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DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

Thomas Richard Brinner, B.S., M.S.

The Ohio State University
1973

Approved by

Adviser
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TABLE OF CONTENTS

ACKNOWLEDGMENTS................................................. ii
VITA................................................................. iii
LIST OF TABLES................................................. viii
LIST OF FIGURES.................................................. ix
LIST OF SYMBOLS.................................................. xv

Chapter

I. INTRODUCTION................................................. 1
   A. Introduction............................................. 1
   B. The Automated Highway.............................. 5
   C. An Overview and Comparison of Longitudinal Guidance Methods 8

II. CONTINUOUS SYNCHRONOUS LONGITUDINAL GUIDANCE -- THEORY.......... 11
   A. Introduction............................................. 11
   B. General Requirements for Synchronous Longitudinal Control........ 12
   C. General Properties of SLG............................. 12
   D. Properties of a CSLG Position Reference............... 17
   E. Vehicle Longitudinal Dynamics and Control............. 28

III. CONTINUOUS SYNCHRONOUS LONGITUDINAL CONTROL -- A PHYSICAL REALIZATION... 49
   A. Introduction............................................. 49
   B. Constant Phase Difference CSLG......................... 49
   C. CSLG Reference Signals................................ 59
   D. Guiding Structure...................................... 67
   E. Longitudinal Position Detector........................ 83

IV. EXPERIMENTAL STUDIES.......................................... 85
   A. Introduction............................................. 85
   B. Reference System Characteristics.................... 85
# TABLE OF CONTENTS
(continued)

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV. EXPERIMENTAL STUDIES (continued)</td>
<td></td>
</tr>
<tr>
<td>C. Full-Scale Feasibility Studies</td>
<td>108</td>
</tr>
<tr>
<td>D. Summary</td>
<td>119</td>
</tr>
<tr>
<td>V. SUMMARY AND RECOMMENDATIONS</td>
<td>123</td>
</tr>
<tr>
<td>A. Summary</td>
<td>123</td>
</tr>
<tr>
<td>B. Recommendations</td>
<td>125</td>
</tr>
<tr>
<td>APPENDIX A</td>
<td>129</td>
</tr>
<tr>
<td>PRINCIPLES OF SINGLE SIDEBAND GENERATION</td>
<td></td>
</tr>
<tr>
<td>APPENDIX B</td>
<td>134</td>
</tr>
<tr>
<td>COMPUTER PROGRAM</td>
<td></td>
</tr>
<tr>
<td>APPENDIX C</td>
<td>139</td>
</tr>
<tr>
<td>EXPERIMENTAL EQUIPMENT</td>
<td></td>
</tr>
</tbody>
</table>
**LIST OF TABLES**

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Position Reference Properties</td>
<td>19</td>
</tr>
<tr>
<td>II</td>
<td>Random Properties of Slot Length and Average $\varepsilon_{ff}$ for Several Frequencies</td>
<td>93</td>
</tr>
<tr>
<td>III</td>
<td>Parameter Values Used</td>
<td>147</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>General configuration of an automated highway network.</td>
<td>6</td>
</tr>
<tr>
<td>2.</td>
<td>Adjoining links of synchronous highway.</td>
<td>15</td>
</tr>
<tr>
<td>3.</td>
<td>CSLG component definition.</td>
<td>18</td>
</tr>
<tr>
<td>4.</td>
<td>CSLG position reference as a function of longitudinal distance and time.</td>
<td>21</td>
</tr>
<tr>
<td>5.</td>
<td>Constant velocity slot-rate change.</td>
<td>24</td>
</tr>
<tr>
<td>6.</td>
<td>Two types of velocity changes.</td>
<td>26</td>
</tr>
<tr>
<td>7.</td>
<td>Limiting acceleration characteristics of a 1965 Plymouth sedan.</td>
<td>29</td>
</tr>
<tr>
<td>8.</td>
<td>Block diagram of synchronous longitudinal control system.</td>
<td>30</td>
</tr>
<tr>
<td>9.</td>
<td>Permissible operating region for simultaneous step changes in position and velocity.</td>
<td>35</td>
</tr>
<tr>
<td>10.</td>
<td>CSLG controller and compensated propulsion system excited by a position contaminating signal.</td>
<td>36</td>
</tr>
<tr>
<td>11.</td>
<td>Controller magnitude vs. frequency for $\xi = .71$ and $\zeta = 1.0$.</td>
<td>38</td>
</tr>
<tr>
<td>12.</td>
<td>Controller phase vs. frequency for $\xi = .71$ and $\zeta = 1.0$.</td>
<td>39</td>
</tr>
<tr>
<td>13.</td>
<td>Variance vs. bandwidth for $\xi = .71$ and $\zeta = 1.0$.</td>
<td>40</td>
</tr>
<tr>
<td>14.</td>
<td>Nonidealized emergency brake situation.</td>
<td>44</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>15.</td>
<td>Components of the position reference system for constant phase-difference CSLG, steady-state case</td>
<td>50</td>
</tr>
<tr>
<td>16.</td>
<td>Transition to a different velocity and headway with slot rate held constant</td>
<td>55</td>
</tr>
<tr>
<td>17.</td>
<td>Phase difference vs distance for several times for a velocity change with slot rate held constant</td>
<td>56</td>
</tr>
<tr>
<td>18.</td>
<td>Transition to a different velocity with slot length held constant</td>
<td>58</td>
</tr>
<tr>
<td>19.</td>
<td>Phase difference vs distance for several times for velocity change with slot length held constant</td>
<td>60</td>
</tr>
<tr>
<td>20.</td>
<td>Typical ranges of $f_0$ and $\Delta f$</td>
<td>62</td>
</tr>
<tr>
<td>21.</td>
<td>Components of a phase-shift single-sideband generator</td>
<td>64</td>
</tr>
<tr>
<td>22.</td>
<td>Measured phase difference as a function of $\theta_d$ and $\alpha_T/c_T = \sum v$</td>
<td>66</td>
</tr>
<tr>
<td>23.</td>
<td>Maximum measured phase difference error</td>
<td>66</td>
</tr>
<tr>
<td>24.</td>
<td>Measured angle vs desired angle for several values of signal-to-vestigial ratio</td>
<td>68</td>
</tr>
<tr>
<td>25.</td>
<td>Lateral cross section of highway showing physical placement of transmission lines</td>
<td>69</td>
</tr>
<tr>
<td>26.</td>
<td>Vertical component of magnetic field above a balanced two-wire transmission line</td>
<td>72</td>
</tr>
<tr>
<td>27.</td>
<td>Horizontal component of magnetic field above a balanced two-wire transmission line</td>
<td>73</td>
</tr>
<tr>
<td>28.</td>
<td>Phase of magnetic field for balanced two-wire transmission line</td>
<td>74</td>
</tr>
<tr>
<td>29.</td>
<td>Relative magnitudes of desired and crosstalk signals</td>
<td>79</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>30.</td>
<td>Measured angle as a function of $A_0$, $A_1$, $\Sigma_v$, $\Sigma_{co}$, $\Sigma_{cl}$, and $\Delta w$.</td>
<td>81</td>
</tr>
<tr>
<td>31.</td>
<td>Test set-up for measurement of field lateral distribution</td>
<td>88</td>
</tr>
<tr>
<td>32.</td>
<td>Horizontal magnetic fields—lateral distribution</td>
<td>90</td>
</tr>
<tr>
<td>33.</td>
<td>Vertical magnetic fields—lateral distribution</td>
<td>91</td>
</tr>
<tr>
<td>34.</td>
<td>Attenuation vs frequency for two-wire transmission line</td>
<td>95</td>
</tr>
<tr>
<td>35.</td>
<td>Magnitudes of desired and crosstalk currents in one transmission line ($f_0 = 3.734 \text{ MHz}$)</td>
<td>97</td>
</tr>
<tr>
<td>36.</td>
<td>Phase difference vs time for $E=1$</td>
<td>99</td>
</tr>
<tr>
<td>37.</td>
<td>Phase offset in the measuring system</td>
<td>100</td>
</tr>
<tr>
<td>38.</td>
<td>Longitudinal phase difference distribution</td>
<td>102</td>
</tr>
<tr>
<td>39.</td>
<td>Amplitude and phase of the single-sideband generator output</td>
<td>104</td>
</tr>
<tr>
<td>40.</td>
<td>Periodic deviations of the phase difference (position reference)</td>
<td>106</td>
</tr>
<tr>
<td>41.</td>
<td>Controlled vehicle position error and velocity response full-scale conditions—lock on and tracking at 14 ft/sec</td>
<td>110</td>
</tr>
<tr>
<td>42.</td>
<td>Controlled vehicle position error and velocity response full-scale conditions—lock on and tracking at 30 ft/sec</td>
<td>111</td>
</tr>
<tr>
<td>43.</td>
<td>Controlled vehicle position error and velocity response full-scale conditions—lock on and tracking at 41 ft/sec</td>
<td>112</td>
</tr>
<tr>
<td>44.</td>
<td>Controlled vehicle position error and velocity response full-scale conditions—step change from 15 to 24 ft/sec</td>
<td>114</td>
</tr>
<tr>
<td>45.</td>
<td>Controlled vehicle position error and velocity response full-scale conditions—step change from 24 to 29 ft/sec</td>
<td>115</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>46.</td>
<td>Controlled vehicle position error and velocity response full-scale conditions—start and stop, 0 to 19 to 0 ft/sec</td>
<td>117</td>
</tr>
<tr>
<td>47.</td>
<td>Controlled vehicle position error and velocity response full-scale conditions—start and stop, 0 to 28 to 0 ft/sec</td>
<td>118</td>
</tr>
<tr>
<td>48.</td>
<td>Controlled vehicle position error and velocity response full-scale conditions—acceleration, 0 to 46 ft/sec</td>
<td>120</td>
</tr>
<tr>
<td>49.</td>
<td>Controlled vehicle position error and velocity response full-scale conditions—deceleration, 46 to 0 ft/sec</td>
<td>121</td>
</tr>
<tr>
<td>50.</td>
<td>A high-quality transmission line</td>
<td>127</td>
</tr>
<tr>
<td>51.</td>
<td>Frequency spectrum of an amplitude modulated signal</td>
<td>130</td>
</tr>
<tr>
<td>52.</td>
<td>Filtering single-sideband modulation</td>
<td>130</td>
</tr>
<tr>
<td>53.</td>
<td>Phase-shift single sideband modulator</td>
<td>131</td>
</tr>
<tr>
<td>54.</td>
<td>Cross section of a parallel planar wire system</td>
<td>135</td>
</tr>
<tr>
<td>55.</td>
<td>Experimental Roadway System</td>
<td>140</td>
</tr>
<tr>
<td>56.</td>
<td>Schematic of phase-shift single-sideband generator</td>
<td>141</td>
</tr>
<tr>
<td>57.</td>
<td>Components of roadway system</td>
<td>142</td>
</tr>
<tr>
<td>58.</td>
<td>Experimental vehicle system</td>
<td>143</td>
</tr>
<tr>
<td>59.</td>
<td>Components of vehicle system</td>
<td>145</td>
</tr>
<tr>
<td>60.</td>
<td>Controller magnitude vs frequency for $\zeta=0.7$, $\tau=4.0$</td>
<td>148</td>
</tr>
<tr>
<td>61.</td>
<td>Controller phase vs frequency for $\zeta=0.7$, $\tau=4.0$</td>
<td>149</td>
</tr>
<tr>
<td>62.</td>
<td>Controller magnitude vs frequency for $\zeta=0.7$, $\tau=8.0$</td>
<td>150</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>63. Controller Phase vs Frequency for $\zeta=0.7$, $\tau=8.0$</td>
<td>151</td>
<td></td>
</tr>
<tr>
<td>64. Controller magnitude vs frequency for $\zeta=1.0$, $\tau=1.0$</td>
<td>152</td>
<td></td>
</tr>
<tr>
<td>65. Controller phase vs frequency for $\zeta=1.0$, $\tau=1.0$</td>
<td>153</td>
<td></td>
</tr>
<tr>
<td>66. Controller magnitude vs frequency for $\zeta=1.0$, $\tau=4.0$</td>
<td>154</td>
<td></td>
</tr>
<tr>
<td>67. Controller phase vs frequency for $\zeta=1.0$, $\tau=4.0$</td>
<td>155</td>
<td></td>
</tr>
<tr>
<td>68. Controller magnitude vs frequency for $\zeta=1.0$, $\tau=8.0$</td>
<td>156</td>
<td></td>
</tr>
<tr>
<td>69. Controller phase vs frequency for $\zeta=1.0$, $\tau=8.0$</td>
<td>157</td>
<td></td>
</tr>
<tr>
<td>70. Controller magnitude vs frequency for $\zeta=2.0$, $\tau=1.0$</td>
<td>158</td>
<td></td>
</tr>
<tr>
<td>71. Controller phase vs frequency for $\zeta=2.0$, $\tau=1.0$</td>
<td>159</td>
<td></td>
</tr>
<tr>
<td>72. Controller magnitude vs frequency for $\zeta=2.0$, $\tau=4.0$</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>73. Controller phase vs frequency for $\zeta=2.0$, $\tau=4.0$</td>
<td>161</td>
<td></td>
</tr>
<tr>
<td>74. Controller magnitude vs frequency for $\zeta=2.0$, $\tau=8.0$</td>
<td>162</td>
<td></td>
</tr>
<tr>
<td>75. Controller phase vs frequency for $\zeta=2.0$, $\tau=8.0$</td>
<td>163</td>
<td></td>
</tr>
<tr>
<td>76. Variance vs bandwidth for $\zeta=0.7$, $\tau=4.0$</td>
<td>165</td>
<td></td>
</tr>
<tr>
<td>77. Variance vs bandwidth for $\zeta=0.7$, $\tau=8.0$</td>
<td>166</td>
<td></td>
</tr>
<tr>
<td>78. Variance vs bandwidth for $\zeta=1.0$, $\tau=1.0$</td>
<td>167</td>
<td></td>
</tr>
<tr>
<td>79. Variance vs bandwidth for $\zeta=1.0$, $\tau=4.0$</td>
<td>168</td>
<td></td>
</tr>
<tr>
<td>80. Variance vs bandwidth for $\zeta=1.0$, $\tau=8.0$</td>
<td>169</td>
<td></td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>81.</td>
<td>Variance vs bandwidth for $\xi=2.0$, $\tau=1.0$</td>
<td>170</td>
</tr>
<tr>
<td>82.</td>
<td>Variance vs bandwidth for $\xi=2.0$, $\tau=4.0$</td>
<td>171</td>
</tr>
<tr>
<td>83.</td>
<td>Variance vs bandwidth for $\xi=2.0$, $\tau=8.0$</td>
<td>172</td>
</tr>
</tbody>
</table>

Figure 82.

