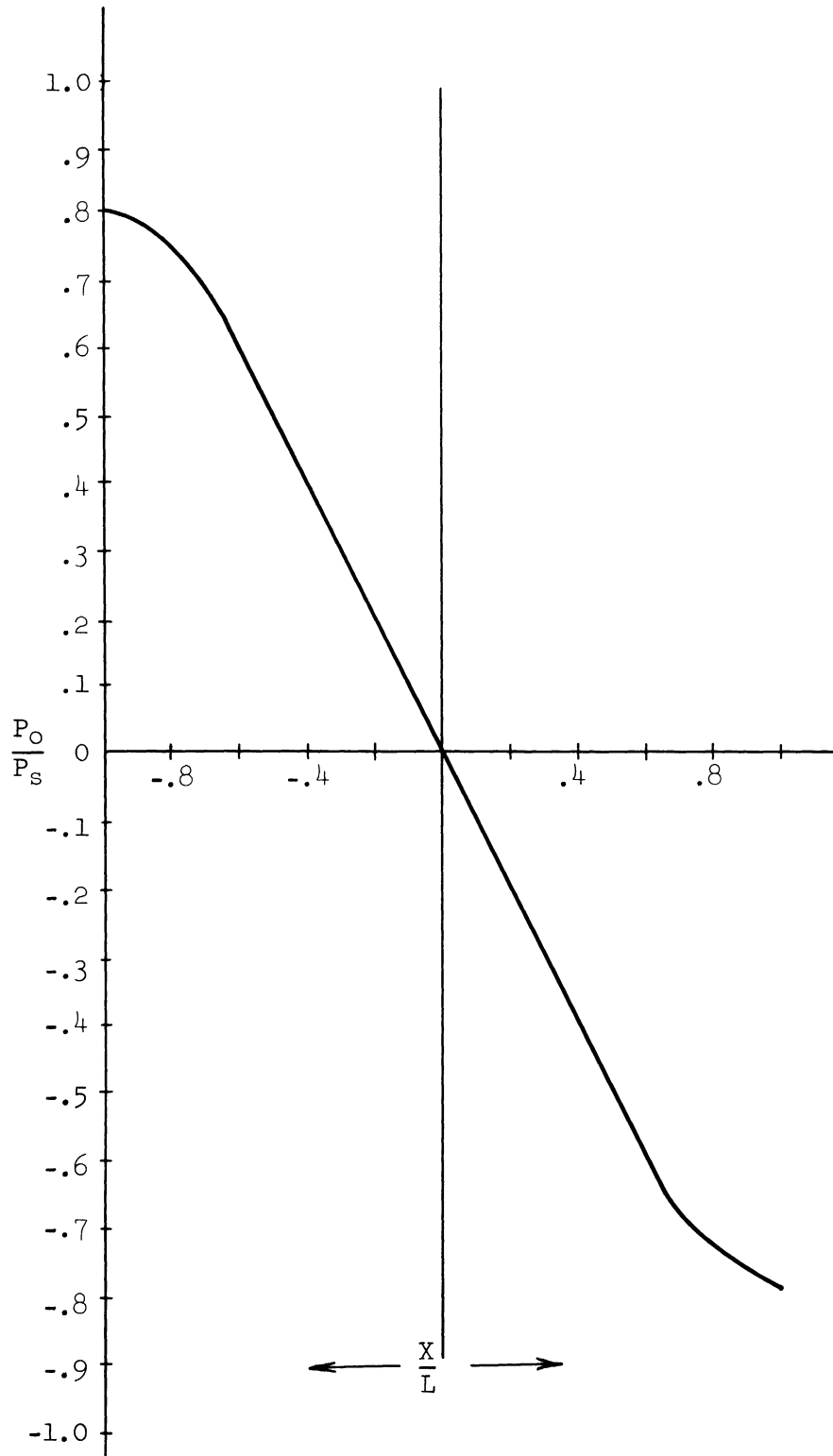


Figure 53. Pressure vs. Displacement for Double Nozzle Flapper Valve with $\frac{dN}{dO} = 1.5$

See Figure 54. When the flapper is moved closer to nozzle one, P_1 and P_2 change as follows:

$$P_1 = \frac{P_s}{\left(\frac{x}{L}\right)^2 + \frac{\left(\frac{x}{L}\right)^2}{4} + 1/2} \quad (6)$$

$$P_2 = \frac{P_s}{\left(\frac{x}{L}\right)^2 - \frac{\left(\frac{x}{L}\right)^2}{4} + 1/2} \quad (7)$$

Now $P_C = P_1 - P_2$

and $P_C = \frac{-16\left(\frac{x}{L}\right)P_s}{\left(\frac{x}{L}\right)^4 + 4}$. (8)

P_C is a nonlinear function, but it does have a relatively linear portion on either side of $\frac{P_C}{P_s} = 0$. This linear portion can be maximized by making $\frac{d_n}{d_o} = 1.5$.

The pressure flow characteristics can be developed from:

$$Q_T = Q_1 + Q_2 \quad P_C = P_1 - P_2$$

$$Q_1 = Q_{N1} + Q_s \quad Q_2 = Q_{N2} + Q_s$$

using -

$$Q = \frac{\pi d_o^3}{4} C_d \sqrt{P_s - P} \quad (9)$$

$$Q_{nx} = \pi d_N(L + x)C_d \sqrt{P} , \quad (10)$$

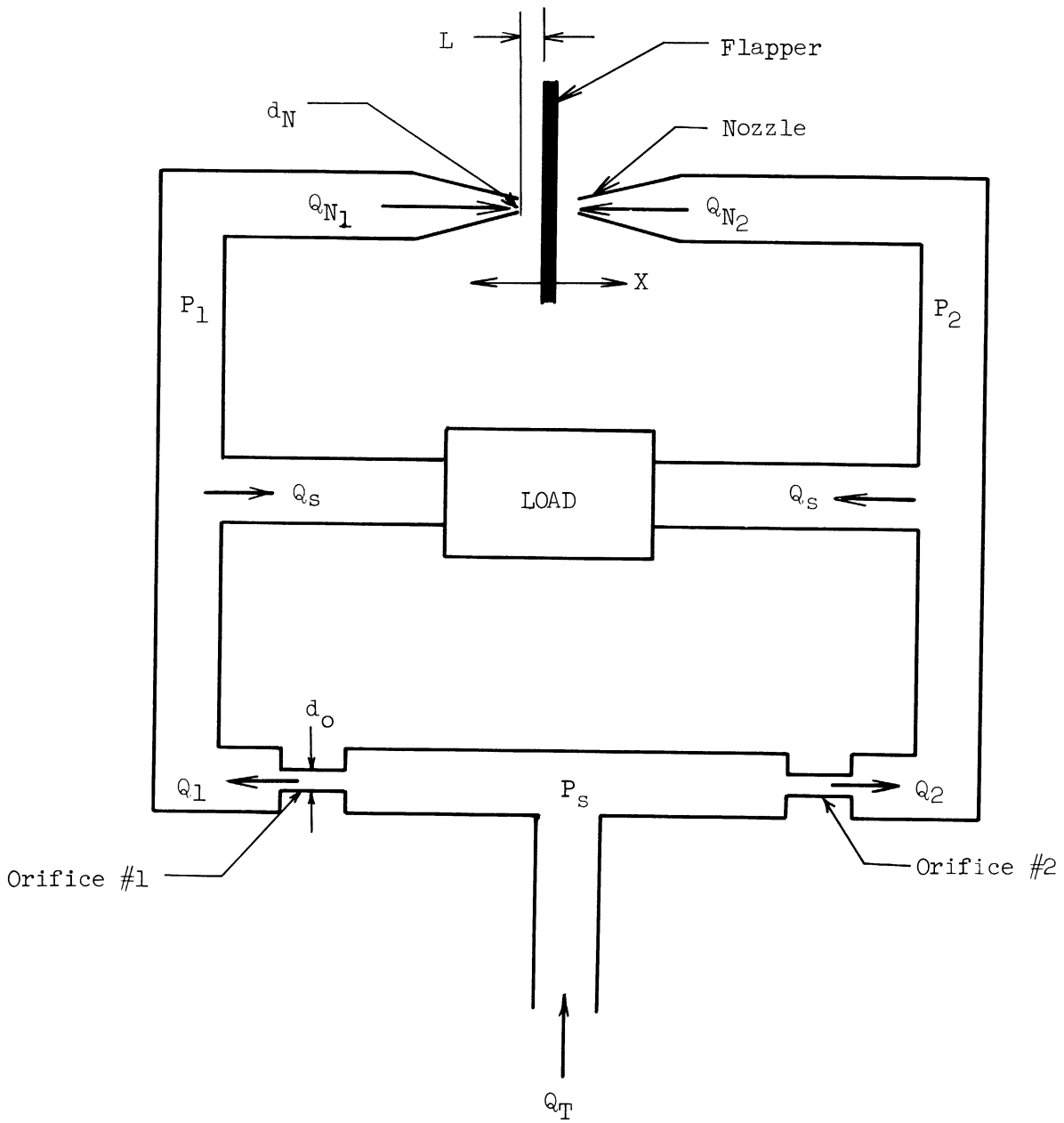


Figure 54. Flapper Valve

we obtain

$$Q_1 = \frac{\pi d_o^2}{4} C_d \sqrt{P_s - P_1}$$

$$Q_2 = \frac{\pi d_o^2}{4} C_d \sqrt{P_s - P_2}$$

$$Q_{N1} = \pi d_N(L+x)C_d \sqrt{P_1}$$

$$Q_{N2} = \pi d_N(L+x)C_d \sqrt{P_2}$$

Q_s is the rate of flow through the load.

$$Q_s = Q_1 - Q_{N1} = Q_{N2} - Q_2$$

$$Q_s = \frac{\pi d_o^2}{4} C_d \sqrt{P_s - P_1} - \pi d_N(L+x) C_d \sqrt{P_1} \quad (11)$$

or

$$Q_s = \pi d_N(L-x)C_d \sqrt{P_2} - \frac{\pi d_o^2}{4} C_d \sqrt{P_s - P_2} \quad (12)$$

Values or ratios of d_o , d_n , C_d , L , X can be obtained from the specification of individual valves. The flapper valve orifices are highly susceptible to being blocked by small particles of dirt. However, high efficiency filters are used in conjunction with the valves, eliminating this difficulty.

c. Jet Pipe System

The jet pipe system consists of a nozzle and receiver block. The nozzle, or jet pipe, converts pressure into kinetic energy and the receiver block converts the kinetic

energy of the fluid back into pressure. The jet tube is on a pivot so the stream of fluid may be directed over a different part of the receiving block, as desired. The receiving block in turn, has two receiving holes. When the jet of fluid is directed equidistant and perpendicular to the plate, the pressures in the receiving holes are equalized. If the nozzle is deflected, more fluid is directed at one hole than the other and a pressure difference is noted. See Figure 54.