Variance vs bandwidth for $\xi=2.0$, $\tau=4.0$
SYMBOLS

\( x \)  
longitudinal distance (ft.)

\( t \)  
time (sec.)

\( \Delta t \)  
time error

\( \rho \)  
flow rate (cars/hour/lane)

\( \rho_{\text{max}} \)  
maximum flow rate

\( x_n \)  
slot position corresponding to \( K \) and \( n \)

\( x_0 \)  
slot position corresponding to \( K \)

\( V \)  
velocity (ft./sec.)

\( V_{\text{min}} \)  
minimum velocity

\( V_s \)  
constant stream velocity

\( L \)  
vehicle length (ft.)

\( L_1 \)  
length of Section 1 (ft.)

\( L_2 \)  
length of Sections 1 & 2 (ft.)

\( H_{\text{max}} \)  
maximum slot length (ft.)

\( H \)  
slot length (ft.)

\( H_s \)  
constant slot length

\( m \)  
positive integer (slots/vehicle)

\( h_{\text{min}} \)  
minimum headway (space between vehicles (ft.)

\( \text{SR} \)  
slot rate (slots/hour/lane)

\( \text{PR} \)  
position reference [ft. (from slot center/unit ]

\( \text{PR}_m \)  
peak value of position reference

\( \text{PR}_0 \)  
initial value of position reference

xv
\( \omega_{vm} \)  
frequency of maximum \( \Delta v_{\eta} \) magnitude

\( \xi \)  
damping ratio

\( p \)  
time derivative \( (d/dt) \)

\( \tau \)  
time constant of compensated vehicle dynamics \( (\text{sec.}) \)

\( T_o \)  
controller time constant

\( T_1 \)  
controller time constant

\( k \)  
\( 2\xi \omega_n \tau \)

\( a \)  
total acceleration \( (\text{ft./sec.}^2) \)

\( a_{mv} \)  
maximum acceleration required for step change in velocity

\( a_{mx} \)  
maximum acceleration required for step change in position

\( \Delta a_{\eta} \)  
acceleration due to sinusoidal \( \eta(t) \)

\( a_c \)  
threshold of feeling acceleration

\( a \)  
desired deceleration rate

\( \Delta a \)  
deviation from the desired deceleration rate

\( \eta(t) \)  
position reference disturbance \( (\text{ft.}) \)

\( A \)  
amplitude of sinusoidal position reference disturbance

\( \gamma \)  
time \( (\text{sec.}) \)

\( b_w \)  
bandwidth \( (\text{Hz}) \)

\( s \)  
complex variable \( (\sigma+j\omega) \)

\( S_{\eta}(s) \)  
power spectral density of \( R_{\eta} \)

\( S_{xx}(s) \)  
power spectral density of controller output due to random \( \eta(t) \)
\( PR_t \) assigned (tracking) position reference

\( \Delta PR \) position reference error

\( T \) minimum time headway between vehicles (sec.)

\( \tau_v \) vehicle response time

\( t_c \) time required for system to both detect an emergency situation and initiate the proper control action

\( \Delta v \) maximum expected quasi-steady-state velocity deviation about \( V_s \)

\( V \) vehicle velocity (ft./sec.)

\( V_s \) velocity change command

\( \delta v_s \) magnitude of velocity step change

\( \Delta v_\eta \) velocity response due to sinusoidal \( \eta(t) \)

\( \Delta v_v \) velocity response due to random \( \eta(t) \)

\( \Delta x_m \) maximum expected deviation of vehicle position from reference position

\( \Delta x \) position error (ft.)

\( \Delta x_r \) position change command (ft.)

\( \Delta X_r \) magnitude of position step change

\( \Delta X_m \) maximum drop-back distance

\( \Delta x_\eta \) position response due to sinusoidal \( \eta(t) \)

\( \Delta x_v \) position response due to random \( \eta(t) \)

\( \omega \) frequency (rad/sec.)

\( \omega_n \) undamped natural frequency

\( \omega_{xm} \) frequency of maximum \( \Delta x_\eta \) magnitude
$R_\eta(\gamma)$ autocorrelation function of random $\eta(t)$

$\sigma_\eta^2$ variance of random $\eta(t)$

$\sigma_{\Delta x v}^2$ variance of position response due to random $\eta(t)$

$\sigma_{\Delta v v}^2$ variance of velocity response due to random $\eta(t)$

$b_0, b_1, b_2, b_3$ longitudinal controller constants

d_0, d_1, d_2, d_3 dummy variables

$y$ lateral distance from center of transmission line (ft.)

vertical distance above pavement

$\beta$ phase constant (wave number) (rad/ft.)

$\theta_d$ phase difference (degrees)

$\theta_o$ initial phase angle (degrees)

$\theta_x$ $\beta_1 L_1 - \theta_o$

$P$ polarity of field component sensed (horizontal or vertical)

$S_0$ detected signal over transmission line 0

$S_1$ detected signal over transmission line 1

$A_0$ amplitude of desired signal detected over line 0 (volts)

$A_1$ amplitude of desired signal detected over line 1 (volts)

$c$ signal propagation velocity (ft./sec.)

$c_o$ signal propagation velocity in free space, $10^9$ ft./sec.

$\lambda$ wavelength (ft.)
carrier or base frequency (Hz)
difference frequency (Hz)
integer (slot assignment)
assigned phase differences (degrees)
output of sideband generator \((f_o - \Delta f)\)
output of sideband generator \((f_o\)\)
amplitude of sideband generator output
angular error (degrees)
amplitude of unsuppressed carrier component in sideband generator output (volts)
maximum angular error
\(a_T/c_T\) \((\text{signal to vestigial ratio})\)
permeability of free space
free space dielectric constant
relative dielectric constant of the medium
horizontal magnitude of magnetic field
vertical magnitude of magnetic field
lateral distance from center of transmission line \(0,\) (ft)
lateral distance from center of transmission line \(1,\) (ft)
vertical distance from center of transmission line \(0,\) (ft)
vertical distance from center of transmission line \(1,\) (ft)
\( \alpha \) attenuation (nepers/meter)

\( r \) resistance/meter (\( \Omega/m \))

\( g \) conductance/meter (\( \mu/m \))

\( Z_0 \) characteristic impedance (\( \Omega \))

PF power factor

\( \varepsilon' \) real component of dielectric constant

\( \varepsilon'' \) imaginary component of dielectric constant

\( A_{0c} \) magnitude of cross-coupled signal from transmission line 0

\( A_{1c} \) magnitude of cross-coupled signal from transmission line 1

\( \theta_\alpha \) \( \theta_\beta \) \( \theta_\gamma \) arbitrary phase terms

\( \Sigma_{c0} \) signal-to-crosstalk ratio for signal 0

\( \Sigma_{c1} \) signal-to-crosstalk ratio for signal 1
CHAPTER I
INTRODUCTION

A. Introduction

Automotive transportation in America during the past seventy years has increased from virtual insignificance to 86% of all intercity travel in 1969 [1] with a major factor in this astonishing growth being the availability of adequate highways. Historically, Americans have been committed to the construction of highways as evidenced in the following brief review of major highway construction milestones.

In 1909 a one-mile stretch of Woodward Avenue in Detroit was paved with Portland cement [2] and shortly afterward, in 1913, the Lincoln Highway Association was created to push for a road from New York City to San Francisco [3]. Highway construction was given a tremendous boost in 1916 with passage of the Federal-Aid Highway Act in which the federal government and state governments shared the cost of road construction with the states being responsible for planning and construction of the desired roads [4].

The Interstate Highway System, with outerbelts and links respectively surrounding and interconnecting major cities, was proposed in 1944 [5]. All Interstate Highways were to be limited access and divided to reduce both accidents at intersections and head-on colli-
sions. Forty-thousand miles of highway were originally planned and today, with more than 79.6% [6] of the Interstate Highway System completed, certain evaluations of its benefits and shortcomings are possible.

The benefits of America's road system are realized daily in lower transportation costs and expanding economic growth; however, its shortcomings are quite evident. At least two major problems exist: decreased mobility with increased usage and an ever-increasing death toll from automobile accidents.

In his studies of traffic flow through the tunnels of New York City, Herman et al. [7] have shown that the flow capacity (cars per hour) of a section of road increases with user demand up to a point but any additional demand results in a decrease in that capacity. Since, during the decade of the sixties, the number of registered vehicles increased by 44%, motor vehicle travel increased 49% and the total road mileage only increased 4.6% all compared to 1960 [1], it would appear that decreased mobility will soon be felt more often than just during peak rush-hour periods. Indeed, it is only reasonable to expect that vehicle registrations and vehicle miles traveled will continue to increase resulting in ever-worsening congestion and decreasing mobility.

A second major problem of the present system of roads is the annual death toll due to motor vehicle accidents which, in 1971, reached 54,700 fatalities [8]. When the number of injuries from automobile accidents, estimated as 2.0 million in 1971 [8], is included, it is
obvious that an automotive safety problem exists. The National Safety Council continues to stress driver education as a solution to this problem; however, Nader [9] has expressed the following view:

"The first-rate accident research that is being done in this country, backed mainly by federal funds, is producing mounting evidence that the more that is known about human behavior, the more fundamental solutions will lie in the engineering of the highway transport system. . . . The traffic safety establishment sees the basic problem of accident prevention in the light of an existing system that requires the driver to judge and act perfectly without fail. But the limitations of human beings in coping with the increasingly complex driving task, even under the most rigid law-enforcement or the most ambitious education programs, make it unrealistic to expect all drivers to control their vehicles perfectly all the time."

These major problems are especially serious in urban areas, and a partial solution — frequently suggested and frequently adopted — has been to build more urban freeways. However, today such construction is increasingly opposed by citizen groups both arguing the deleterious effects of new highways and fighting condemnation of property for that purpose. Increasing the efficiency of today's freeways via urban traffic control, ramp metering, etc. has proven moderately successful, but more dramatic improvements are necessary especially in view of the expected future increase in the number of motor vehicles.

A number of partial solutions involving innovative transportation concepts have been advanced. The dial-a-bus [10], for example, is a bus-type system activated via telephone by potential passengers. Information from each call (origin, destination, number of passengers, etc.) would be tabulated by a central computer which would route buses
to pick up passengers in the most efficient manner. The Network Cab [11] provides a similar service; however, neither solution is likely to drastically change the transportation role of the individual privately-owned vehicle, and no legislated restrictions on automobile usage appear imminent.

A futuristic class of solutions involving the use of individual automated ground-transportation units has been proposed with three general categories suggested [12]:

1. Captive vehicle systems for use in restricted geographical areas.
2. Dual-mode systems for general coverage of urban areas.
3. Intercity automated highways.

The United States Department of Transportation, (DOT), has financed a prototype study of the first category at the University of West Virginia at Morgantown [13]. This site was selected because of its unusual terrain and the particular transportation requirements of the University. The project is presently nearing completion and system evaluation should begin soon. Little development effort has been expended in the second category; however, DOT did recently solicit proposals to develop various components for a dual-mode system [14].

The third category, the intercity automated highway, has received considerable attention in the past and is described next.
B. The Automated Highway

An automated highway network, as depicted in Fig. 1, would generally consist of three distinct areas. Low-intensity traffic areas would typically correspond to limited-access freeways linking outer-belts surrounding cities. High-intensity traffic areas could correspond to city traffic networks with numerous merges, diverges and interconnections or merely to intersections of major highways. Organizing areas would be provided to facilitate smooth transition of traffic flow between low- and high-intensity areas.

On an automated highway, all vehicles would be under automatic control with this control encompassing not only the basic aspects of vehicle guidance (i.e., lateral control and longitudinal control), but also the network-level aspects (e.g., scheduling and routing). Typically a driver on an entrance ramp would indicate his destination, and after his vehicle's automatic controls were quickly checked by roadside electronics, the vehicle would be merged with the mainstream traffic and proceed under complete automatic control to the exit closest to its destination. Once the vehicle were off the automated highway, manual control would be returned to its driver.

Partial solutions to the problems of decreasing mobility and increasing accident rates would be provided by an automated highway. Compared to manual operation, an electronic control system could more quickly detect and compensate for possible hazards. This should not only increase safety but would also increase mobility, since the minimum distance between vehicles could safely be decreased and higher flow rates should result.
Fig. 1—General configuration of an automated highway network.
The transition from the present system of highways to automated highways must take place gradually and compatibility between manual and automatic usage must be ensured for many years. Initially this could mean that automatically and manually controlled vehicles would operate "side by side"; but ultimately, to gain maximum efficiency and safety, manual control might only be allowed in case of emergency. In addition to compatibility, an automated highway should be designed for maximum versatility because of the possibility of incurring tremendous costs modifying millions of vehicles and thousands of miles of road due to unforeseen difficulties with the initial design.

There are two general and closely related aspects of automated highway research -- a macroscopic aspect and a microscopic one. The former involves the systems-level aspects of network operation, and particular works of note are the merging strategies formulated by Godfrey [15], the scheduling studies by Carlson [16], and the network studies by TRW [17] and Rule [18].

The microscopic aspect concerns the control of individual vehicles, and the earliest such work was done by RCA in conjunction with General Motors [19]. Subsequent work was done by Ford [20], and Road Research Laboratory (Great Britain) [21], Government Mechanical Laboratory (Japan) [22], Massachusetts Institute of Technology [23] and the Ohio State University [24].

All automotive vehicles have two basic control modes -- a lateral mode (steering) and a longitudinal mode (acceleration and braking). To date, no completely adequate means of implementing these
modes has been demonstrated. For a single lane of traffic, lateral control seems quite simple; however, the tracking accuracy around curves with presently proposed systems is not adequate. The problem of longitudinal control is probably more complex because of the diverse nature of the many required maneuvers; thus, more emphasis has been placed on it per the discussion in the next section.

C. An Overview and Comparison of Longitudinal Guidance Methods

The complex problem of automatic longitudinal guidance involves the following:

1. Steady-state (constant speed) operation.
2. Merging vehicles safely onto the highway.
3. Exiting vehicles from the highway to secondary roads.
4. Organizing vehicles (i.e., changing their relative positions so as to merge two high-speed traffic streams).
5. Emergency procedures to avoid collisions.

Two general approaches for controlling the longitudinal state of all vehicles in a system have been proposed -- Asynchronous Longitudinal Guidance (ALG) and Synchronous Longitudinal Guidance (SLG).

In an ALG system, the control of a vehicle would generally depend upon its state with respect to an n-vehicle traffic stream. In its simplest form, vehicle control would depend only on a vehicle's state with respect to its nearest forward neighbor -- a form of guidance
originally investigated by RCA [19]. From subsequent work on this "car following" approach at the Ohio State University [25], it was concluded that, by careful choice of constants, a longitudinal controller could be made asymptotically stable, i.e., variations in a lead-vehicle's velocity would not cause greater velocity variations in any following vehicle. Levine and Athans [26] concluded, after studying the optimal control problem of a string of high-speed vehicles, that each vehicle would require information on the state of every other vehicle, a situation too costly and complex to implement. Thus, although ALG appears satisfactory for vehicles in low-intensity traffic, it would clearly be unsuited for vehicle control in areas where large traffic volumes would frequently be present; and therefore, it was necessary to investigate other methods of longitudinal guidance.

Synchronous longitudinal guidance, originally proposed by Cluck [27], is best understood by visualizing an imaginary conveyor belt moving along the highway. This conveyor belt would be divided into equal sections or slots and no more than one vehicle would be assigned to each slot. A vehicle would stay with one particular slot over some sections of roadway; however, before reaching its destination the slot assignment could change many times due to macroscopic control considerations.

Two sampled-data systems for implementing SLG have been proposed. Weiss [28] proposed a system employing pre-scheduling trips with a vehicle only leaving a station when the controlling computer determines that a free path is available to its destination. The com-
puter would determine the proper position-time characteristics for each vehicle and would monitor the actual position of all vehicles via sensing coils in the roadbed. TRW Systems [29] have proposed a pulse-comparison technique in which each vehicle would receive position-reference pulses as it passed over specific points in the road. These road-position pulses would be compared against periodic-synchronizing pulses to determine a vehicle's position with respect to its prescribed position-time profile.

In the above cases vehicle position error would only be determined at discrete times which results in uncertainties in a vehicle's position and velocity. It would appear that minimum position and velocity errors could be achieved if the position reference were continually available. Toward this end Brown [30] utilized a slowly moving standing wave; however, a moving constant phase-point technique [31] appears to be superior, and thus, its general properties are considered next.
CHAPTER II
CONTINUOUS SYNCHRONOUS LONGITUDINAL GUIDANCE - - THEORY

A. Introduction

The network, or macroscopic, aspects of system control pertain to the highest-level of the control structure hierarchy. The primary role assigned to such control is to ensure safe and efficient system operation. This would include, but not be limited to, control of entering traffic, route selection as a function of traffic conditions, and initiation of emergency operations when an anomalous situation developed, and it would generally involve the coordination of lower hierarchies of control. The functions of the latter might involve the monitoring of a merging maneuver to ensure that a vehicle entering the system were merged into its assigned slot, the organization of two high-speed streams of traffic prior to a merge so that no conflict occurs, and operations at an exiting facility. The lowest hierarchy of control (microscopic control) deals with the control and guidance of individual vehicles, and is the one of primary concern here.

In this chapter, the general properties of an SLG system are first considered, and subsequently some general principles of continuous synchronous longitudinal guidance (CSLG) are developed with respect to individual vehicle control.
B. General Requirements for Synchronous Longitudinal Control

Any synchronous longitudinal control system must satisfy the following requirements:

1. The guidance system must be cost-effective, maintainable and sufficiently redundant.

2. Each vehicle must be stable relative to its prescribed slot.

3. The slot dimension must be chosen so as to satisfy some performance index which is based on considerations of safety, capacity and system cost.

4. For passenger comfort, acceleration should be less than 0.1g (0.8g maximum during emergencies).

5. Acceleration requirements must not exceed the capabilities of a vehicle's propulsion system.

These are later related to the continuity properties of a CSLG Position Reference.

C. General Properties of SLG

One major advantage of SLG is the use of quasi-deterministic vehicle trajectories or position-time profiles, which greatly simplify the macroscopic routing and scheduling problems within an automated highway network. In practice, the maximum permissible
flow rate for a section of such a network would be determined by such factors as user demand patterns, routing policies, and network geometries; thus the specification of this rate in general terms is beyond the intended scope of this effort. For this work, it is sufficient to note, that for a given linear section of roadway, the flow rate $\rho$ must be less than the maximum value defined by

$$\rho_{\text{max}} = \frac{3600 V}{h_{\text{min}} + L} \quad \text{(cars/hour/lane)} \quad (1)$$

where

- $V$ = stream velocity (ft/sec)
- $L$ = vehicle length (ft)
- $h_{\text{min}}$ = minimum headway (space between vehicles) (ft)

If, of course, $\rho = \rho_{\text{max}}$, it would be impossible to merge additional vehicles onto that section.

It is imperative to note the distinction between $\rho$ and slot rate (SR in slots/hour/lane) since slot length ($H$) could be less than $L + h_{\text{min}}$. Thus let

$$mH = L + h_{\text{min}}$$

where

- $m$ = minimum number of slots/vehicle (a positive integer)

Slot rate is defined as

$$\text{SR} = \frac{3600 V}{H} \quad \text{(slots/hour/lane)} \quad (2)$$
and from Eqns. (1) and (2)

\[ \frac{SR}{\rho_{\text{max}}} = m \]

and SR and \( \rho_{\text{max}} \) are equal only if \( m = 1 \).

Normally, an open-road section of highway would be operated at both a constant stream speed and constant slot rate; however, it would sometimes be necessary for adjoining sections of roadway to operate at different stream speeds and slot rates as shown in Fig. 2. Here, a change in vehicle speed and slot rate could be initiated at the "boundary." Assuming that vehicles travel from left to right, the number of vehicles entering at the left must equal those leaving at the right. Thus, under maximum flow conditions

\[ \rho_{\text{max},1} = \rho_{\text{max},2} \]

and

\[ \frac{V_1}{m_1H_1} = \frac{V_2}{m_2H_2} \]  \hspace{1cm} (3)

where subscripts 1 and 2 refer to the respective sections. Often it is desirable to maintain a constant slot rate across a boundary, in which case \( m_1 = m_2 \) and

\[ \frac{V_1}{H_1} = \frac{V_2}{H_2} = \frac{m_1}{T} \]  \hspace{1cm} (4)
i.e., the minimum permitted time headway $T$ between vehicles is invariant.

Fig. 2—Adjoining links of synchronous highway

<table>
<thead>
<tr>
<th>$x = 0$</th>
<th>$x = L_1$</th>
<th>$x = L_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;boundary&quot;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$x =$ longitudinal distance (ft)
Alternatively, the slot rate could be changed with the velocity and maximum flow capacity held constant; then

\[
\frac{SR_2}{SR_1} = \frac{H_1}{H_2} = \frac{m_2}{m_1}
\]  

(5)

There are applications, such as merging and moving vehicles between high- and low-intensity traffic regions, where changing \( \rho_{max} \) might be advantageous for reasons of safety and efficiency.\(^1\) In this case,

\[
\frac{\rho_{max_2}}{\rho_{max_1}} = \frac{m_1}{m_2} \left( \frac{SR_2}{SR_1} \right)
\]  

(6)

For example, if it were desirable to halve the maximum flow rate, this could be achieved by either doubling the number of slots per vehicle \( \left( \frac{m_1}{m_2} = \frac{1}{2} \right) \) and maintaining a constant slot rate, or by keeping the former invariant and halving the latter \( \left( \frac{SR_2}{SR_1} = \frac{1}{2} \right) \).

In the remainder of this work, the primary emphasis will be focused on the case for which \( m_1 = m_2 = 1 \). Also, only velocity changes with invariant slot rate \( \rho_{max} = SR \) or invariant slot length will be considered.

It should be noted that for a fixed \( \rho_{max} \) on a given section of roadway, one has a minimum permitted velocity \( (V_{min}) \) on that section. Per Eqn. (1) with \( h_{min} = 0 \),

\(^1\) In practice, this could be done only under well-defined conditions.
This, of course, corresponds to bumper-to-bumper traffic and the limitation on velocity, together with the limitations posed by Eqn. (4), limit one's options in designing under a constant flow-rate condition.

D. Properties of a CSLG Position Reference

1. General

In a CSLG system, the position of each vehicle relative to its assigned moving slot would be determined continuously. The physical situation involved is shown in Fig. 3 where the position reference signals are coupled from a guiding structure to a vehicle via a non-contacting communication link. The general properties of the position reference must include the following:

(1) The lateral motion of a vehicle should not affect the detected longitudinal reference; or concurrently, the position reference should be "constant" over a specified lateral-vertical area.

(2) The reference should be movable at all required vehicle speeds and should be spatially periodic to facilitate slot definition.
I S o w a y (juiding S t r u c t u r e.

5 y s  err) (n o n - c o n t a c t i n g

c o n t a c t i n g

c o m m u n i c a t i o n  l i n k)

Longi hjdfna

/ Fbsit/on

D e t e c t o r

C S L G  Reference

Position Reference

Fig. 3 - CSLG Component Definition
(3) The measurement resolution should be the same over an entire slot—regardless of a vehicle's position in that slot or the slot's position in the roadway section.

It might also be desirable to have continuity of the measured reference signal and its velocity. However, this may not be essential since practical systems could exhibit controlled discontinuities to which vehicles would be capable of responding.

All of the considerations are summarized in Table I.

TABLE I
POSITION REFERENCE PROPERTIES

LATERAL AND VERTICAL
Constant over reasonable areas

LONGITUDINAL
1. Movable at all desired vehicle speeds
2. Periodic for slot definition
3. Constant measurement resolution
4. Continuous (desirable)
5. Continuous velocity (desirable)
2. The Linearly Distributed Position Reference

a. Steady-State Performance

Ideally, the continuous position reference would be linearly distributed over a slot length with either a positive or negative slope in the direction of vehicle travel. Such a reference is shown plotted versus distance \( x \) for a fixed time \((t = 0)\) in Fig. 4a. Here the dimension of the position reference is feet (from slot center) per unit, and the unit would be the fundamental quantity associated with a measured parameter, e.g. volts, degrees, etc.

Hence

\[
PR_m = \frac{H/2}{\text{peak value of parameter}}
\]

and

\[
PR_0 = \text{initial value of the position reference}
\]

The choice of slope is arbitrary and a negative slope is shown. The corresponding reference signal-versus-time relationship which would result when the spatially-distributed
Fig. 4 - CSLG Position Reference as a function of Longitudinal Distance and Time
waveform were moved past a fixed value of $x (x=0)$ at a constant speed $V_s$ is shown in Fig. 4b. Clearly,

$$V_s = \frac{H}{T}$$  \(8\)

Since each controlled vehicle would be assigned to a specific point (PR) within a slot (e.g., the slot center), the vehicle could fall back or move ahead a maximum distance of $(H/2-L/2)$ and still remain within its slot. If each vehicle tracked a zero reference point, the loci of such points (as the linear waveform of Fig. 4a were moved along the highway at a constant speed) would define specific tracking paths or desired position-time profiles. Slot boundaries would be defined between and parallel to tracking paths as shown in Fig. 4d. Sufficient information is contained in this figure for most CSLG maneuvers and it will be used extensively later.

The relationship between tracking paths and slot boundaries is most easily understood by reference to Fig. 4c. Here the position reference is shown as a "sheet" function in distance and time where slot boundaries are shaded areas and tracking paths are dashed lines.

If a vehicle were assigned to track the zero reference point, $PR_t=0$, then the measured position reference would be the position error or deviation.
If the slot rate were either doubled or halved (with the velocity remaining fixed), the zero-reference trajectories would be shown in Figs. 5a and 5b, respectively. In practice, vehicles would occupy alternate slots, before the slot rate was halved in order to avoid slot-assignment conflicts. The reference signals versus time, for the case in which the slot rate is doubled at the boundary \((x=L_1)\), are shown in Fig. 5c. The reference signals at this point would be continuous only for an instant every \(T_1\) seconds. Thus, per the figure, a vehicle leading its reference by \(\Delta t\) would encounter a jump \(\Delta PR\) in the detected reference signal when it passed \(x=L_1\). This effect could have deleterious effects on system performance, and would clearly have to be minimized if slot doubling were used.

b. Velocity-change performance

For steady-state operation the position reference could be linearly distributed as shown in Fig. 4; however, for some velocity changes this may not be true. Thus, if \(V_1/H_1 = V_2/H_2\) the slot length must contract from \(H_1\) in Section 1 to \(H_2\) in Section 2, and it must assume intermediate values in the transition region between these sections. Similarly, if the slot length were fixed for a velocity change as shown in Fig. 6b, the time headway would vary with time in the transition period. Such considerations lead to the following generalization of Eqn. (8) where

\[
V = [H(x,t), T(x,t)]
\]
Fig 5-Constant Velocity Slot-Rate Change
is a function of position and time, and the restrictions inherent in two special cases are investigated.