The pressure recovered from the jet (Figure 55) depends upon the kinetic energy of the flow. Using Bernoulli's equation, it is noted that:

$$P_A = P_s - \rho_A \frac{V_A^2}{2} \quad (13)$$

Where ρ_A = density of the fluid (oil)

V_A = velocity of the fluid A

To obtain the highest pressure at the receiver block, the velocity of the fluid must be maximum between the jet tube and the receiver. At this point where maximum velocity occurs, the pressure will equal zero. Therefore, Equation 12 becomes

$$P_A = \rho_A \frac{V_A^2}{2} \quad (14)$$

To find the stagnation pressure at the receiver block, Bernoulli's equation is again applied.

$$P_R = P_A + \rho_A \frac{V_A^2}{2}$$

where

$$P_A = 0$$

$$P_R = \rho_A \frac{V^2}{2}$$

The pressure distribution is as in Figure 56.

An interesting characteristic of the jet valve is the fact that turbulence is always present in the stream of fluid striking the receiver plate, creating a high-frequency noise. This noise is useful in eliminating friction in the load.

d. Two Stage Electrohydraulic Servo-Valves

When large input pressures are required, the spool valve is used. If the system requires large pressures but only has a small input signal, as in our problem, a two stage valve system is required. High pressure makes movement of the spool valve difficult with small signal input. In this case, the spool valve becomes the load for one of the three valves previously mentioned, thereby forming a two stage valve system. Now a small signal on the first stage will get accurate and effective operation of the second stage.

The second stage, when fed a small electrical signal, can be operated with a solenoid or torque motor.

The solenoid will be discussed shortly and will not be used for the reasons described.

3. Torque Motor

The torque motor is another magnetic device. The magnetic circuit consists of an Alnico permanent magnet and poles of

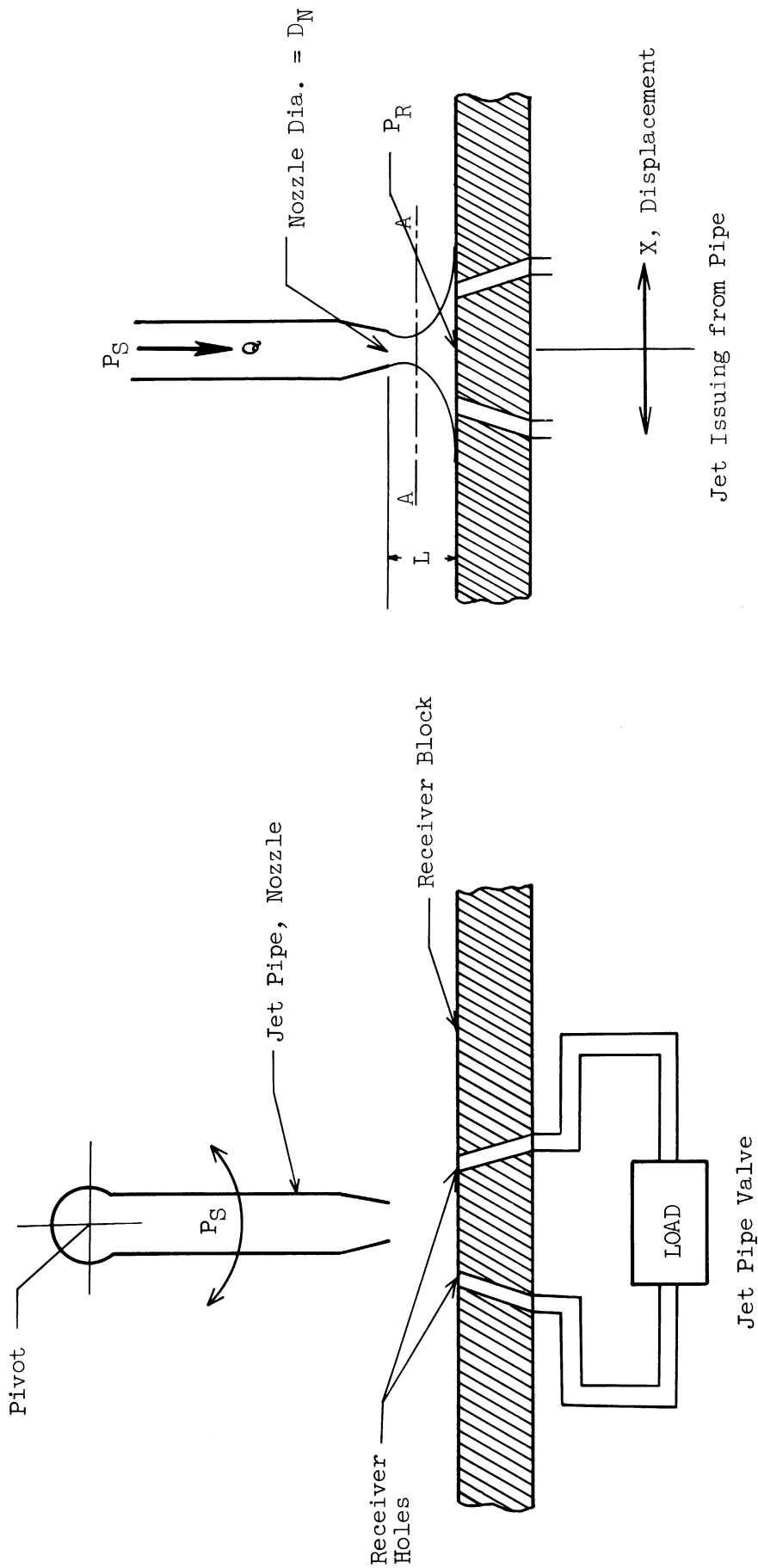


Figure 55. Jet Pipe Schematic

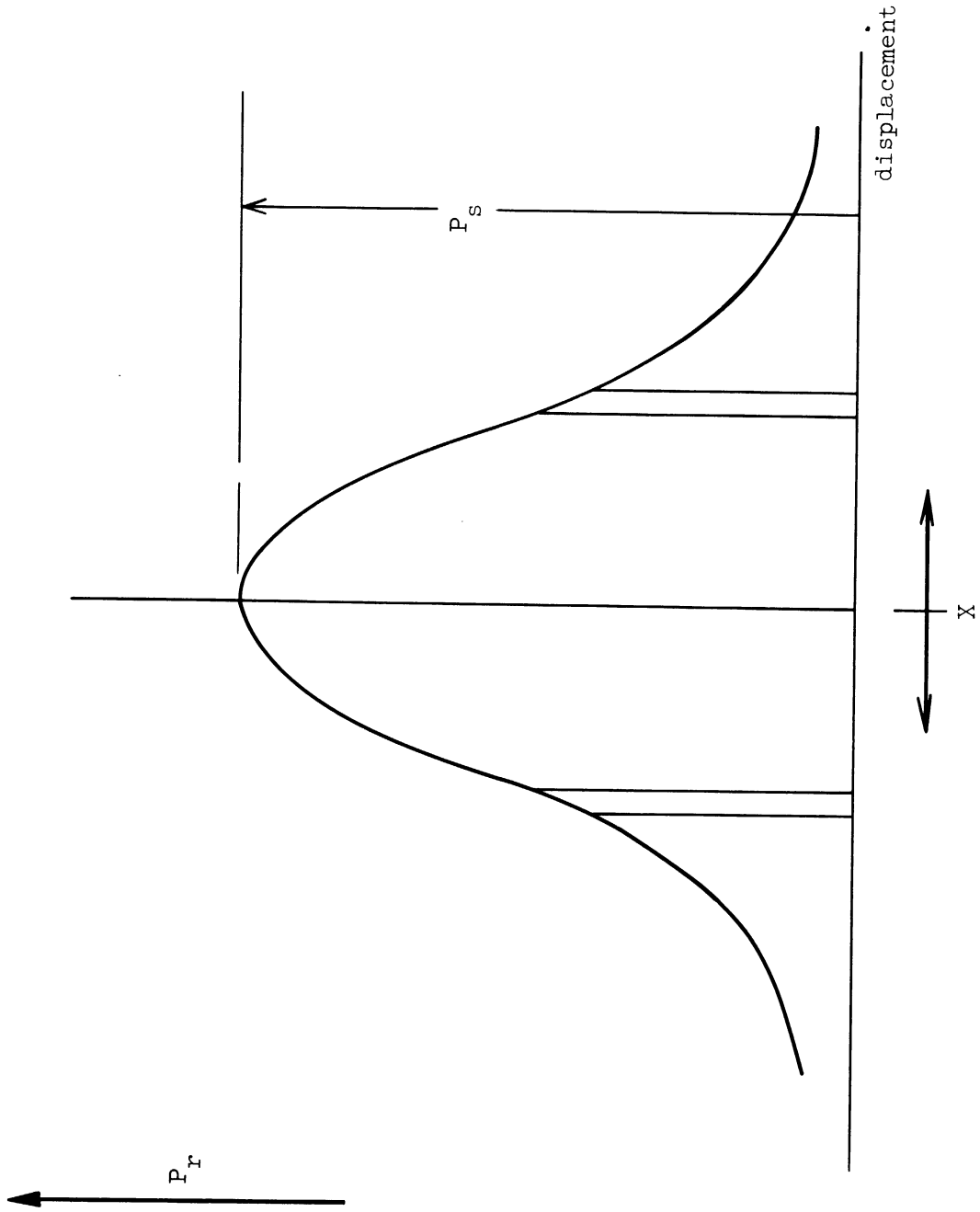


Figure 56. Approximate Pressure Distribution on Receiver from Jet

magnetic permeable material. An armature, again a magnetic permeable material, is placed between the pole pieces as shown in Figure 57.