1. A velocity change with slot rate fixed

If it were required that a constant slot rate be maintained across the transition region shown in Fig. 6a, then

\[ \frac{V_1}{H_1} = \frac{V_2}{H_2} = \frac{I}{T} = \text{constant} \]

and the slot length must change in proportion to the required changes in \( V(x,t) \). Here, since both the boundaries of the transition region and \( H_1 \) and \( H_2 \) would be specified a priori,

\[ H(x,t) = H(x) \]

and

\[ V = V(x) = \frac{H(x)}{I} \]  \hspace{1cm} (10)

In theory,

\[ L < H(x) < \infty \]

however, it is clear from Eqn. (10) that bounds on \( V \) would result in bounds on \( H(x) \).

In the limiting case, a step change in velocity\(^2\) would be initiated at the boundary (Fig. 2), and the transition region would have a zero length. The headway between adjacent vehicles would vary in a manner determined by the nature of the command signal and the vehicle response characteristics.

\[^2\text{Note from Eqn. (10) that such a step change (from } H_1 \text{ to } H_2 \text{) would be equivalent to a step change in velocity (from } V_1 \text{ to } V_2 \text{).}\]
Fig. 6 - Two Types of Velocity Changes

(a) Velocity change with slot rate fixed

(b) Velocity change with slot length fixed
ii. A velocity change with slot length invariant

If it were required that slot length be invariant with a change in velocity, then

\[ H(x, t) = H_s \]

and

\[ V(t) = \frac{H_s}{T(t)} \]  \hspace{1cm} (ii)

At least two limiting factors are involved here---the minimum permissible time headway and the maximum permitted velocity.

The reader should consider the limiting case wherein a step-command velocity change is initiated at \( t = t_0 \), and further, it should be noted that any command velocity change would affect all vehicles over a section.

If two sections of roadway, similar to Fig. 2 were operated at different time headways, the resulting slot rates would also be different. With different slot rates on either side of the boundary it is impossible for the position reference to be continuous across the boundary. A specific example of this is the slot doubling discussed earlier.

To this point only general theoretical properties of CSLG have been discussed. However, to be of practical value the position reference must be adapted to accommodate practical vehicle dynamics per the discussion in the following section.
D. Vehicle Longitudinal Dynamics and Control

1. General Vehicle Performance

The performance characteristics of automotive vehicles range from high-performance cars, capable of accelerating from zero to sixty miles per hour in less than seven seconds, to economy cars with top speeds of some 70 miles per hour. In an automated ground transport system, standardization would be essential; hence, it is assumed here that all vehicles would have identical performance characteristics. Following Bender and Fenton [32], the characteristics selected were those of a 1965 Plymouth primarily because such a vehicle was available and, to a lesser extent, because it was felt to be representative of present-day vehicles. The limiting acceleration characteristics of this vehicle are shown in Fig 7; however, the presence of headwinds, road grades, etc. would, of course, reduce these limits. Clearly, these can not be exceeded, and any mathematical representation of vehicle longitudinal dynamics must take this into account.

2. A CSLG Controller

The vehicle control system shown in Fig. 8 was proposed by Bender [33] as a practical method of controlling vehicle speed via the position reference. The controller was designed to follow step changes in velocity and position while maintaining finite acceleration and jerk; and as may readily be derived from Fig. 8,
Fig. 7 - Limiting acceleration characteristics of a 1965 Plymouth Sedan

wheel spin, 0.59 g
$v = \text{vehicle velocity}$

Compensated vehicle dynamics

$\frac{b_2}{b_3p}$

Position reference measuring device

$\frac{1}{p}$

$\Delta x_r$

$b_0, b_1, b_2$ and $b_3$ are constants

$p = \frac{d}{dt}$

Fig. 8 - Block diagram of synchronous longitudinal control system
Bender defined the time constant of the compensated vehicle dynamics (see Fig. 8) as

$$\tau = \frac{b_2}{b_1}$$

and demonstrated that the propulsion system response time imposed a lower limit on this quantity. The other parameters of Eqn. (12) are related to the constants in Fig. 8 by

$$T_i = \frac{b_1}{b_0} \omega_n^2 = \frac{\tau}{1 - 2\xi \omega_n \tau}$$

$$T_o = \frac{b_1}{b_0} = T_i + \frac{2\xi}{\omega_n}$$

and

$$\frac{2\xi T_i}{\omega_n} + \frac{1}{\omega_n^2} = \frac{b_x}{b_o}$$

Stable operation is obtained provided

$$0 < k = 2\xi \omega_n \tau < 1$$

It must be noted that $v_s$ and $\Delta x_r$ must be restricted to values...
which are within the response capabilities of the vehicle. Other control configurations are possible; however, only this one is considered here since it is the simplest configuration which will satisfy the desired performance requirements.

Bender has exhaustively examined the behavior of this control configuration for a variety of parameters and determined that

\[ \zeta = 1 \quad (\text{sec}) \]

and

\[ \xi = 0.7 \]

were "good" choices for satisfactory system response. Larger values of either parameter resulted in slower response times and smaller values resulted in either oscillatory or unstable conditions. With \( \xi \) and \( \zeta \) chosen, the drop-back distance for step changes in velocity was minimized for \( k = 0.8 \) (this set of parameter values was used in the full-scale testing described in Chapter 4).

a. Vehicle response to step changes in velocity and position

In a practical CSLG system a vehicle could experience step changes in both position and velocity. The maximum magnitude of these changes is determined by the available acceleration and maximum permissible drop-back distance. With the above values of \( \xi, \zeta \) and \( k \) and the controller in Fig. 8 Bender [33] showed that for a step change (\( \Delta v_s \)) in velocity the maximum drop-back
distance is

\[ \Delta X_m = -1.948 \delta v_s \quad (\text{ft}) \quad (13) \]

and the maximum required acceleration is

\[ a_{mv} = 0.355 \delta v_s \quad (\text{ft/sec}) \quad (14) \]

Further, for a required step change in position (\( \Delta X_r \)) the maximum required acceleration is

\[ a_{mx} = 0.0407 \Delta X_r \quad (15) \]

Typically, maximum values for available acceleration and allowable drop-back distance are 0.1 g, which is the maximum available acceleration at 100 ft/sec, and \( H/2 - L/2 \), which is the maximum permitted position deviation for a vehicle from the center of its slot, respectively. By assuming that maximum accelerations occur simultaneously and that maximum distance deviations also occur simultaneously, a conservative upper bound on the magnitude of discrete velocity and position changes can be obtained. The maximum total acceleration would be

\[ a = a_{mv} + a_{mx} = 0.355 \delta v_s + 0.0407 \Delta X_r < 3.22 \quad (\text{ft/sec}) \]

and similarly, the total position deviation would be

\[ \Delta x = \Delta X_m + \Delta X_r = 1.948 \delta v_s + \Delta X_r < \frac{H}{2} - \frac{L}{2} \]

From these equations

\[ \delta v_s < 9.06 - 0.1147 \Delta X_r \quad (16) \]

and

\[ \delta v_s < 1.948 \left( \frac{H - L}{2} \right) - \frac{\Delta X_r}{1.948} \quad (17) \]
Eqns. (16) and (17) are plotted in Fig. 9 where the region of permissible simultaneous step changes in velocity and position are defined. Considering only step changes in velocity with continuous position reference

\[
\delta v_s < 9.06 \quad (\text{ft/sec})
\]

and considering only step changes in position with continuous velocity

\[
\Delta x_r < \frac{H-L}{2}
\]

Throughout the above analysis only commands which resulted in positive vehicle acceleration were evaluated. Obviously step changes could occur so as to produce deceleration or some weighted combination of deceleration and acceleration. Thus, three additional situations could exist, but since vehicle deceleration capabilities always exceed acceleration capabilities, restricting operation to the permissible region of Fig. 9 and assuming that the axes are absolute values should result in safe operation for all four situations.

b. Periodic Position Error

In practice, the position reference could be contaminated by both periodic and random noise. Consider the situation shown in Fig. 10, where the output of the position-reference sensing device is contaminated by a signal \( \eta(t) \). In this section \( \eta(t) \) is taken as sinusoidal, and in the next section, it will be treated as a continuous random variable.
Fig. 9 – Permissible operating region for simultaneous step changes in position and velocity
Compensated propulsion system

Position reference sensing device

Quiescent value offset by $V_S$

Vehicle velocity $v = V_S + \Delta v$

$p = \frac{d}{dt}$

$\eta(t)$ = contaminating signal

$\Delta x$ = position deviation

Fig. 10 - CSLG controller and compensated propulsion system excited by a position contaminating signal
The position deviation, $\Delta x_\eta$, due to $\eta(t)$ is easily determined to be

$$\Delta x_\eta = \frac{-\left(\frac{1}{T_p}I\right)}{\left(\frac{2\xi}{\omega_n} + \frac{2\xi^2}{\omega_n^2} + 1\right)} \eta(t) \quad (18)$$

When $\eta(t) = A \sin \omega t$

$$\frac{\Delta x_\eta(j\omega)}{A} = |H(j\omega)| \angle H(j\omega) \quad (19)$$

where

$$|H(j\omega)| = \sqrt{\frac{\frac{T_o^2 \omega^2 + 1}{T_o^2 \omega^2 + 1}}{\left(\frac{\omega_o^2 - \omega^2}{\omega_o^2 - \omega_n^2} \right)^2}} \quad (20)$$

and

$$\angle H(j\omega) = 180^\circ + \tan^{-1}(T_o \omega) - \tan^{-1}(T_o \omega) - \tan^{-1}\left[\frac{2 \xi \omega_n \omega}{\omega_n^2 - \omega^2}\right] \quad (21)$$

Plots of Eqns. (20) and (21) for the chosen values of $\xi$ and $\omega$ and three values of $k$ are shown in Figs. 11 and 12, respectively. Additional plots, showing the effects of larger values of $\xi$ and $\omega$, are included in Appendix D. Typically $\Delta x_\eta$ is less than $A$ for the range of $\omega$ used.

Passenger comfort is related to vehicle acceleration and jerk. In the above

$$\Delta x_\eta(t) = A |H(j\omega)| \sin(\omega t + \angle H(j\omega))$$

and the corresponding periodic acceleration $\Delta a_\eta$ would be

$$\Delta a_\eta(t) = \frac{\partial^2}{\partial t^2} \Delta x_\eta(t) = -A \omega^2 |H(j\omega)| \sin[\omega t + \angle H(j\omega)]$$

For reasons of passenger comfort, this acceleration must be less than some threshold value $\alpha$ and
Fig. 11 - Controller magnitude vs frequency for $\omega = 0.71$ and $\zeta = 1.0$
Fig. 12 - Controller phase vs frequency for $\zeta=0.71$ and $\xi=1.0$
Ideally, $a_c$ would have to be slightly below the level of feeling since no perceptible oscillation would be acceptable. Usually $A$ and $\omega$ would be fixed and $|H(j\omega)|$ could be decreased by increasing $f$ and $\gamma$; however, this would increase the response time and some trade-offs would be necessary.

Additionally, any oscillatory motion of the vehicle would modify a vehicle's headway—a factor which must be accounted for in the specification of $h_{\text{min}}$; however, this topic is deferred until the effects of random variations superimposed on the position reference have been investigated.

c. Random Position Error

Random variations in the position reference could be caused by noise in the position-measuring device or variations in the speed of the reference; however, the precise nature of this randomness will be discussed in later chapters. Assume $\eta(t)$ to be a stationary, zero-mean, normally distributed random variable with variance $\sigma^2_\eta$, where $\eta(t)$ is defined in Fig. 10. Further, the process is assumed to be low-pass with the autocorrelation function

$$R_\eta(\tau) = \sigma^2_\eta e^{-4\nu/\gamma}$$

where

$\gamma = \text{time (sec)}$

$4\nu = \text{bandwidth (Hz)}$. 

\[ A\omega^2/|H(j\omega)| < a_c \]
The corresponding power spectral density is

\[ S_H(s) = \frac{2b_w \sigma^2}{b_w^2 - s^2} \quad (s = \sigma \omega) \]  

(22)

The power-spectral density of the output can be determined as follows:

\[ S_{XX}(s) = H(s)H(-s)S_H(s) = |H(s)|^2 S_H(s) \]

From this

\[ \sigma_{\Delta x_r}^2 = R_{xx}(0) = \frac{1}{\pi} \int_{-\infty}^{\infty} S_{xx}(s) ds \]

Where \( \Delta x_r \) = random position response to \( \eta(t) \).

After substituting the appropriate expressions from Eqns. (20) and (22), this integral can be evaluated by using tabulated integrals for rational spectra [34]; thus,

\[ \sigma_{\Delta x_r}^2 = \frac{d_0 d_1 d_2 d_3 - d_1 d_4}{d_1 d_2 d_3 - d_2 d_3^2 - d_3 d_4} \]  

(23)

where

\[ d_0 = b_w \quad d_1 = 1 + T_0 b_w \quad d_2 = T_0 + b_w \left( \frac{2 T_0 s}{\omega_n^2} + \frac{1}{\omega_n^2} \right) \]

\[ d_3 = \left( \frac{2 T_0 s}{\omega_n^2} + \frac{1}{\omega_n^2} \right) + \frac{T_0 b_w}{\omega_n^2} \quad d_4 = \frac{T_0}{\omega_n^2} \]

In Fig. 13, \( \sigma_{\Delta x_r}^2/\sigma_r^2 \) is plotted versus \( b_w \) for \( \xi = .7, \ z = 1 \) and three values of \( k \). Additional plots for larger values of \( \xi \) and \( z \) are included in Appendix E, and in all cases,

\[ \frac{\sigma_{\Delta x_r}^2}{\sigma_r^2} < 1 \]

for all positive \( b_w \), indicating that the uncertainty in actual vehicle position is less than the uncertainty associated with the position reference.
Fig. 13 - Variance vs bandwidth for $\xi = 0.71$ and $\bar{z} = 1.0$
Once the bandwidth and variance of $\eta(t)$ have been determined, it is simply a matter of referring to the appropriate response curve to find $\sigma_{\Delta x}^2$. Hence

$$|\Delta x_r| \leq 2\sigma_{\Delta x}$$

with 99% confidence, and this value will be used in the subsequent discussion of minimum headways. It should be noted that, as in the sinusoid case, increasing $\delta$ and $\varepsilon$ will decrease the amplitude of the vehicle response but will also increase the response time.

In the following section the above expressions for position deviation are shown to affect the minimum headway, and hence the maximum capacity of a given roadway section.

3. Minimum Headway

Ideally the position reference signal would move at a constant speed during steady-state operation, but in practice, one would expect to encounter real or apparent variations in this speed, dc offsets due to either roadway or vehicular instrumentation, and noise inextricably mixed in with the detected signal. Bender and Fenton [35] have investigated this problem and the resulting effects on $h_{\text{min}}$ by considering the nonidealized emergency situation shown in Fig. 14. Here the time required for a following vehicle to detect an emergency situation (a sudden deceleration of a lead vehicle) and respond to it, is $t_c + \varepsilon_v$. To avoid a collision, the headway must be
Fig. 14—Nonidealized emergency brake situation
greater than zero for all time, which results in the following

\[ h_{mn} = 2\Delta x_m + (v_s + \Delta v)(t_c + \Delta t_v) + \frac{(v_s + \Delta v)^2}{2(\Delta a - \Delta \alpha)} - \frac{(v_s - \Delta v)^2}{2(\Delta a + \Delta \alpha)} \]  

(24)

where

- \( t_c \) = time required for system to both detect an emergency situation and initiate the proper control action
- \( \Delta t_v \) = vehicle response time
- \( \Delta v \) = maximum expected quasi-steady-state velocity deviations about \( v_s \)
- \( a_o \) = desired deceleration rate
- \( \Delta a \) = deviation from the desired deceleration rate
- \( \Delta x_m \) = maximum expected deviation of vehicle position from reference position.

It is convenient to let

\[ \Delta x_m = \Delta x_m^1 + \Delta x_m^2 \]

and

\[ \Delta v = \Delta v^1 + \Delta v^2 \]

where subscript 1 applies to errors due to wind, grade, etc. and subscript 2 applies to the random and periodic errors discussed.

Unfortunately \( \Delta x_m^2 \) and \( \Delta v^2 \) are not independent, as consideration of the periodic and random components shows.

For the periodic components

\[ \Delta x^1 = \frac{A}{|H(j\omega)|} \sin[\omega t + \angle H(j\omega)] \]
and
\[ \Delta v_\eta = \frac{d}{dt} \Delta x_\eta = A \omega |H(j \omega)| \cos[\omega t + \angle H(j \omega)] \]

It is easily seen that \( \Delta x_\eta \) and \( \Delta v_\eta \) are orthogonal and have maximum values at different frequencies. Similarly, for the random components
\[ |\Delta x_r| \leq 2 \sigma_{\Delta x_r} \]
and
\[ |\Delta v_r| = \left| \frac{d}{dt} \Delta x_r \right| \leq 2 \sigma_{\Delta v_r} \]
where
\[ \sigma_{\Delta v_r}^2 = R_{\Delta x_r \Delta v_r}(0) = \frac{1}{2 \pi} \int_{-\infty}^{\infty} |H(s)|^2 \left( \frac{b_w s^2}{b_w^2 - s^2} \right) \frac{s^2}{b_w^2 - s^2} ds \]

Here, the magnitude of the standard deviations is a function of the bandwidth, \( b_w \). If these random components are orthogonal, the crosscorrelation
\[ R_{\Delta x_r \Delta v_r}(t) = 0 \]
Thus, it appears that maximum position and velocity errors would not occur simultaneously.

A precise determination of the maximum \( h_{\text{min}} \) would require a specific controller, knowledge of the random variable parameters, the magnitude of periodic variations and the maximum range of dc offsets from the position measuring device. For these reasons a precise analysis is avoided, and only bounds on \( h_{\text{min}} \) are considered.

To establish these bounds it was necessary to specify maximum values. From the above, the maximum periodic position error is
$$\Delta x_{\eta_{\text{max}}} = A \frac{1}{H(j\omega_{\eta})}$$

where

$$\omega_{\eta} = \text{frequency of maximum } \Delta x_{\eta} \text{ magnitude}$$

and the maximum periodic velocity error is

$$\Delta v_{\text{max}} = A \omega_{\eta \text{max}} \frac{1}{H(j\omega_{\eta})}$$

where

$$\omega_{\eta} = \text{frequency of maximum } \Delta v_{\text{max}} \text{ magnitude}$$

For 99% confidence with a specified bandwidth the maximum random parameters are

$$\Delta v_{\text{max}} = 2\sigma_{\Delta v_{\text{max}}}$$

and

$$\Delta x_{\text{max}} = 2\sigma_{\Delta x_{\text{max}}}$$

The position-measuring device could have consistent inaccuracies and the maximum permissible offset from a true reading is $$\Delta x_d$$.

Combining these effects

$$\Delta x_{\eta} = \Delta x_{\eta_{\text{max}}} + \Delta x_{\eta_{\text{max}}} + \Delta x_{\eta_{\text{max}}} + \Delta x_{\eta_{\text{max}}} = A \frac{1}{H(j\omega_{\eta})} + 2\sigma_{\Delta v_{\text{max}}} + \Delta x_{\eta_{\text{max}}}$$

and

$$\Delta v = \Delta v_{\eta_{\text{max}}} + \Delta v_{\eta_{\text{max}}} + \Delta v_{\text{max}} = A \omega_{\eta \text{max}} \frac{1}{H(j\omega_{\eta})} + 2\sigma_{\Delta v_{\text{max}}} + \Delta v_{\text{max}}$$

Hence, with these values the bounds on minimum headway would be

$$h_{\text{min}} > \left\{ \begin{array}{l}
2\Delta x_{\eta} + V_s(t_c + \Delta v) + \frac{V_s^2 \Delta a}{a_o^2 - (\Delta a)^2} \\
(V_s + \Delta v)(t_c + \Delta v) + \frac{(V_s + \Delta v)^2}{2(a_o - \Delta a)} - \frac{(V_s - \Delta v)^2}{2(a_o + \Delta a)}
\end{array} \right\}$$

(27)
and

\[ h_{\text{min}} < 2 \Delta x_m + (v_s + \Delta v)(c_e + \Delta c) \cdot \left( \frac{(v_s + \Delta v)^2}{2(a_o - \Delta a)} - \frac{(v_s - \Delta v)^2}{2(a_o + \Delta a)} \right) \]  

(28)

Since it is desired to have \( h_{\text{min}} \) as small as practical, it is essential that the effects described here be minimized. The origin of some of these effects is considered in the next chapter.
CHAPTER III
CONTINUOUS SYNCHRONOUS LONGITUDINAL CONTROL — A PHYSICAL REALIZATION

A. Introduction

One method of obtaining a continuous position reference is via a phase-measurement technique. Both steady-state and transient aspects of such a reference approach are examined, related to slot length and flow capacity, and used to determine the ranges of various critical parameters. These ranges and the CSLG properties listed in Table I are used in defining the design criteria for the various components (reference-signal generator, guiding structure and position detector) of one practical phase-measurement system. Finally the physical limitations of this system are defined.

B. Constant Phase-Difference CSLG

1. Basic Theory

The constant phase-difference technique is illustrated in Fig. 15b. Here a roadway section of length $L_\perp$ contains two separate and parallel transmission lines excited from opposite ends of this section. A vehicle would detect the signal over each line, measure the phase-difference between these two signals and move in such a way as to keep this phase-difference constant. Ideally,
a.) Longitudinal phase difference distribution and typical vehicle slot assignments

\[ S_0 = A_0 \cos \left( \omega_0 t - \beta_0 x \right) \]

\[ S_i = A_1 \cos \left( \omega_1 t + \beta_1 (x-L_i) + \Theta_0 \right) \]

b.) Reference signals and guiding structure

Fig. 15 - Components of the position reference system for constant phase-difference CSLG, steady-state case
the detected signals would be

\[ S_0(x,y,z,P,t) = A_0(x,y,z,P,t) \cos(\omega_0 t - \beta_0 x) \]  \hspace{1cm} (29)

and

\[ S_1(x,y,z,P,t) = A_1(x,y,z,P,t) \cos[\omega_1 t + \beta_1(x-L) + \phi_0] \]  \hspace{1cm} (30)

where subscripts 0 and 1 designate transmission line 0 and 1 respectively, and

\[ y = \text{lateral distance from center of transmission line (ft) (see Fig. 25)} \]
\[ z = \text{vertical distance above pavement (ft)} \]
\[ P = \text{polarity of field component measured} \]
\[ \omega = \text{angular frequency of signal (radians/sec)} \]
\[ \phi_0 = \text{initial phase angle (radians)} \]

and \( A = \text{amplitude of detected signal (volts)}. \)

The rather complicated nature of \( A \) will be examined in detail later; here, if the effect of \( A_0 \) and \( A_1 \) on the phase measurement were neglected, the phase difference (\( \Theta_d \)) between the detected signals would be

\[ \Theta_d(x,t) = (\omega_0 - \omega_1) t - (\beta_0 - \beta_1) x - \phi_0 - \phi_1 \]  \hspace{1cm} (34)

Assuming that\(^3\)

\[ \omega_0 = \omega_1 \]

and

\[ \omega_0 - \omega_1 = \Delta\omega = 2\pi\Delta f \]

then

\[ \beta_0 + \beta_1 \approx 2\beta_0 = \frac{2\omega_0}{c} = \frac{4\pi}{\lambda} \]

\(^3\)The assumption that \( \omega_0 \approx \omega_1 \) can be justified by considering typical speeds and slot lengths in an automated highway system. If \( H=100 \) (ft), \( V=100 \) (ft/sec) (68mph) and \( c=5\times10^8 \) (ft/sec), then from Eqns. (34) and (36), \( f=2.5\times10^6 \) Hz, \( \Delta f=1.0 \) Hz and since \( \omega_0 = \omega_1 + \Delta\omega \) it is clear that \( \omega_0 \approx \omega_1 \).
where \( c \) = propagation velocity of transmission lines (ft/sec)

and \( \lambda = \frac{c}{\nu} \) = wavelength (ft)

On substituting these expressions into Eqn. (31), there results

\[
\Theta_d(x,t) = \frac{2\pi}{T} t - \frac{2\pi}{H} x + \Theta_x
\]  \hspace{1cm} (32)

where

\[
T = \frac{1}{\Delta f} \quad (33)
\]

\[
H = \frac{\lambda}{2} = c/2\nu \quad (34)
\]

and

\[
\Theta_x = \beta_L - \Theta_o \quad (\text{35})
\]

\( \Theta_d(x,t) \) is a periodic function in both time and space, and it is convenient to require

\[-180^\circ \leq \Theta_d \leq +180^\circ.\]

The correspondence between a given position in a slot and \( \Theta_d \) is given by

\[
(H/\nu) \frac{\Theta_d}{180^\circ} \quad (ft)
\]

and is depicted in Fig. 15a. If a vehicle were assigned to that position, its position reference (PR) in the slot is defined as

\[
PR = (H/\nu) \frac{\Theta_d}{180^\circ}.
\]

Thus, if a vehicle were tracking a constant phase difference, then it would measure

\[
\Theta_f = K
\]

where \( K \) = a specific phase difference between \(-180^\circ \) and \(+180^\circ\) (e.g. \( 0^\circ \) as shown in Fig. 15a). The position in the \( n \)th slot corresponding to \( K \) would be

\[
x_n = x_0 + nH + \frac{H}{T} t
\]  \hspace{1cm} (35)
where

\[ \chi_0 = \left( \frac{\Theta_d - \kappa}{2\pi} \right) H \]

and the velocity

\[ V = \frac{d\chi_0}{dt} = \frac{H}{T} = \frac{c\Delta f}{2\epsilon_0} \]  \hspace{1cm} (36)

This situation is illustrated in Fig. 15a where vehicles traveling at \( V \) ft/sec and tracking the \( \Theta_d = 0 \) point are spaced \( H-L \) ft apart.

In the above it was tacitly assumed that \( V \) was constant; however, \( V \) can be varied per at least the two types of velocity changes discussed in Chapter 2.

2. Velocity Changing Maneuvers

a. Constant Slot Rate

If velocity were to change and the slot rate were constant, then per the discussion in Chapter 2,

\[ T = \frac{1}{\Delta f} = \text{constant} \]

and per (36), \( V \) can be changed only by varying \( c \) and/or \( f_0 \). The former is a function of the relative dielectric constant of the transmission-line media; hence it could probably be changed by constructing a line with a specified longitudinal variation of \( \epsilon_r \). However, the cost involved in constructing such transmission lines precluded any investigation of this approach. Thus, the dielectric constant was assumed to be nearly fixed.

The velocity could also be changed by the "longitudinal" variation of \( f_0 \), e.g., distinct transmission lines could each support
different frequencies, and thus, \( f_0 \) could be changed in discrete steps. Such a situation is depicted in Fig. 16 where the transmission lines in Section 1 support a frequency \( f_1 \) while those in Section 2 support \( f_2 \). The phase difference in the former is

\[
\Theta_{d1} = \Delta \omega t - \beta_1 x - \beta_1 (x - L_1) - \Theta_i \quad (0 \leq x < L_1)
\]

and in the latter

\[
\Theta_{d2} = \Delta \omega t - \beta_2 (x - L_1) - \beta_2 (x - L_2) - \Theta_i \quad (L_1 < x \leq L_2).
\]

For reference continuity at the transition point \( x = L_1 \),

\[
\Theta_{l1} = \Theta_{d2}
\]

or

\[
\Theta_{d2} - \Theta_{i} = \beta_1 L_1 + \beta_2 (L_2 - L_1).
\]

Hence, if the difference between initial phases is equated to the total phase shift over both sections, the phase difference (position reference) is continuous at the transition point for all time. This fact is shown in Fig. 17 for four discrete times, and it should be noted that the velocity is discontinuous at the transition point, \( x = L_1 \), i.e. a step change in velocity from

\[
V_i = \frac{\dot{H}_i}{\dot{\alpha}} \quad \text{to} \quad V_2 = \frac{\dot{H}_2}{\dot{\alpha}}
\]

occurs.