The armature output is used to actuate a spool valve or act as the flapper in a flapper valve. If a jet pipe is connected to point B of the torque motor, the motor can pivot the jet pipe and afford means of controlling this valve.

The movements of the torque motors are very small, i.e., they are in the range of .002 to .050 in. Since the movement of the three types of valves are very small, the torque motor is very effective. For low supply pressures, the torque motor can be used to actuate the single stage units. The torque motor is a very accurate and efficient means of actuating valves with small signal inputs.

4. Electric Servo-Motors

Servo-motors are available which will give the type of performance that is required. However, motors of this type are costly and, for larger power requirements, very space consuming. A smaller torque motor may be used with a gearing apparatus to achieve the torque requirements, but with this device the output reaction time is increased. In the servo-motor there has to be some physical contact between the control wires and the commutator on the armature. This is done with carbon brushes. Oxidation of the commutator, a defective brush, or dust can cause a poor electrical connection, resulting in a high contact resistance, more voltage drop and consequently a loss in reliability.

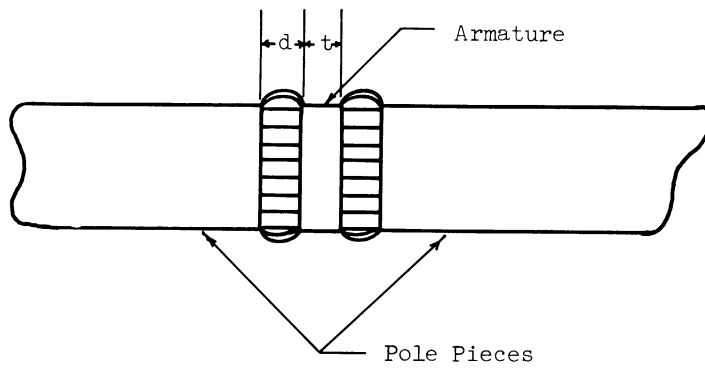
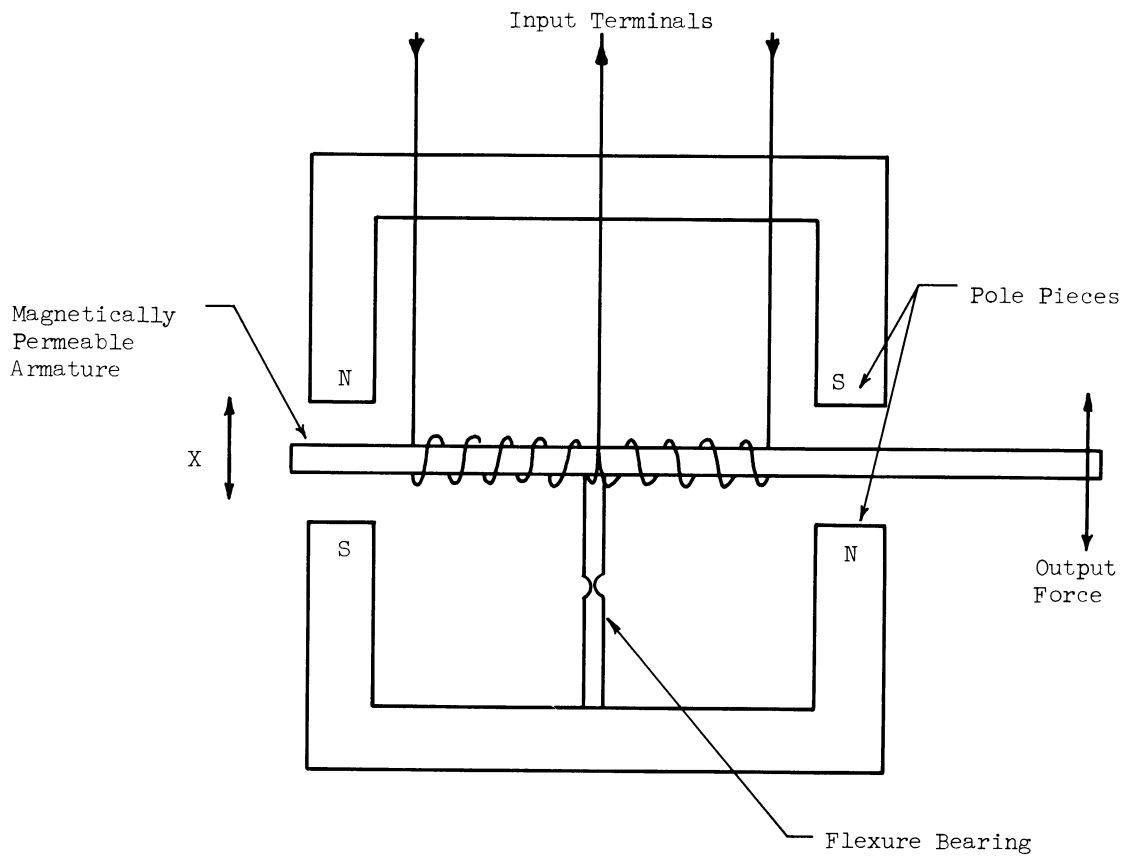


Figure 57. Torque-Motor Armature and Pole Pieces

5. Solenoids

A solenoid is a lateraly moving device. The force exerted by the solenoid depends on the current supplied to the coil and the construction of the coil and ram.

The main disadvantages of a solenoid are:

1. For large output forces large currents are needed (in the range of 1 ampere).
2. There is a spongy or cushioning effect of the ram which produces an indefinite reaction.

6. Conclusion

A two stage electrohydraulic servo-valve will be used to control the steering actuator. This valve will employ a flapper valve as the first stage and a spool valve as the second. A valve of this nature can be obtained from Moog Servocontrols, Inc.

The units are made for specific jobs and, because of the low volume produced, are rather costly (\$100 +). However, increased production will greatly reduce the price per unit.

For the most part, this type of valve is easily adapted to the total system. Therefore the hydraulic needs of the actuator can be controlled with a small signal input to this valve.

F. ACTUATION

1. Steering:

a. Introduction

In the design of a controlled highway vehicle, actuation of the steering system is of critical importance. As mentioned previously, the problem is that of converting an electrical error signal into a mechanical output so as to direct the vehicle along the control strip. Furthermore, the system must be capable of manual operation so as to be completely compatible with control and non-control highway transportation, and it must be designed to allow for emergency over-ride. The following analysis considers the systems listed below:

1. Rotary actuation of the steering column.
2. Complete electro-hydraulic actuation.
3. Actuation of existing linkages.
4. Direct actuation of the power-assist unit.

b. Rotary Actuation of the Steering Column

It is possible to use the linkage and steering gear, manual or power-assist, without alteration, and directly rotate the steering column by installing a rotary actuator between the steering wheel and the steering gear. As mentioned, an electrical input signal will operate an electro-hydraulic valve to control the rotary actuator.

The advantages of such a system are as follows. The actuator can make use of the mechanical advantage of the existing steering system, resulting in more desirable input-output characteristics. The unit is highly adaptable to any vehicle; and,

although slightly more expensive, the system is less complicated than others considered. Furthermore, over-ride of the steering system can be entirely mechanical, providing improved reliability and safety.

Although there are commercially available actuators capable of rotating 360 degrees (well within the requirements of the controlled system), it is necessary to have standard response for non-control transportation, i.e., parking, city driving, etc. Therefore, it is advisable to equip the system with an inexpensive dog clutch to allow positive drive by the actuator during automatic use, and normal operation for non-automatic use. (See Figure 58). A detail discussion of rotary actuators would be included later in this discussion.

c. Complete Electro-Hydraulic Actuation

With complete electro-hydraulic actuation, all of the steering mechanisms below the conventional steering box are used without alteration. A two-way lateral hydraulic piston is used in place of the gear box, activated by an electro-hydraulic valve which moves the piston proportional to an electrical input signal (See Figure 59). This electrical signal is in turn proportional to the lateral displacement and the effective angular displacement of the front wheels with reference to the control strip as discussed previously (See System Design: Steering).

Since the vehicle must also be manually operated, it is necessary to employ a potentiometer linkage between the steering wheel and the electro-hydraulic valve to supply an electrical input proportional to wheel displacement.