The result presented in Eqn. (37) can be applied to the situation wherein both constant speed and a continuous phase difference are required across a boundary between two sections. Such a situation could result from the use of signal amplification
Fig. 16 - Transition to a different velocity and headway with slot rate held constant
Fig. 17 - Phase difference vs distance for several times for a velocity change with slot rate held constant
to overcome signal attenuation due to the line losses. The necessary booster amplifiers could have identical phase-shift characteristics; however, this is an overly stringent requirement. Since $\beta_1 = \beta_2$, from Eqn. (37)

$$\Theta_2 - \Theta_1 = \beta_1 L_2 = \beta_2 L_2$$

(38)

i.e. only the initial phase differences must be adjusted for phase-difference continuity.

b. Constant slot length

If the velocity were to be changed with the slot length held constant, then per the discussion in Chapter II,

$$\frac{H}{c} = c/2f_0 = \text{constant}$$

$$\beta = 2\pi f_0/c = \text{constant}$$

and, per Eqn. (36), velocity can only be changed by varying $\Delta f$. If $\Delta f$ were varied on one section of roadway, all vehicles over the section would experience the same velocity change commands. Clearly, such a variation must be consistent with vehicle dynamic response capabilities and safety.

If it were desired to have each vehicle change velocity between roadway sections, as shown in Fig. 18, then $\Delta f = \Delta f_1$, would be used in Section 1, and

$$\Theta_{d1} = \Delta \omega_1 t - \beta x - \beta(x-L_1) - \Theta_1 \quad (0 \leq x < L_1)$$

and $\Delta f = \Delta f_2$ in Section 2, and

$$\Theta_{d2} = \Delta \omega_2 t - \beta(x-L_1) - \beta(x-L_2) - \Theta_2 \quad (L_1 < x \leq L_2).$$
$x = \text{longitudinal distance (ft)}$

$V_1 = H \Delta f_1$

$V_2 = H \Delta f_2$

Parallel Transmission Lines

Section 1, phase difference $\theta_{d1}$

Section 2, phase difference $\theta_{d2}$

transition point

Fig. 18 - Transition to a different velocity with slot length held constant
It is easily shown that the phase differences are equal only at the following discrete times:

\[ t_n = \frac{\gamma L_2 - (\theta_1 - \theta_2) + 2\pi n}{\Delta \omega_1 - \Delta \omega_2} \]  

(39)

However, at these times the value of \( \theta_{d1} \) or \( \theta_{d2} \) at \( x=L_1 \) could be anything between \(-\pi\) and \(+\pi\). Previously it was assumed that a vehicle would attempt to continuously track the \( \theta_d=0 \) point, and consequently it would be preferred that \( \theta_{d1} = \theta_{d2} = 0 \) for \( x = L_1 \) and \( t = t_n \).

From this

\[ \frac{\Delta \omega_1}{\Delta \omega_2} = \frac{V_i}{V_2} = \frac{SR_1}{SR_2} = \frac{q}{p} \frac{m_1}{m_2} = \frac{q n_1}{p n_2} = \frac{n_1}{n_2} \]

where \( q, n_1, \) and \( n_2 \) are positive integers, and the ratio \( n_1/n_2 \) is a reduced fraction. Clearly, the phase difference is continuous only once for every \( n_1 \) slots in Section 1 or \( n_2 \) slots in Section 2. This is shown in Fig. 19 for several values of \( t \) and \( n_1 = 2, n_2 = 1 \). Severe difficulties could be present at the boundary because of the discontinuous nature of the phase difference.

C. CSLG Reference Signals

1. Criteria

Per Eqns. (34) and (36), the speed and spacing of all controlled vehicles are specified by \( f_0 \) and \( \Delta f \). If it were assumed that the minimum permissible slot length were \( L \), and that no more than one slot were assigned to each vehicle, then the range of both of these frequencies could be estimated.

In practice, \( c \) is essentially constant in the range

\[ \frac{c_1}{2} < c < c_0. \]
Fig. 19 - Phase difference vs distance for several times for velocity change with slot length held constant
The corresponding range of \( f_\circ \) is
\[
\frac{c_\circ}{\delta H_{\text{max}}} < f_\circ = \frac{c_\circ}{2H} < \frac{c_\circ}{2L}
\]
where \( H_{\text{max}} \) = maximum permissible slot length (ft). This relationship is graphically portrayed in Fig. 20a.

It is also clear that variations in \( f_\circ \) must not cause large discontinuities in the phase difference at the ends of any given section of roadway. If \( H = 100 \) ft and \( f_\circ = 2.5 \) MHz, then for a 50,000 ft section there would be 500 slots. If \( f_\circ \) increased by 1\% (possibly due to thermal drift) these 500 slots would only occupy 49,505 ft and a sizeable error would be created. Fortunately the stability of modern tunable oscillators is less than 0.01\% and the stability of some fixed frequency oscillators is less than 10^{-9}. Thus, the expected stability requirement on \( f_\circ \) appears to be well within state-of-the-art capabilities.

The range of \( \Delta f \) can be estimated by
\[
\rho_{\text{max}} = \frac{3600}{T} = 3600 \Delta f
\]
and if
\[
\rho_{\text{max}} = 10,000 \text{ (cars/lane/hour)},
\]
then the relationship between \( \Delta f \) and \( \rho_{\text{max}} \) would be as shown in Fig. 20b. The range (0-3Hz) shown here is typical for parameter values which would probably be selected for a practical system.

In the previous discussion of velocity change maneuvers, the fixed slot-rate case appeared to be the more practical. For
Fig. 20 - Typical ranges of $f_0$ and $\Delta f$
this case phase-difference continuity across a boundary between sections, with or without a velocity change, was only possible if the phase offset between the two $\Delta f$ generators remained invariant with time.

Thus, two high-frequency signals, $f_0$ and $f_0 - \Delta f$, differing only by a few Hz and satisfying stringent stability and synchronism properties, must be generated.

2. Phase-shift single-sideband generation with sub-audio modulation

In practice, two sinusoidal signals, $f_0$ and $\Delta f$, are easily generated, and the sinusoidal signal $f_0 - \Delta f$ can be obtained by single-sideband modulation techniques. Two types of single-sideband generation are in general usage, a filtering method and a phase-shift method. The former is widely used in communication applications: however, because of the extremely close proximity of $f_0$ and $f_0 - \Delta f$, it is impractical here. Therefore, the second approach, which is discussed in detail in Appendix A, was employed.

The constituent blocks of a phase-shift single sideband generator are shown in Fig. 21. In the present work a crystal-controlled oscillator was used to obtain $f_0$, and $\Delta f$ was obtained from a motor-driven resolver potentiometer, i.e. electromechanically. However, considerable difficulty was encountered generating $f_0 - \Delta f$, and the resulting system performance degradation is discussed next.
Fig. 21 - Components of a phase-shift single-sideband generator
3. Vestigial suppression

Phase-shift single-sideband generation is seldomly used in communications because of the excessive number of critical adjustments that must be made before performance approaching that of a filtering system can be achieved. Of prime concern is the suppression of vestigials, i.e. elimination of the carrier and unused sideband. In the application of concern here, the measured phase difference can be strongly influenced by poor suppression of these vestigials. Consider the following analysis in which all harmonics are neglected as their effects are entirely negligible. From the development in Appendix A, the output signal $Y$ from a phase-shift single-sideband generator is contaminated by a part of the carrier: thus,

$$ Y = a_t \cos[(\omega_c - \Delta \omega)t] + c_t \cos \omega_c t $$

As shown in Fig. 22 the angle between the two components of $Y$ is $\theta_d$, and since $Y$ and $c_T$ are related (by magnitude scaling) to the two signals on the guiding structure, the angle measured in the constant phase-difference method would be

$$ \theta - \phi = \sin^{-1}\left(\frac{\Sigma_v \sin \theta_d}{\sqrt{\Sigma_v^2 + 1 + 2 \Sigma_v \cos \theta_d}}\right) \quad (40) $$

where $\Sigma_v = a_T/c_T$ is the signal-to-vestigial ratio. Here $\phi$ is an angular error which should be minimized. The maximum angular error occurs when $Y$ and $c_T$ are perpendicular (see Fig.

---

4In the previous development $\theta_d$ was specified as having a spatial-time distribution along the guiding structure; thus, at the generator $\theta_d(x,t)|_{x=0} = \theta_d(0,t) = \theta_d(t)$. 
Fig. 22 - Measured phase difference as a function of $\theta_d$ and $a_T/c_T=\Sigma_v$

Fig. 23 - Maximum measured phase difference error
23), i.e.

\[ \theta_d - \phi = 90^\circ \]

Then

\[ \phi_{\text{max}} = \sin^{-1}\left(\alpha_r/c_r\right) = \sin^{-1}\left(1/\Sigma_v\right) \] (41)

for

\[ \theta_d = \cos^{-1}\left(-1/\Sigma_v\right) \] (42)

A plot of \((\theta_d - \phi)\) versus \(\theta_d\) (Eqn. (40)) for several values of \(\Sigma_v\) is given in Fig. 24. Additional vestigial components could be included by suitably extending the phasor relationship of Fig. 22; however, this would only complicate the above development and would not greatly alter the result. Hence, for constant phase-difference CSLG, the effect of periodic contamination of the measured angle is adequately displayed in Fig. 24.

D. Guiding Structure

1. Desired characteristics

The guiding structure proposed for implementing the constant phase-difference method of CSLG was two parallel transmission lines separated to minimize interaction as shown in Fig. 25. The fields due to currents flowing in these lines, would couple the desired longitudinal information from the roadway to "overhead" vehicles. Some desired operating characteristics and/or requirements would be:
Fig. 24 - Measured angle vs desired angle for several values of signal-to-vestigial ratio.
Fig. 25 - Lateral cross section of highway showing physical placement of transmission lines
1. Constancy of some aspect of the fields to minimize longitudinal error due to vehicle lateral-position fluctuations.
3. Wideband design so that a communication capability could be incorporated.
4. Minimum attenuation (and radiation).
5. Minimum disruption of fields by "overhead" vehicles.
6. Minimum interaction between the two lines.
7. Easily maintainable and impervious to weather and traffic conditions.

Many of these are of a relative nature and thus several trade-offs are necessary.

2. Balanced two-wire transmission lines

For automated highway applications any transmission lines would be flush mounted in the pavement for obvious safety reasons. In subsequent experimental work, no major modification of the pavement was permitted, and since the wires were laid on the pavement, half the medium consisted of cement, aggregate, reinforcing steel and earth. The physical situation is shown in Fig. 25 where each transmission line has been assigned a coordinate system.

a. Lateral field analysis

Consider transmission line 0 in Fig. 25 and assume that
this line can only support a TEM-mode wave. Following the free space \((\mu_0, \varepsilon_0)\) analysis given by Magnusson [37], the horizontal magnitude \(|H_{y0}|\), the vertical magnitude \(|H_{z0}|\) and the phase of the magnetic field were calculated (see Appendix B) for a balanced two-wire transmission line and the results are plotted in Figs. 26 and 27. The selected wire separation was 1 in; however, other wire separations may be accommodated by appropriate scaling. Clearly the amplitudes vary considerably with changes in lateral or vertical position; however, there are distinct areas in which the phase is constant. Thus consider the relative amplitudes of the magnetic fields produced by the equal and opposite currents shown in Fig. 28. For the horizontal component of the field only two phases, differing by 180° and thus adding algebraically, are possible, \(H_{2y0} > H_{1y0}\) for \(y_0 > 0\) and all \(z_0\), and the horizontal phase can be taken as the phase of the current in the nearest wire (wire 2 in the figure). A similar argument could be used to determine the regions of constant vertical phase.

b. Longitudinal fields

Two longitudinal transmission-line properties appear to be of concern here, propagation velocity and loss. These properties,
a) Amplitude vs lateral distance

b) Phase vs lateral distance

Fig. 26 - Vertical component of magnetic field above a balance two-wire transmission line
Fig. 21 - Horizontal component of magnetic field above a balanced two-wire transmission line
Fig. 28 - Phase of magnetic field for balanced two-wire transmission line
and particularly the enhanced effect of crosstalk due to the latter, are major sources of degraded performance in the system presented.

Earlier it was assumed that the predominant mode of propagation was TEM, and consequently, the medium surrounding a transmission line would be uniform. The relative dielectric constant of the medium, \( \varepsilon_{\text{eff}} \), would be a combination of the free space dielectric constant, \( \varepsilon_0 \), and the dielectric constant of the cement-aggregate-earth medium. Since the slot length

\[
H = \frac{c_0}{2f_0 \sqrt{\varepsilon_{\text{eff}}}},
\]

any variations in \( \varepsilon_{\text{eff}} \) would cause corresponding variations in the position reference. Along a section of roadway, it would be expected that such variations would be random.

Losses within the transmission lines not only result in degraded performance but ultimately limit the length of highway which can be instrumented without using booster amplifiers. Two types of losses exist, resistive losses and dielectric losses, and a general expression for these is derived next.

The attenuation \((\alpha)\) for low-loss transmission lines over the range of \( f_0 \) defined in Fig. 20a, is per Skilling [38]

\[
\alpha = \frac{r}{2Z_0} + \frac{qZ_0}{2} \quad \text{(nepers/meter)}
\]

where

\[
r = \text{resistance/meter (}\Omega/\text{m})
\]
g = conductance/meter \((\mathcal{U}/m)\)

and \(Z_0\) = characteristic impedance \((\mathcal{Z})\).

Here \(r\) must be increased by an amount proportional to \(\sqrt{f}\)
because of "skin effect".

Losses due to conductive dielectric material can be
described in terms of a power factor

\[
PF = \frac{e''}{e'},
\]

where \(e'\) and \(e''\) are the real and imaginary components of the
dielectric constant, respectively. The latter is essentially
constant and has been tabulated for some materials [39]; however,
some frequency dependence has been observed, and one should use
values corresponding to the frequency range of interest.