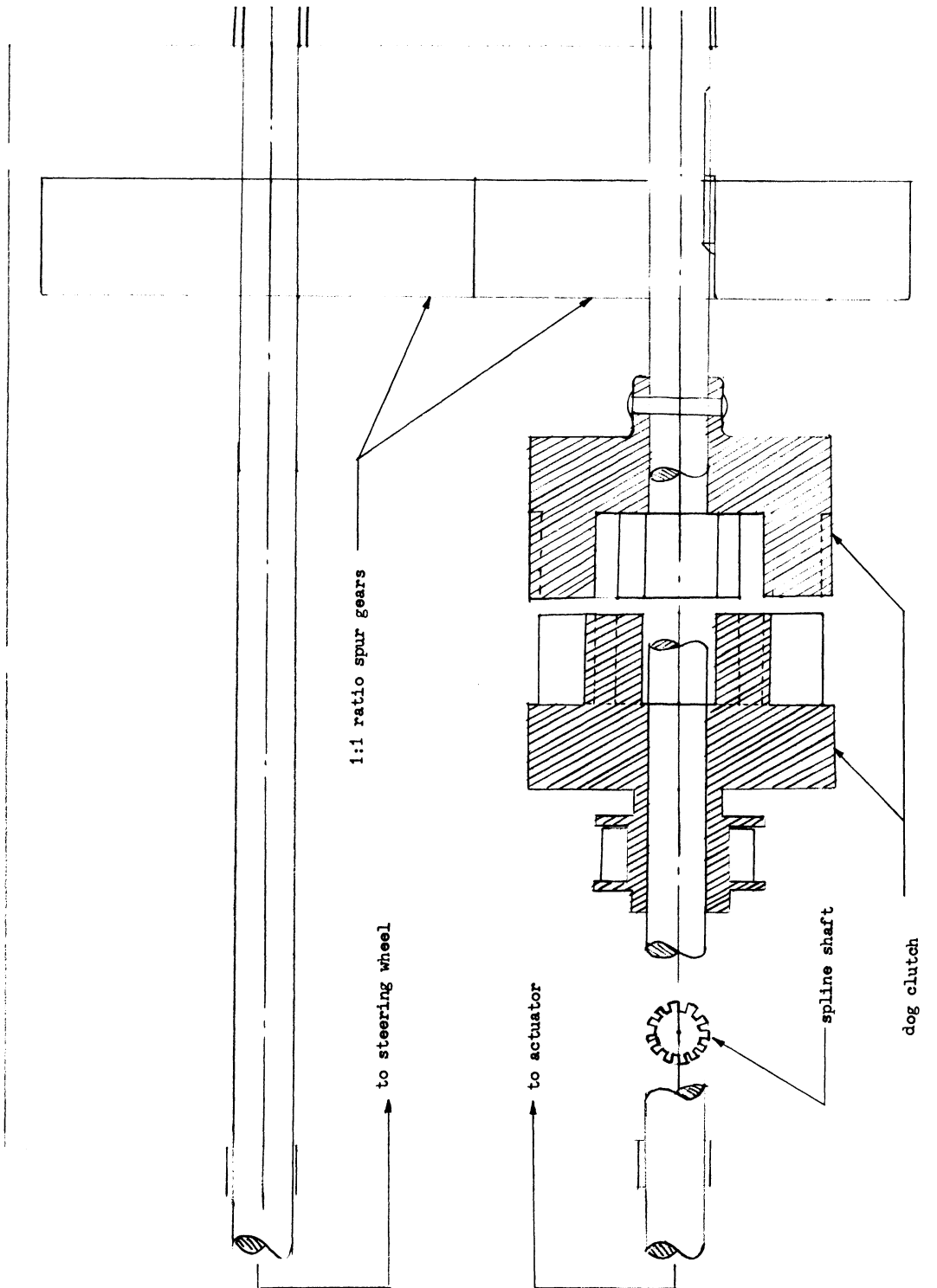


Figure 58. Gear Box Used to Adapt Actuator to Present System

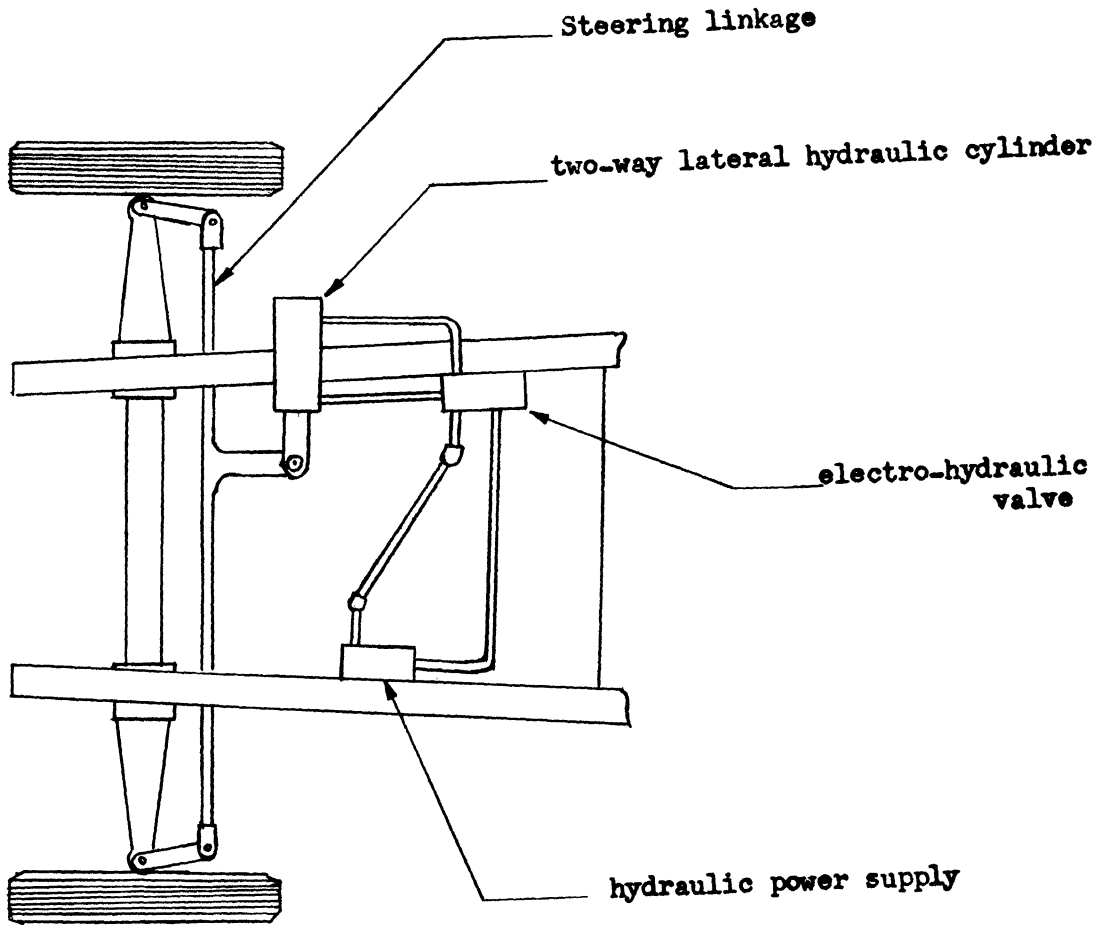


Figure 59. A Completely Electro-Hydraulic System

Although such a system is mechanically and economically feasible, over-ride limitations make the unit relatively unacceptable. While there is increased safety with the removal of the steering column, there is no longer a direct mechanical linkage between the steering wheel and the front wheels. This means that all of the steering over-ride features would be electronic--a publicly unacceptable safety reduction.

d. Actuation of Existing Linkages.

A third approach utilized the existing steering gear (manual or power-assist) for manual control transportation, and a two-way hydraulic cylinder attached to the linkage for automatic use. As before, this cylinder would be operated by an electro-hydraulic valve.

As in the second system the complete force to the wheels is applied through a lever arm, resulting in reduced stability and mechanical advantage. Also, since the two hydraulic cylinders (the power-assist unit and the lateral cylinder) are operating in series, one of the units will always be driving the other cylinder, resulting in excessive wear. Although the system would be highly adaptable to existing vehicles, the necessary replacement parts warrant an increased cost.

e. Direct Actuation of the Power-Assist Unit.

The most practical and economical system would appear to incorporate direct actuation of the power-assist or power steering units commercially available as optional equipment. It seems reasonable that the gear box could be altered to operate the steering spool valve in accordance with the electrical input

signal during automatic use. Under manual control, the steering system would remain as in any non-controlled vehicle.

However, it must be noted that the present power units are power-assist, not full power steering systems. Therefore, a difficulty arises in "assisting" the present power systems. To do this, the spool valve must be opened to actuate the power-assist cylinder. However, the available pressures are not sufficient to drive the steering gear directly. Were it possible to separate the pitman arm from the steering gear, these pressures could operate the linkages directly. However, this cannot be accomplished without complete redesign of the existing power-assist unit.

f. Discussion of Rotary Actuation

Most vehicles require approximately six or less turns of the steering wheel from lock-to-lock, requiring less than fifty inch-pounds of torque on the steering wheel.⁽³²⁾ At ordinary highway speeds, the steering wheel need only be turned 135 degrees clockwise or counter-clockwise to negotiate any turns encountered, and during this travel, the steering wheel never rotates in excess of twenty degrees per second. Furthermore, since most vehicles are equipped with hydraulic pumps delivering pressures up to 1000 psi., the rotary system should operate within this pressure limit. Using a torque safety factor of six, a rotary actuator delivering a 300 inch-pound torque capacity would be more than sufficient.⁽³⁷⁾

In general there are three main types of rotary actuators:

1. vane type

2. helical shaft type
3. rack and pinion type

There are commercially available vane type actuators which produce 500 inch-pounds torque and operate on less than 1000 psi. Although they are relatively small and inexpensive, their maximum rotation of 270° limits the application to our problem. (See Figure 60).