The attenuation for a two-wire transmission line comprised
of \#14 solid copper wire is thus

\[
\alpha (\text{db}) = \frac{1.31 \times 10^{-2} \sqrt{f}}{Z_0} + \frac{2.77 \times 10^3 \sqrt{e_{\text{eff}} (PF)}}{c_0} \quad \text{(db/100ft)} \quad (43)
\]

if the permeability of the media is assumed to be \(\mu_0\). In
subsequent experimental work, it was observed that \(\alpha\) was nearly
a linear function of \(f\) for the frequency range investigated; a
fact indicating that the predominant loss factor was the cement-
aggregate-reinforcing steel-earth-water dielectric material (i.e.
the second part of Eqn. (43)).
3. Coupling between lines

The problem of crosstalk interference between adjacent parallel transmission lines has, in the past, been considered in regard to other specialized applications. Carson [40] considered the problem encountered in telephone lines where wire transposition and balancing were primary solutions, and more recently, Gray [41] has treated the problem with respect to its limitations on high-speed computer performance. Both inductive and capacitive coupling must be considered, and thus, the proposed transmission system with its reinforcing steel and non-uniform dielectric would be extremely difficult to model. A further complication arises from the fact that signals are sensed above (not in) each transmission line. Because of the complexity of the problem, a thorough treatment would detract from the principle purpose of this work, and hence, certain reasonable approximations were made to facilitate the analysis.

In a study of the properties of directional couplers Oliver [42] considered several symmetric, low-loss structures typically less than one wavelength long. Although the structure considered here is different, the following conclusions by Oliver appear to be applicable in this study:

1. The predominant coupled mode is contradirectional, i.e. traveling in the opposite direction of the inducing signal. (Codirectional modes are possible but require additional capacitance between specific wires)
2. The magnitude of the coupled signal is proportional to the magnitude of the inducing signal.

Ignoring vestigials, the effect of crosstalk would then be represented by the following modified forms of Eqns. (29) and (30):

\[ S_0 = A_0 \cos (\omega_0 t - \beta_0 x) + A_{1c} \cos [(\omega_0 - \Delta \omega) t - \beta_0 x + \theta_a] \]

and

\[ S_1 = A_1 \cos [(\omega_0 - \Delta \omega) t + \beta_0 (x-L_1) + \theta_o] + A_{oc} \cos [\omega_0 t + \beta_0 (x-L_1) + \theta_o] \]

where \( A_{1c} \) and \( A_{oc} \) are the magnitudes of the cross-coupled signals and \( \theta_a \), \( \theta_o \) are arbitrary phases. The algebraic signs preceding \( \beta_0 \) in the crosstalk terms were chosen to represent contradirectional waves. Since \( A_{1c} \) and \( A_{oc} \) are proportional to \( A_1 \) and \( A_0 \) respectively, their amplitude must vary longitudinally, due to attenuation, as shown in Fig. 29.

Let the signal-to-crosstalk ratio for signals 0 and 1 be

\[ \Sigma_{co} = \frac{A_0}{A_{1c}} \]

and

\[ \Sigma_{cl} = \frac{A_1}{A_{oc}} \]

respectively. The effect of crosstalk on the measured angle can be estimated by replacing \( \Sigma_v \) in Eqn. (40) by either \( \Sigma_{co} \) or \( \Sigma_{cl} \). Clearly, the effect is most prominent at the ends of the roadway where \( A_{1c} \) and \( A_{oc} \) have their greatest values and \( A_0 \) and \( A_1 \) their least ones.

4. Periodic phase error
Fig. 29 - Relative magnitudes of desired and crosstalk signals
Periodic errors, due to inadequate vestigial suppression and crosstalk, can be combined in the following manner. By proper scaling, the signal-to-vestigial ratio is

\[ \frac{Z_v}{\left(\frac{A_1C_T}{Z}\right)} \]

and obviously only applies to the signal over line 1. Hence

\[ S_0 = A_0 \cos \left[ \omega_0 t - \beta_0 x \right] + \left(\frac{A_0}{Z}C_0\right) \cos \left[ \left(\omega_0 - \Delta \omega\right) t - \beta_0 x + \theta_0 \right] \]

and

\[ S_1 = A_1 \cos \left[ (\omega_0 - \Delta \omega) t + \beta_0 (x - L_1) + \theta_0 \right] + \left(\frac{A_1}{Z}C_1\right) \cos \left[ \omega_0 t + \beta_0 (x - L_1) + \theta_1 \right] + \left(\frac{A_1}{Z}C_1\right) \cos \left[ \omega_0 t + \beta_0 (x - L_1) + \theta_1 \right] \]

where \( \theta_0 \) is an arbitrary angle. Clearly the measured phase difference is the angle between \( S_0 \) and \( S_1 \) as shown in Fig. 30; however, it should be noted that the crosstalk signals need not be considered simultaneously as they occur at opposite ends of the roadway.

The periodic nature of the phase difference is evident if the phase difference is measured at stream speed,

\[ V_S = \Delta \omega / 2 \beta_0 \]

Then

\[ x = V_S t = (\Delta \omega / 2 \beta_0) t \]

and substituting this expression into Eqns. (46) and (47) the contaminating signals rotate in opposite directions at
Contaminating signals rotate as shown with frequency $\Delta \omega$.

Fig. 30 - Measured angle as a function of $A_o$, $A_1$, $\Sigma_v$, $\Sigma_{oo}$, $\Sigma_{cl}$ and $\Delta \omega$. 
\[ \Delta \omega \text{ with respect to } A_0 \text{ and } A_1 \text{ as shown. Considering only the crosstalk contamination on } A_0, \text{ the corresponding phase error would be} \]

\[ \phi_0 = \sin^{-1}\left[ \theta_0 + \frac{\sin(\Delta \omega t)}{\sqrt{\sum e_0^2 + 2 \sum e_0 \cos \Delta \omega t}} \right] \]

Thus, a constant phase-difference point would have a nearly sinusoidal component superimposed on it whose amplitude varied with longitudinal position, being greatest at the ends of the section and least in the middle. (If the crosstalk were assumed to be codirectional, there would be no such effect, and this is contrary to the experimental results presented later.)

5. Field-probing considerations

The position reference with certain of its anomalies has been discussed in some detail above; however, a distinct dichotomy should be made between the position reference, which is available to all vehicles, and the manner in which individual vehicles detect and respond to the reference. The first link between a vehicle and the reference is the probes which sense the fields above the transmission lines.

Several properties appear to be generally applicable to probe design. These are:

1. Probes should receive a maximum signal without
appreciably disrupting the fields.

2. Probes should be of wideband design to be compatible with all desired usages.

3. Polarity sensed should optimize signal-to-noise ratios.

4. Lateral position variations should not affect the longitudinal position reference. (This is not only a function of probe design but also of the guiding structure)

D. Longitudinal position detector

The longitudinal position detector must accurately measure the phase difference between the signals sensed by the probes. Additionally, it must be capable of operating over the frequency range specified and its output should have a linear relationship to the measured phase. Any offset between the measured and actual phase difference should be readily adjustable so that the vehicle can accurately track its prescribed point. Since the amplitudes of the input signals could vary over a wide range, the phase detector must have limiting capabilities.

The response of the vehicle system (probes-detector-controller-propulsion) to the position reference determines the minimum headway and maximum flow capacity, and since the accuracy and flexibility of the detector is related to cost,
some compromise between flow capacity and vehicle cost would be necessary. In this work the absolute measurement accuracy of the detector is not considered, as it is related to the specific detector used.

Some random noise is associated with the output of the position detector; however, it would probably be negligible compared to the other sources of noise such as the random variations in the transmission-line dielectric. Another source of such random errors would be due to steering fluctuations (see Chapter 4). These along with periodic errors would cause uncertainty in the position measured which must be considered when the minimum operating headways are specified.
CHAPTER IV
EXPERIMENTAL STUDIES

A. Introduction

The feasibility of the phase-difference method for obtaining a vehicle guidance signal was evaluated under full-scale conditions, and the results of those tests are presented here. A constant slot-length approach, rather than one involving constant slot rate, was employed because it was adequate for this preliminary single-vehicle study and was more easily implemented.

This chapter is divided into two sections. In the first, various measured characteristics of the guiding structure-reference signal combination are presented, some anomalous effects are noted, and their effects on a controlled vehicle are considered. In the second section, the results from preliminary full-scale vehicle testing are presented and compared against those previously predicted.

B. Reference System Characteristics

Various characteristics of the reference system were experimentally determined including the lateral-spatial magnetic-field distribution, sample statistics of $\lambda$ as a function of $f$, and line attenuation. These characteristics and their effect on a vehicle's
measured position accuracy are defined and discussed in detail.

1. Experimental configuration

The test site was a section of unopened interstate highway; however, due to the guiding structure limitations, only 1600 feet of this section were instrumented. The guiding structure consisted of two two-wire transmission lines separated by 7.16 ft (inside wire to inside wire) and a 9 in. separation between the wires of each line (see Fig. 25). The former value was selected for reasons of crosstalk reduction and the finite vehicle width. Thus, while crosstalk effects can be reduced by increasing this separation, it cannot be much wider than the vehicle or the signal-detecting probes cannot be conveniently mounted. The 9 in. separation was a compromise since larger separations result in larger steering regions but increased crosstalk. Further, the choice of this dimension appeared to have little effect on signal attenuation. To facilitate certain measurements, the instrumented section of roadway was marked off in 100-ft increments north and south of its center point.

The transmission lines were usually terminated in their characteristic impedance ($Z_0 = 400\Omega$) although, due to the high attenuation present, the effect of using either an open-circuit or a short-circuit termination was minimal. When line characteristics were measured (e.g. attenuation), the excitation consisted of a single frequency signal applied to one line. For all vehicle tests, the lines were excited at opposite ends—one by a sinusoidal signal of frequency $f_0$ and the other by a sinusoidal signal of frequency $f_0 - \Delta f$.
(see Fig. 15b). In both cases matching units were required to both ensure balanced currents in each line and to match the line impedances to that of the coaxial-cable, reference-signal generator combination.

The magnetic fields produced by line currents were measured using the equipment displayed in Fig. 31. Here, a probe was positioned to detect the desired field component (horizontal or vertical), as a cart, on which the probe was mounted, was rolled laterally across the line. The amplitude and phase of the detected field were measured by a vector voltmeter, whose phase-reference was supplied via a coaxial cable from the generator as shown. The lateral position of the probe was determined by the simple potentiometer arrangement shown.

This equipment was also used to measure the attenuation properties of the lines. Signal-amplitude measurements were made at 100 foot intervals, and the attenuation was calculated from these measurements. Variations in the precise probe location above a wire could introduce inaccuracies into amplitude measurements made in this manner. Thus, greater credence was given to additional measurements made with a current probe (Tektronix P6042) and oscilloscope (Tektronix 422).

Much of the equipment shown on the cart in Fig. 31 was subsequently mounted in a test vehicle and used in full-scale vehicle testing; however, in this work additional amplifiers were included between the probes and vector voltmeter (see Fig. 37). A detailed discussion of all equipment used for these latter studies is included.
Fig. 31 - Test set-up for measurement of field lateral distribution
in Appendix C.

2. Lateral distribution of magnetic fields

The calculated amplitude and phase of the magnetic fields from a balanced two-wire transmission line in free space were presented in Figs. 26 and 27; however in practice, the guiding structure consisted of balanced two-wire lines in a complex dielectric media comprised of air, concrete, aggregate, reinforcing steel and earth (see Fig. 25). Hence, it was necessary to measure the field configurations to determine the correlation with the calculated ones.

Measured values of the horizontal and vertical components of these fields are shown in Figs. 32 and 33 for a probe height of 3 inches \(z_0=3\) inches, and after appropriate scaling due to current amplitude and wire-spacing differences, it appears that the measured and calculated curves have nearly the same shape. Thus, the assumption used for the calculation (that the predominant propagation mode is TEM) seems valid.

Since the amplitudes of the fields exhibit substantial variations with lateral position, they would be unsuited for use as a position reference; however, the phase is virtually constant within ranges of lateral position and these ranges are defined in Figs. 32 and 33 as "possible steering regions." The size of these regions is also a function of signal amplitude since below a certain signal level \(A_o=A_{1c}\) in Fig. 32), crosstalk would predominate as described in Chapter 3. Quite evidently the lateral range between possible steering regions must be avoided as the phase can abruptly change by \(180^\circ\). Such a change would produce a position error equal to half
Fig. 32 - Horizontal magnetic fields — lateral distribution
Fig. 33 - Vertical magnetic fields -- lateral distribution
a slot length and would result in an excessive demand on a vehicle's propulsion system. The steering regions shown in Fig. 32 would be approximately 7 inches in width and would begin 1-1/2 inches away from the center of the transmission line; however, at the ends of the section, where crosstalk is most prevalent, the regions would be substantially smaller since crosstalk effects would tend to dominate the desired signal.

Even within the steering regions there is some variation of the phase, and hence, any lateral motion due to steering variations could result in longitudinal position errors. In this case, if only one region were considered, say the right-hand region in Fig. 32, the unwanted phase variation would be approximately \((3/7)^\circ\) per inch of lateral error.

3. Wavelength measurements

If the dominant mode of energy propagation on each transmission line were TEM, the dielectric media would have an effective relative dielectric constant, \((\varepsilon_{\text{eff}})\), where

\[
\varepsilon_{\text{eff}} = \left(\frac{c_0}{2f_0 H}\right)^2 = \left(\frac{c_0}{f_0 \lambda}\right)^2.
\]

Thus, any variations in \(\varepsilon_{\text{eff}}\) would cause corresponding variations in both the slot length and the position reference.