The helical shaft and piston type actuators again produce ample output torques, but must be approximately 21 inches long to provide 360° of rotation. Furthermore, a power failure causes this system to lock in position, making over-ride impossible.⁽³⁹⁾ (See Figure 61).

The rack and pinion type actuator is the most common type found in industrial applications. As implied by its name, this unit positions a rack hydraulically, which in turn rotates a pinion connected to the output shaft. While this action is not only the least complicated, it is also the most rugged and the least expensive available type of rotary actuator, costing approximately \$50 per unit.

Models are available that produce the required torque of 500 inch-pounds at the specified pressure. A typical unit is 2" x 4" x 10" with a $\frac{1}{2}$ " output shaft. The output-input ratio is independent of temperature from -40°F to 200°F.

The following is a list of manufacturers of acceptable rotary actuators:

Behlen Corp.

Conoflow Corp.

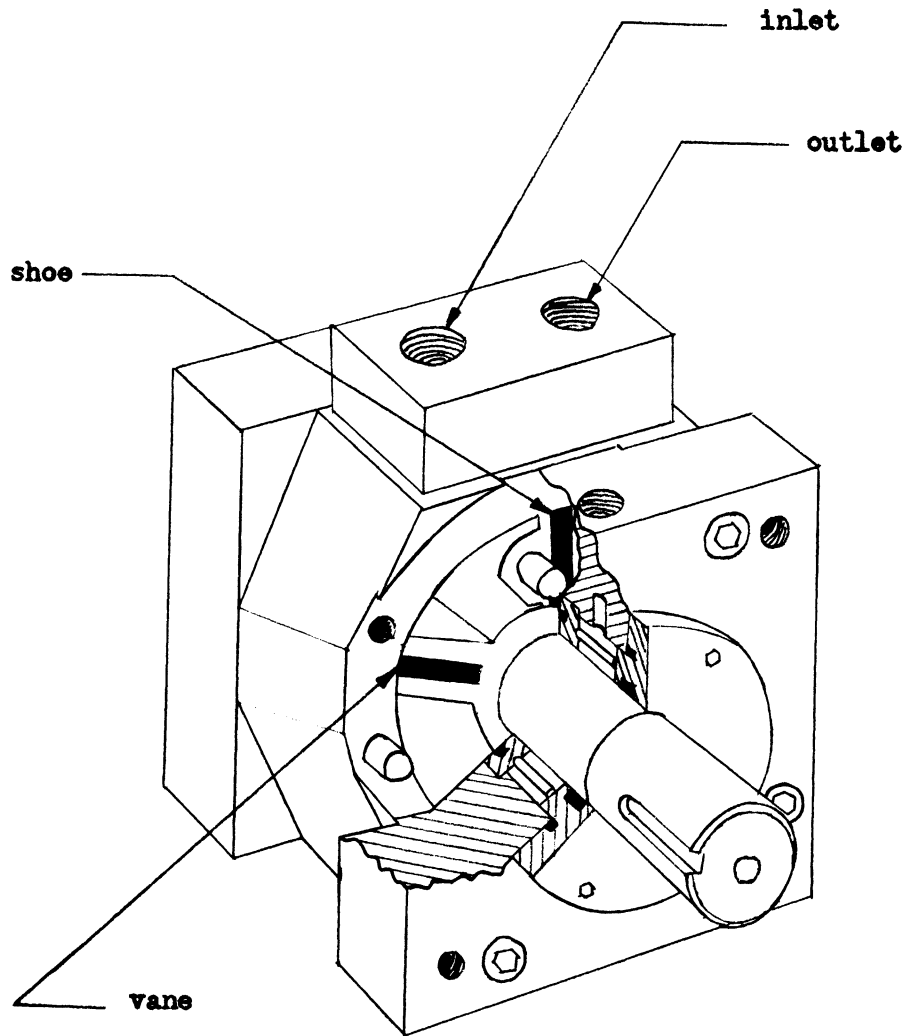


Figure 60. Vane Type Rotary Actuator

From Rotac - Reference 42

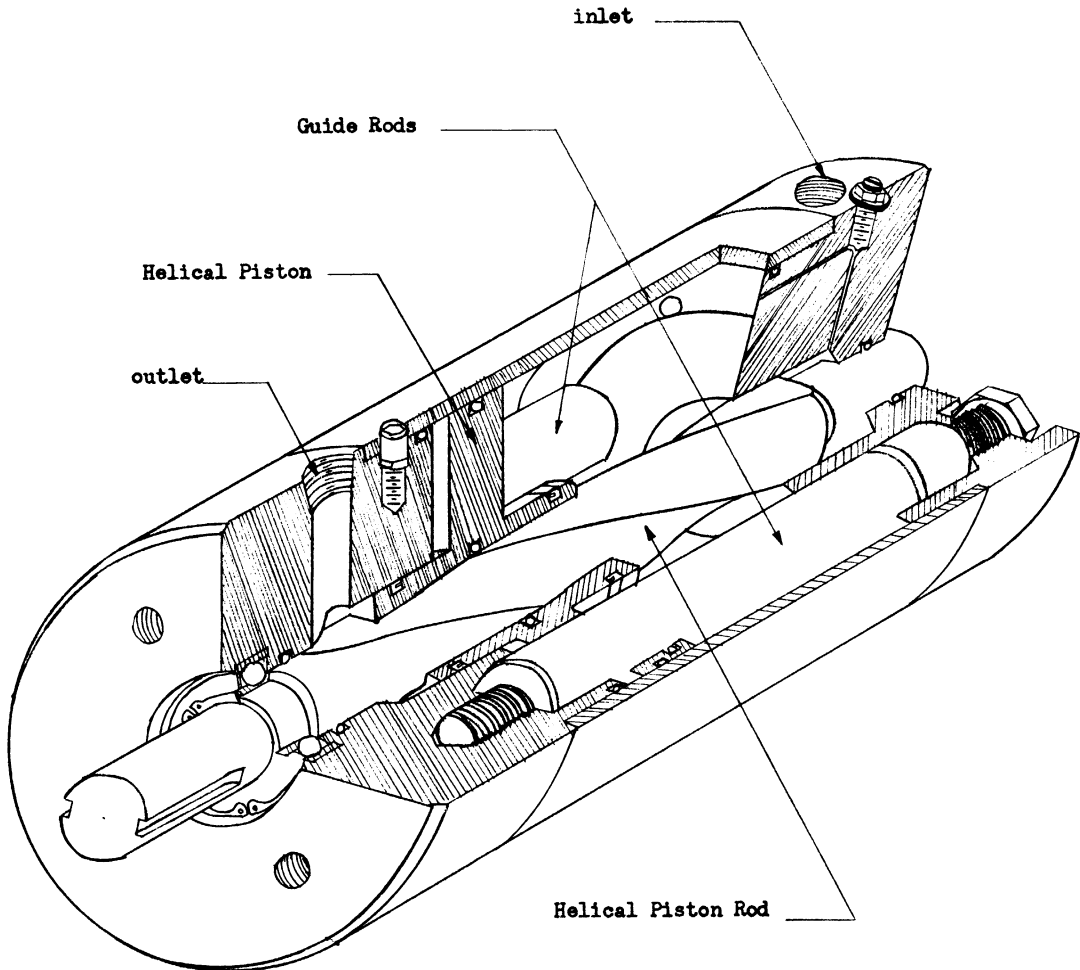


Figure 61. Helical Shaft Rotary Actuator
From Carter - Reference 32

Electrol
Ohio Oscillator
Carter Controls, Inc.

However, the most desirable unit in accordance with the design specifications is manufactured by Carter Controls, Inc. (See Figure 62).

Figure 58 describes how the Carter Rotary Actuator would be incorporated in the present system. As mentioned previously, since the actuator only rotates 360° , it must be disconnected for non-automatic control of the vehicle using a clutch mechanism as shown.

The capacity of the power steering reservoir will be increased by the maximum displacement of the additional equipment, and in some cases it may be necessary to equip the vehicle with a pressure regulator to ensure a proper operating pressure.

The estimated production cost of the complete steering mechanism including valves, regulators, actuators, clutch, etc., is within \$140.

1- 3 stage electro-hydraulic valve	\$ 50
1- rack and pinion rotary actuator	50
1- gear and clutch assemble	15
installation	<u>25</u>
	\$ 140

2. Braking

a. Introduction

Obtaining intermediate ranges between engine drag and panic braking presents a major difficulty in the total braking system.

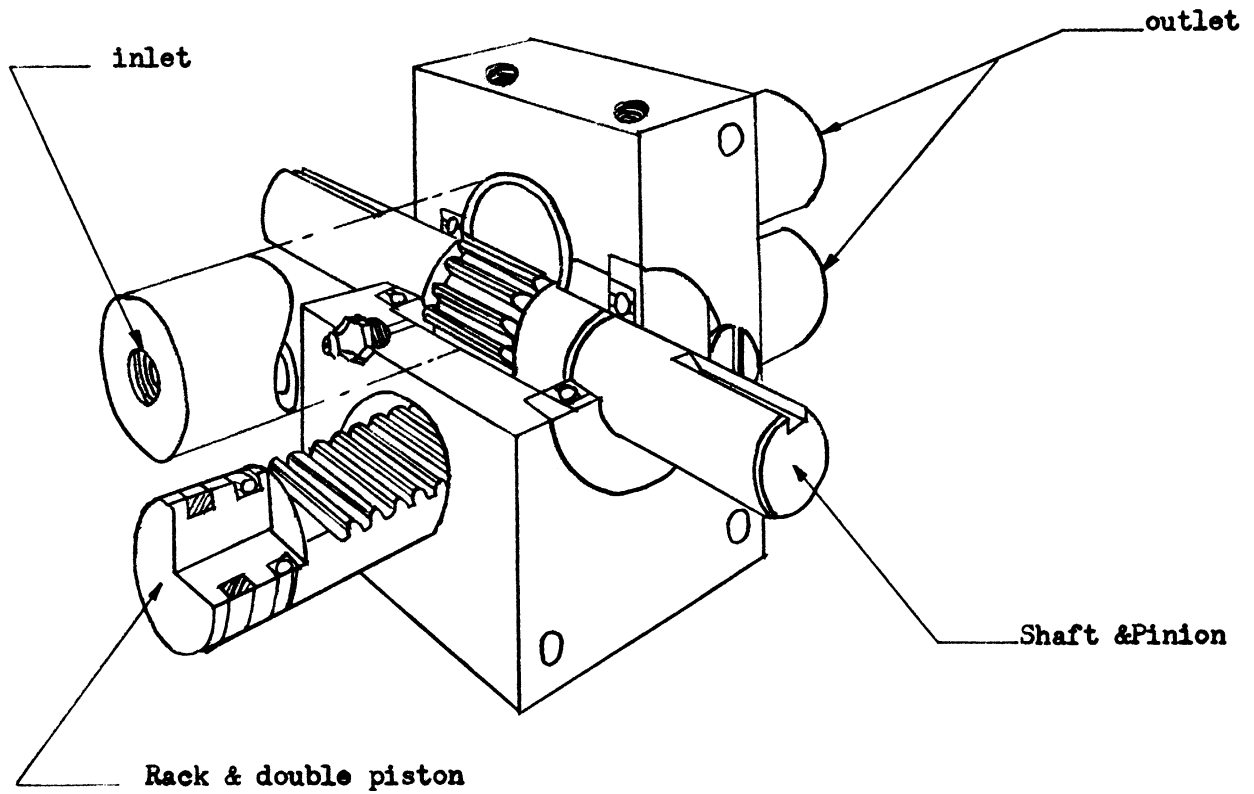


Figure 62. Rack and Pinion Rotary Actuator

This section is primarily concerned with the intermediate ranges of braking.

To accomplish the above, a two stage electro-hydraulic servo-valve system with a pressure feedback will be used.

This system will allow any number of degrees of braking.

b. Discussion

The operation of this system is as follows: a command signal is received by the vehicle indicating necessary deceleration. The signal received by the vehicle will be of the pulse form, i.e., of short duration and at a given amplitude. This signal is then amplified to the signal strength needed by the servo-valve and fed into a circuit which generates a constant amplitude signal. This signal is held constant until another signal is fed into the circuit. This is called a Box Car Effect. (See Figure 63.)

From the box car circuit the signal goes to the electrical input terminals on the first stage of the servo-valve, which consists of an electric torque motor driving a hydraulic valve. With a given input signal, the torque motor will produce a movement of the first stage hydraulic valve.

This valve operates the second stage spool valve of the two stage valve system. When this second stage spool is moved, a pressure difference occurs across the actuator flow ports of the valve. This pressure difference operates the hydraulic actuator which in turn operates the master brake cylinder of the vehicle. (NOTE: The actuator and brake hydraulics are independent.) When the master cylinder is activated, pressure is increased in the brake lines. This pressure in turn causes a back pressure

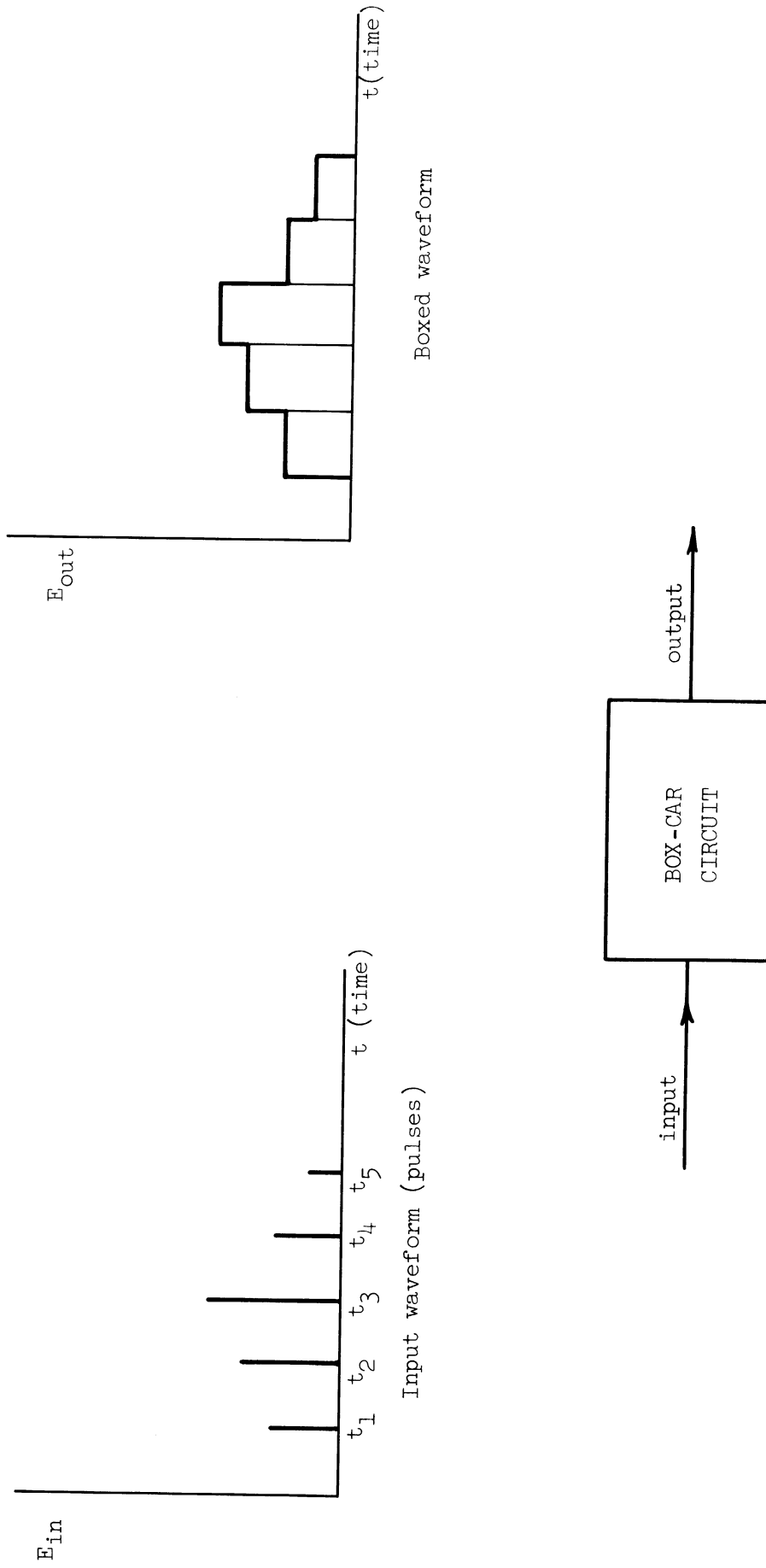


Figure 63. Box-car Circuit Effect on Waveform

in the actuator. This back pressure is then transferred to the hydraulic valve by means of a pressure feedback line.

When the back pressure in the actuator becomes great enough, the second stage spool valve of the two stage valve is moved back to the shut-off position. Until another signal is received, the valve will remain in this off position, the actuator holds the master cylinder, and a constant brake line pressure is maintained. (See Figure 64).

If a different input signal is received, the brake line pressure will correspond to the intensity of the signal.

Contrary to general belief, a definite brake line pressure does not produce a uniform deceleration of a vehicle. The variations in the deceleration of the vehicle are due to changes in the parameters of the braking assembly.

Since fluctuations in decelerations exist, it is advisable to control deceleration with brake line pressure changes because these pressure changes are dependent on the signal received by the vehicle.

The spacing control group has indicated that varying amplitude signals are received at intervals up to 300 feet behind vehicles in the automated lane. See Figure 65 and the spacing control section of this report.

As vehicle No. 2 comes within the signal pattern of vehicle No. 1, the first signal (a) is received by vehicle No. 2. How this signal is transmitted and received is not important here; the important part is that the signal is received. This first signal will function as an over-ride, i.e., a new command to

the speed control (that part of the automated system which normally keeps the vehicle at a constant speed.) This means that the throttle will be cut back to an idling position. With the throttle in this position the vehicle achieves its first and smallest deceleration rate due to friction and engine drag (about 2 ft./sec.²). If vehicle No. 2 approaches within the next signal range of vehicle No. 1, signal (b) is received. With this change of signal (amplitude) there will be a pressure change in the brake lines and an additional amount of deceleration will occur. If the vehicle is not decelerating sufficiently, it will approach another signal of greater amplitude. Again through the servo-valve, this stronger signal causes a change in pressure in the braking lines.

Each time a higher amplitude signal is received by the vehicle, a higher deceleration rate will occur. When the last signal is reached the vehicle will achieve the highest braking possible, i.e., a panic stop. Therefore, the range of braking will be from the engine friction drag to the panic stop with two intermediate ranges.

$$\frac{4-6 \text{ ft.}}{\text{sec.}^2} \quad , \quad \frac{10-12 \text{ ft.}}{\text{sec.}^2}$$

This range of braking will allow the vehicle to stop under normal operating conditions with a comfortable safety factor.

NOTE: In a compatible highway system, if a vehicle suddenly pulls in front of a controlled vehicle, other problems may develop. The controlled vehicle may go into a panic stop condition when it would not be necessary. A means of detecting the

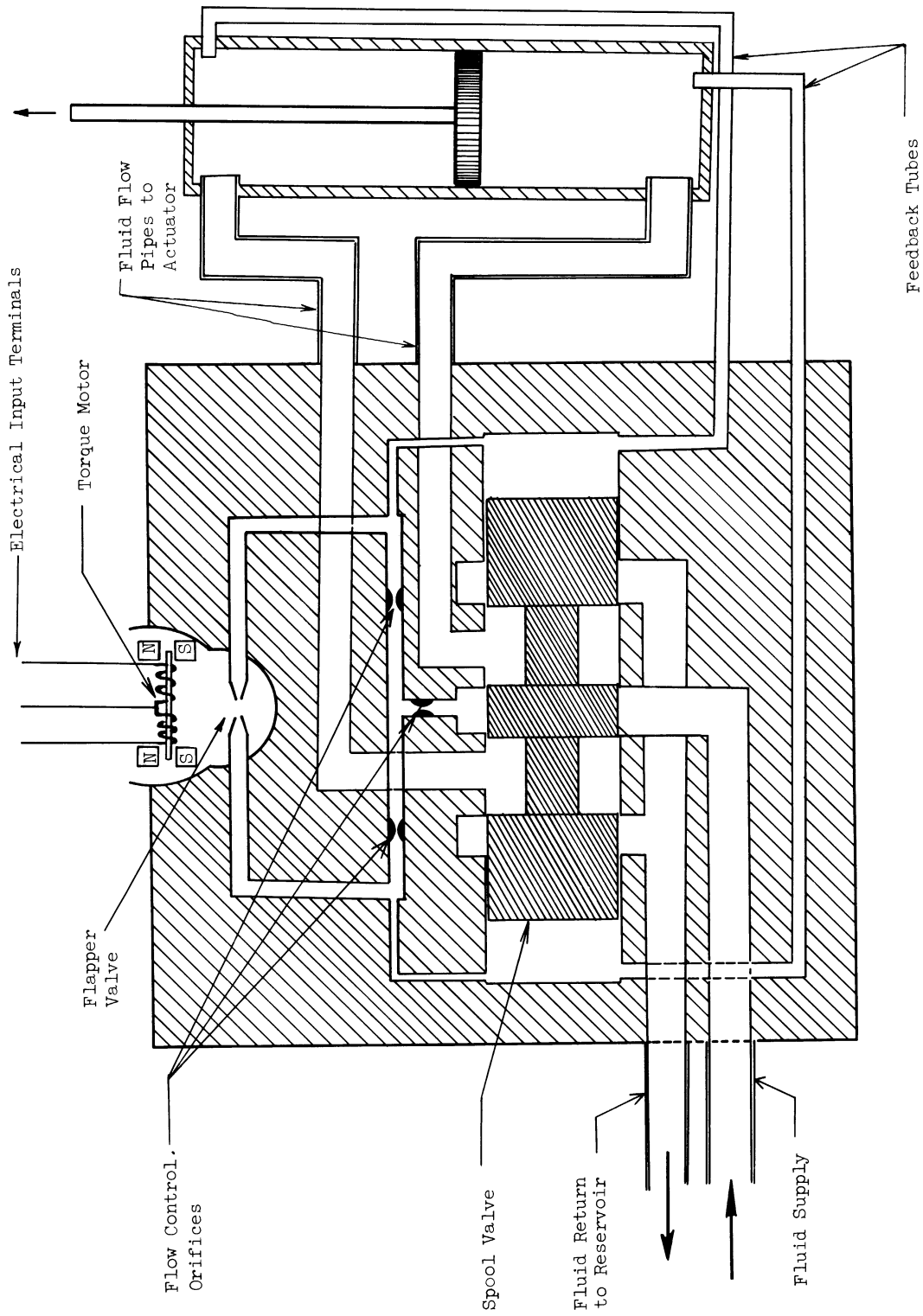


Figure 64. Two-stage Electro-hydraulic Servo-valve

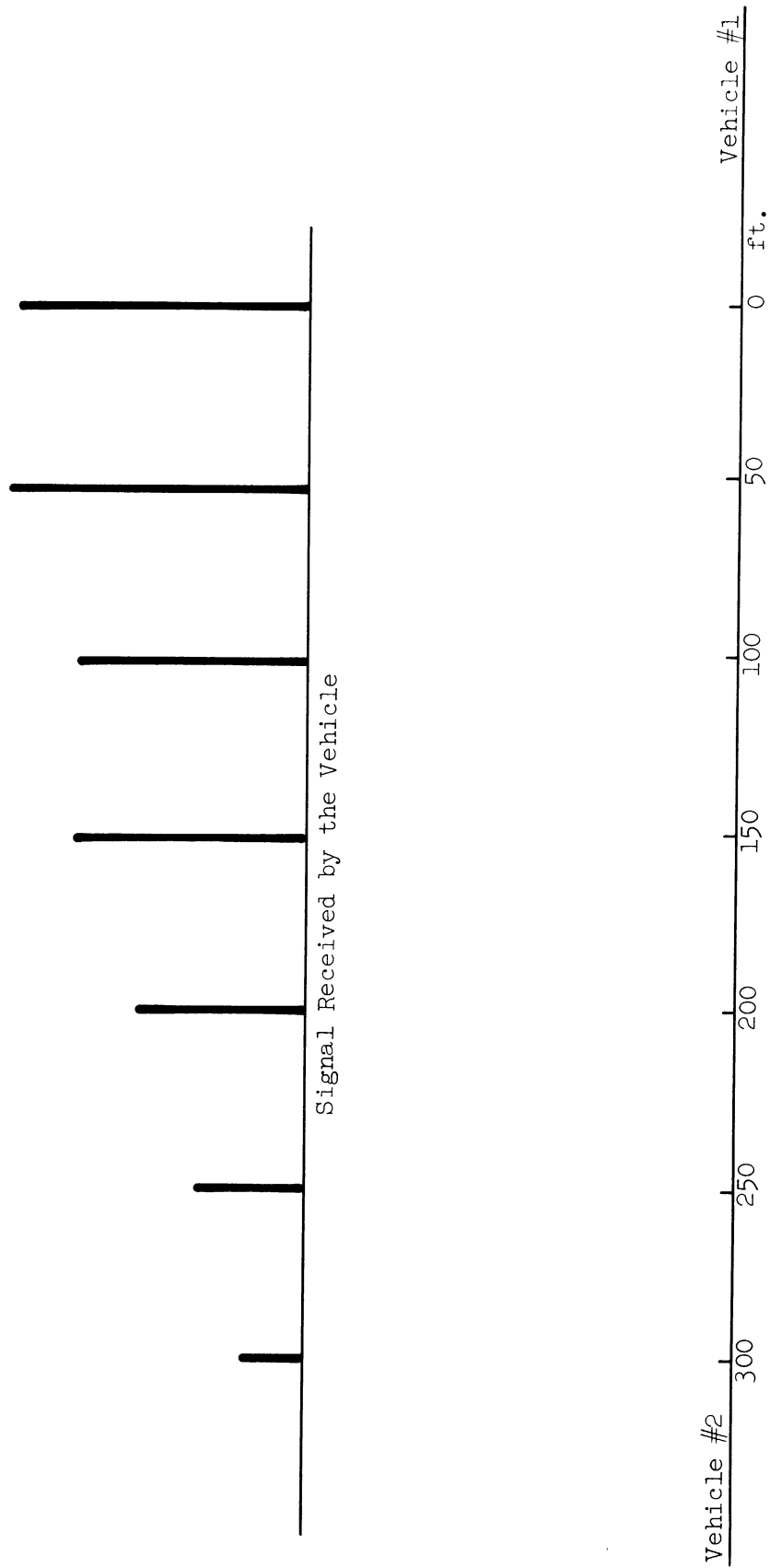


Figure 65. Signal Variation with Distance

relative speed of the lead vehicle would supply the needed information to the trailing vehicle so that appropriate action can be taken. This would be considered in a further study of the braking system and has been discussed under the spacing control part of this report.

Braking actuation costs

1 - 3 stage electro-hydraulic valve	\$ 50
1 - lateral single action cylinder	10
installation	25
	<hr/>
	\$ 85

IV. SAFETY AND OVER-RIDE DISCUSSION

A. INTRODUCTION

One of the most important considerations in the design of a system of automatically controlled highway vehicles is safety. However, without a working proto-type, a complete and thorough analysis of safety and reliability is extremely difficult. The best that can be done at this point is a brief qualitative analysis.

B. SAFETY

Clearly, any emergency which may arise is the result of a condition external to the system or an internal failure of the system.

1. EXTERNAL EMERGENCIES

External conditions which cause emergencies include adverse weather, tire failure, obstacles in the road, and miscellaneous mechanical failure.

Adverse weather conditions may be handled by adjustments of the velocity command signal as was indicated earlier. Furthermore, the velocity command signal can be varied for small sections of the highway to account for icy spots under bridges, slippery curves, etc. Unfortunately, a very dangerous situation occurs when an automatically controlled vehicle goes into a skid, because the

automatic steering system tends to steer **in the wrong** direction (against the skid). It must then be the responsibility of those in control of the road to see that the command velocity is low enough so that the probability of skidding is at a minimum.

Flat tires pose a problem which cannot be totally analysed without experimentation. Other automatic systems which have already been tested show good resistance to this type of emergency, and so it is assumed, for the present, that a flat tire can be safely handled by ACHV.

Obstacles in the road pose a somewhat more serious problem to ACHV. Metallic objects of any sort will of course be detected by the loops in the road. However, obstacles of non-metallic nature will not be detected, and in this instance (however rare) it will be necessary for the driver to over-ride the system.

2. Internal Failures

Internal failures may be classified under the basic functions of the system: steering, velocity control, and spacing control.

The two main causes of failure in the steering system are lapse of the control signal and loss of

hydraulic pressure. Lapse of the control signal is of course a rare instance if proper redundancy is employed, but in any event it would trigger the driver warning system. A loss of hydraulic pressure would, by means of a pressure switch, also set off the warning system. Furthermore, even if the system did not disengage the steering clutch, it would be possible to steer one half turn in each direction with the hydraulic pressure off.

Failures in the velocity control system are, as might be expected, uncritical. If there should be a lapse in the velocity command signal, the system cars will brake to a halt. On the other hand, the velocity sensing signals put out by the permanent magnets are highly dependable and essentially indestructable.

The major components of the spacing control system, the detection loop sensors and the transmitters, are reputed to be very reliable. Proper redundancy of these components will of course further reduce the possibility of failure. Furthermore, the failure of one detection loop would render unsafe only one small section of the road and only for a short time (because it would be detected immediately by a central control so that corrective action could be taken).

The above discussion, of course, does not include the possibility of failure of minor electrical or mechanical parts. The more serious of the two is probably the failure of electrical components, so it will be necessary to use high reliability equipment with sufficient redundancy in the final system.

C. OVER-RIDE SYSTEM

When an emergency in the system arises, it is clearly necessary to inform the operator (driver). ACHV intends to use both audio and visual signals: i.e., a buzzer or a flashing light.

The actual mechanism of the over-ride must not only be instantaneous but also totally natural. In other words, it would be unfeasible under emergency conditions to require a driver to flip a switch or push a button on the dashboard, because he is not conditioned to do anything more complicated than operate the steering wheel, the accelerator and the brake. Also, it is clear that in any emergency the driver will automatically reach for the steering wheel. In ACHV, therefore, it was decided to attach the over-ride mechanism to the steering wheel.

The type of switch proposed is an electrostatic one, consisting of a charged metallic strip around the back side of the steering wheel. When the driver grounds the electrostatic switch with his hands, the automatic control of the vehicle is over-ridden. If this is deemed undesirable by

safety experts, then it would certainly be possible to design a mechanical switch. It should also be noted at this point that even if the system is not over-ridden, the brakes will still be operable.

Realizing that a more detailed analysis of over-ride and reliability is essential, the following proposal includes testing of such a system.

V. FUTURE PROPOSAL

A. INTRODUCTION

This report proposes one possible method of automatic vehicle control. Some of the subsystems discussed involve new ideas yet to be thoroughly tested, while other subsystems involve concepts used in previous automatic systems. In these latter subsystems, we believe the most efficient and effective solution has been found. Our philosophy has been to investigate and arrive at theoretical solutions to all phases of the problem, then with time permitting, to actually construct prototype equipment. This we believe is more of an engineering approach than merely to examine and solve one phase of the problem. Man-power as well as time and money limitations have prevented the construction of a complete prototype. However, some of the electronic circuits have been constructed and tested in the laboratory. All of the subsystems have been completely specified, and a thorough cost analysis has been conducted. The result of this analysis is presented in brief below.

B. PRESENT COST ANALYSIS AND PREDICTED TESTING COSTS

VEHICLE INSTALLATIONS (\$/veh.)		HIGHWAYS INSTALLATIONS (\$/mile)	
Receiving System	\$ 26.00	Transmitters, Detection	\$23,045.00
installation	9.00	loops and associated	
		equipment	
Steering and Braking	250.00		
Actuators & Detection		installation	3,585.00
Equipment			
installation	50.00	Magnets for speed	
		control	1,200.00
Speed Control recept-			
ion equipment	20.00	installation	<u>800.00</u>
installation	5.00		
Counting equipment for			
spacing control	50.00		
installation	<u>5.00</u>		
<u>TOTAL</u>	\$415.00/vehicle		

NOTE: If steering and braking actuators were purchased in large quantities, the price per vehicle would be reduced by approximately \$100.00/veh.

For this system to be tested adequately, a two mile figure eight test track as well as at least five modified vehicles of different models would be desirable. The cost of building and operating such a facility for one year is as follows:

Construction of two mile track	\$75,000.00
Five new vehicles at \$3,000.00	15,000.00
Building for engineering laboratory	10,000.00
Five full time engineers for one year at \$10,000.00	50,000.00
Three technicians at \$7,000.00/yr.	21,000.00
Electronic equip. for test track	48,000.00
Electronic equip. for Lab.	10,000.00
Photographic equip.	2,000.00
Utilities/yr.	1,200.00
Misc./yr.	<u>2,000.00</u>
PER YEAR TOTAL	\$234,200.00

Thus for less than one quarter million dollars, an eight man team could concentrate on the construction, testing, and modification of the proposed system.

Should the final system prove operative, reliable, and completely safe, the next step would be to conduct a marketing feasibility study to determine public acceptability of an automatic vehicle control system. Such research would cost approximately \$100,000.00 and would require one year to organize, conduct, and evaluate. (Refer to comments in Section 1 - Background.)

If the results of this research were favorable, test strips of heavily traveled highways should be converted. These strips should be at least twenty miles long, and located such that modified vehicles would travel these test highways frequently (such as between Detroit and Ann Arbor). The major problem is to populate these test strips with enough modified vehicles to conduct a valid traffic research program and evaluate the system. If the electronic modifications could not be sold on new vehicles as a convenience or luxury accessory, it could be installed free of charge on selected vehicles. Heavy publicity should be given the test operation and public interest should be aroused as well as influenced in a positive direction. If the marketing research proved negative, perhaps the system could be eased into operation by installing only the steering or speed control systems. One virtue of the system is that it could be installed one subsystem at a time. This approach may be necessary. If four test strips were installed and 1,000 vehicles modified, the cost would be as follows:

Four strips of 20 mi/strip (80 mi total)	\$2,050,400.00
1,000 modified vehicles at \$250.00/veh.	250,000.00
Public relations and advertising for 1 yr.	20,000.00
Traffic Survey and evaluation for 1 yr.	<u>30,000.00</u>
PER YEAR TOTAL	\$2,350,400.00

NOTE: The detection equipment could be used for counting vehicles in the traffic survey, thereby reducing its cost since additional equipment would not be necessary. This is taken into account in the above figures.

The installation and use of such test strips would provide enough information to determine the desirability of such a system as

well as its acceptability to the public. Favorable results would justify further installation of automatic highway strips and ultimately the widespread use of such a system in intra-urban traffic lanes.

C. CONCLUSION

We have shown that a system can be constructed, tested, and incorporated in three sequential steps: 1) construction and operation of a test track, 2) marketing feasibility study, and 3) highway test strips. We see that the third and most important, as well as most expensive, step would be undertaken only after the positive outcome of the first two. Such a sequentially dependent approach would be best not only since it is logical, but because it provides the safest investment of the entrepreneur's dollar.

VI. CONCLUSION:

The increasing concern with highway traffic safety has encouraged the development of an automatic highway system. Having made background studies in traffic safety, traffic congestion, electronic highways, and consumer acceptability, an analysis of vehicle dynamics was completed in order to define the controllability of the vehicle.

The actual system design includes:

- A. Steering Control -- the steering system uses as reference a cable buried in the highway energized by a frequency generator. Position readings record the lateral displacement of the vehicle from the cable, as well as the effective wheel angle from the cable tangent.
- B. Speed Control -- a command speed signal is obtained from the steering cable, and the actual vehicle speed is recorded by means of a pulse width demodulating system which determines the average speed between successive electronic spacing markers.
- C. Spacing Control -- two systems have been proposed. The first, for compatible use on present highways, correlates a phase shift in a highway detection loop with the presence of a vehicle. The second, to be incorporated in future highways, records strain patterns in the highway and relates deflection to a vehicle's pressure. In both cases, the spacing information is relayed to trailing vehicles.
- D. Servo-Mechanism Control and Actuation -- a detailed study of control techniques led to the development of a two-stage electrohydraulic servo-valve, controlling a rotary steering

actuator. A similar servo-valve employing pressure feedback is used to control the necessary degrees of braking.

In addition, the economic feasibility of the overall system was investigated, and the following proposal was made:

Whereas an Automatic Controlled Highway System is one highly desirable solution to the transportation problem, and whereas the development and incorporation of such a system is impossible without extensive study and testing, it is proposed that:

1. a two mile test track be constructed, staffed, and operated for one year at a total cost of \$234,200.00.
2. A marketing feasibility study be conducted to determine public acceptance at an estimated cost of \$100,000.00.
3. Sections of a heavily traveled inter state highway be converted for automatic use and 1000 vehicles be equipped for use on these test sections. Proposed cost -- including traffic survey and evaluation for a one year period -- \$2,350,400.

Should incorporation of the total system be undesirable, it is noted that any one of the individual subsystems (steering, speed, spacing) can be implemented and tested individually, making gradual introduction of a controlled highway system possible.

Having completed an initial study of traffic control, it is felt that the automatically controlled highway is a future necessity to reduce highway deaths and injuries as well as to increase travel

comfort and efficiency. Again realizing that great efforts still must be taken to insure high reliability of the total system, it has been shown that the automatic system is both mechanically and economically feasible at this time.

The analysis outlined in this paper can serve as a reference for future design considerations, and it is felt that the system described is worthy of close perusal as one valid means of obtaining a future automatic highway.

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