A number of measurements of \(\lambda\) were made by moving the cart, with its equipment, longitudinally along the lines and measuring the distance required before the phase changed by \(360^\circ\). (A fewer number were made using an instrumented vehicle). In all cases, both lines were excited with \(\Delta f=0\). The results, the mean and standard deviation of wavelength, are shown in Table II. Of special interest
TABLE II

RANDOM PROPERTIES OF SLOT LENGTH AND AVERAGE $\varepsilon_{eff}$ FOR SEVERAL FREQUENCIES

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>1.1323</th>
<th>3.000</th>
<th>3.734</th>
<th>4.740</th>
<th>7.351</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMBER OF SAMPLES</td>
<td>1</td>
<td>5</td>
<td>17</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>MEAN SLOT LENGTH, (ft)</td>
<td>206.33</td>
<td>81.29</td>
<td>64.65</td>
<td>51.33</td>
<td>34.45</td>
</tr>
<tr>
<td>SLOT LENGTH STANDARD Deviation (ft)</td>
<td>1.67</td>
<td>1.92</td>
<td>.71</td>
<td>.31</td>
<td></td>
</tr>
<tr>
<td>MEAN $\varepsilon_{eff}$</td>
<td>3.35</td>
<td>4.20</td>
<td>4.28</td>
<td>4.20</td>
<td>3.88</td>
</tr>
</tbody>
</table>
are the data collected at \( f = 3.734 \) MHz as this frequency was used in subsequent full-scale tests. These data, which were obtained using an instrumented vehicle, were processed to obtain a mean slot length of 64.65 ft and a standard deviation of 1.92 ft.

The measurement results presented in Table II could be contaminated by "lateral phase" deviations or equipment inaccuracies, and thus, the standard deviations shown probably included these effects. Curiously, the standard deviation at 3.734 MHz was larger than at 3 MHz: a result possibly caused by a lateral phase deviation compounded with inaccuracies due to crosstalk. In any event, it is clear that the media surrounding the transmission lines has a dielectric constant which exhibits small random variations, and hence, randomly affects slot size.

4. Attenuation

The attenuation data obtained on July 31, 1972 are shown in Fig. 34. Note that attenuation was nearly a linear function of frequency, thus indicating that the predominant attenuation factor in the frequency range of interest was dielectric loss. Consequently, the slope of this function would be the coefficient of \( f \) in Eqn. (43), and with \( Z_0 = 400 \Omega \)

\[
\alpha = 3.28 \times 10^{-5} \sqrt{f} + 5.62 \times 10^{-7} f \quad \text{(db/100')}.
\]  

(43)

Assuming that roadway materials parameters are not a function of \( f \), one can now use the linear part of Eqn. (43) to predict attenuation at lower frequencies. This part would nearly equal the total attenuation down to the region in which the first part of Eqn. (43) is comparable to the second, i.e. where skin effect loss is comparable.
Fig. 34 - Attenuation vs frequency for two-wire transmission line
to dielectric loss. The center of this region occurs at approximately 3,410 Hz where the losses are equal.

The above expression is only an approximation since the moisture content, which varies from day to day, seems to have a pronounced effect on the attenuation. For example, at a frequency of 3.734 MHz an attenuation of approximately 7 (db/100') was measured during a light but steady rain, and on two seemingly dry days, values of 2.33 and 1.76 (db/100') were recorded. The first of these two was the only attenuation measurement obtained with the current probe and oscilloscope, and as this measurement technique was more accurate, this value was used in subsequent calculations.

5. Crosstalk

A good measure of the field strength above the wires is the current magnitude in the wires. Thus, with only one transmission line excited, measurements of desired and crosstalk currents were made. If the lines had approximately equal attenuations and driving currents, the currents on one line would be as shown in Fig. 35. Here it appears that these currents would be equal (i.e. $\Sigma_{co}=1$) at the 600 N mark, and the resulting effects are considered next.

Crosstalk signals are only prevalent at the ends of a roadway section and would not occur at the same spatial point on the two lines; i.e. when

$$\Sigma_{co}=1$$

then

$$\Sigma_{c1}=\infty$$

and
Fig. 35 - Magnitudes of desired and crosstalk currents in one transmission line ($f_0 = 3.734$ MHz)
$\Sigma_v \gg 1$

from the discussion in the next section. Utilizing the above quantities, the effect of crosstalk on the measured angle (phase difference) is described by the angle between the two phasors $S_o$ and $A_1$ in Fig. 30, i.e. $S_1 = A_1$, and the angular error can be represented by the rotation of the $A_o/\Sigma_{co}$ component about $A_o$.

One effect of crosstalk is shown in Fig. 36a where the measured phase difference is plotted versus time. This measurement was made with both lines excited ($\Delta f > 0$) and the instrumented vehicle stopped over the lines near the 600 N point. The position-reference signal would ideally be moving past the vehicle as displayed in Fig. 4b. At this point $\Sigma_{co} = 1$, and it should be recalled that the effects of crosstalk can be analyzed via a technique similar to that used for the vestigial effects. Thus by simply setting $\Sigma_v = \Sigma_{co}$ in both Eqn. (40) and Fig. 24 an accurate prediction of the curves given in Fig. 36a is obtained.

A similar measurement of phase difference versus time was made on a different day and the asymmetric result is displayed in Fig. 36b. Since the probes and preamplifiers (see Fig. 37) were tuned differently on different days, the phase shifts ($\phi_A$ and $\phi_B$) in the two channels varied; thus the actual angle measured included the difference between these phase shifts. The actual angle measured was

$$\theta_d = \phi + (\phi_A - \phi_B)$$

and for the data presented in Fig. 36a,

$$\phi_A - \phi_B = 0 ;$$
Fig. 36 - Phase difference vs time for \( \Delta x \)l

- **a.) Symmetric case**
- **b.) Asymmetric case**
Fig. 37 - Phase offset in the measuring system
however, for that in Fig. 36b,
\[ \phi_A - \phi_B = +50^\circ. \]
Thus, it should be noted that if a phase offset of 50\(^\circ\) were added to \( \Theta_d - \phi \) with \( \Sigma_v = 1.2 \) (see Fig. 24), one would obtain a curve quite similar to those shown in Fig. 36b. (Unfortunately, the origin of this phase offset was not determined until after all vehicle testing was completed. In any future testing, both probes should be held over one wire and the channels tuned for zero-phase offset so that \( \Theta_d \) is a symmetric function of time).

Another example of crosstalk and phase-measurement offset is contained in the longitudinal phase-difference distribution shown in Fig. 38 which was obtained by driving the instrumented vehicle at a constant speed over the excited guiding structure. Vestigial effects were eliminated by setting \( \Delta f = 0 \). From Fig. 35 \( \Sigma_{co} = 1 \) at the 600 N point and the phase difference should only swing from -90\(^\circ\) to +90\(^\circ\) per Fig. 24; however, this type of performance with a phase offset of -90\(^\circ\) is observed near the 700 N point in Fig. 38. This discrepancy in distance is attributed to the different measurement techniques used to obtain the two figures.

6. Vestigial Effects

The source of vestigials in single-sideband generation is discussed in Appendix A, and their effect on actual phase-difference measurements was presented for a simplified case in Eqns. (40) to (42). Consider now the vestigial effects due to the phase-shift, single-sideband generator used in this study. The phase difference between
Fig. 38 - Longitudinal phase difference distribution
the $f_0$ and $f_0 - \Delta f$ outputs of this generator, and the amplitude of
the latter were measured using a vector voltmeter with the results
shown in Fig. 39. Here,

$$a_T = 402.5 \text{ mV rms},$$
$$c_T = 32.5 \text{ mV rms},$$
$$\Sigma_v = 12.4$$

and from Eqn. (41),

$$\phi_{\text{max}} = \sin^{-1} \frac{32.5}{402.5} = 4.63^\circ$$

This value compares favorably with the maximum angular difference of
some $5^\circ$ between the measured phase and the ideal straight-line shown
in Fig. 39b.

This vestigial effect would cause reference-signal oscillations whose peak-to-peak amplitude would be

$$\left(\frac{2\phi_{\text{max}}}{180^\circ} \frac{H}{2}\right) = 1.67 \text{ ft.}$$

This amplitude would remain fixed over the entire length of roadway,
and all vehicles over that roadway would experience synchronized
oscillations.

A resolver potentiometer driven by a motor was used in the
single-sideband modulator to produce the two required quadrature
low-frequency ($\Delta f$) signals. Thus, additional phase-difference non-
linearity could result from both potentiometer nonlinearity and
variations in the speed of the motor. These considerations were
neglected since it was concluded from measurements that their effect
was much less than that due to inadequate carrier suppression.
Fig. 39 - Amplitude and phase of the single-sideband generator output
7. Combined Effects

Previously, anomalies superimposed on the position reference signal have been categorized as either periodic or aperiodic. One measurement of the former was made by driving the instrumented vehicle along the excited guiding structure at a fixed speed of

\[ V_s = \frac{\Delta f}{2f_0} \]

and maintaining \( \theta_d \) = constant. The results are shown in Figs. 40a and 40b for vertical sensitivities of 2 ft/mm and 1 ft/mm respectively. One undesired feature shown in these figures is a periodic noise spike attributed to a worn resolver potentiometer in the single-sideband generator. After compensating for this feature it can be seen that in the center of the section an oscillation with a peak-to-peak amplitude of approximately 1.67 ft is present, and indeed it appears that only vestigial contamination need be considered here. Note that the amplitude of the oscillation increased near each end, as crosstalk interference became substantial, and both effects were prevalent.\(^7\)

The aperiodic effects associated with the reference signal would result in uncertainty in a vehicle's location with respect to that reference. This uncertainty could either be in the form of a dc offset or random noise contaminating the measured signal.

There appear to be at least three sources of dc offset:

1) The imperfect phase characteristics of the magnetic-field distri-

\(^7\) The very low frequency oscillation, which is also shown here, was probably due to vehicle velocity being slightly different from \( V_s \).
Fig. 40 - Periodic deviations of the phase difference (position reference)
bution in the plane perpendicular to that of the transmission line (see Fig. 32); 2) Small random variations in the dielectric properties of the roadway materials and the corresponding variations in slot length; and 3) The signal detecting and processing equipment in the vehicle. The first of these, per the results already presented, would result in a maximum offset of some 0.6 ft under the conditions examined.

An upper bound of $2\sigma$ can be assigned to the second effect. It seems probable that $\sigma < 1/2$ ft, despite the larger values reported in Table II. The uncertainties in the measurement process used to obtain these values were approximately on the order of the values reported. Also note that since $H = \frac{\lambda}{2}$ corresponds to $360^\circ$, then as $\lambda$ varies, one would have the same number of degrees in a different slot length corresponding to a different gain value. Thus, this effect would give rise to a time-varying gain, which would have only a limited effect on system performance.

The effect due to the third source would depend on the equipment used; however, with a suitable choice of same, it should be no more than 0.1 - 0.2 ft.

The effects of a normally distributed random disturbance were considered in Chap. 2, where it was noted that system response would be a function of the bandwidth of the disturbance and the controller parameters—$\xi, \tau$ and $k$. The net effect on vehicle position uncertainty would be described by the quantity $\sigma_{\Delta x_v}$ per the development in

---

*It is obvious that very precise measurements must be made to accurately determine this quantity.*
Chapter 2. In practice, this value would probably be less than 0.2 ft.

The combined effect would be an uncertainty of some 2-2.5 ft in vehicle position—a value which must be accounted for in specifying minimum permissible operating headways. It is also clear that various other factors, including a vehicle's maximum state deviations during transient maneuvering, wind gusts, and road grades, must be included in this specification.

C. Full-Scale Feasibility Studies

Preliminary full-scale tests of the synchronous reference system and an instrumented vehicle—a 1965 Plymouth sedan—were conducted to evaluate the feasibility of the former. The basic vehicle controller, which is depicted in Fig. 8, was comprised of the vehicle, its instrumentation and appropriate analog compensation per the discussion in Appendix C. The reference input to the controller was the detected phase-difference signal, which, of course, provided an indication of the vehicle's state with respect to the moving reference. This input was obtained via the use of signal-detecting probes, preamplifiers, and a vector voltmeter connected as shown in Fig. 37.

The vehicle was automatically steered using a controller similar to that designed by Olson [42]. The parameters of this controller were adjusted so that the vehicle lateral deviation remained within the bounds defined in Fig. 32.

The maximum velocity at which tests could be conducted was limited by two factors. First, a usable signal could be obtained only over 1600 ft of line because of line attenuation and the presence of crosstalk. Second, to reduce the vehicle's response to
oscillatory disturbances mixed in with the position reference signal, the response characteristics of the controller-propulsion system was changed from the more optimum ($\zeta = .7$, $\tau=1$, $k=.8$) case considered in Chapter 2. This resulted in longer controller response times, and thus a longer distance was required for the vehicle to reach steady state after a command input was applied. Such factors, plus the limited length of instrumented roadway available for testing, resulted in a maximum testing speed of 46 ft/sec.

In all tests, the position error ($\Delta x$) was proportional to the measured value of $\theta_d$. During each test, the following data were recorded:

a) Vehicle velocity versus time;

b) Vehicle position error versus time; and

c) The slot time.

1. Steady-state, constant-velocity operation

In these tests, the reference signal was moved along the highway at a constant speed—14, 30, or 40 ft/sec. The vehicle speed was adjusted so that it was slightly less than the chosen signal speed when the vehicle entered the section of instrumented roadway. Then the vehicle sensors would measure a continuously increasing position error, such as it displayed in Fig. 41. When $\Delta x = 0$, the vehicle was switched to the automatic control mode and required to follow the reference signal. The vehicle responses at reference signal speeds of 14, 30 and 40 (ft/sec) are shown in Figs. 41-43, respectively. In each of these figures, after the command to lock
Fig. 41 - Controlled vehicle position error and velocity response full-scale conditions—lock on and tracking at 14 ft/sec
Fig. 42 - Controlled vehicle position error and velocity response
full-scale conditions—lock on and tracking at 30 ft/sec
Fig. 43 - Controlled vehicle position error and velocity response
full-scale conditions--lock on and tracking at 41 ft/sec
on and track was given \( (t_0) \), \( \Delta x \) would initially increase and the vehicle would accelerate, overshoot \( V_s \) and decrease \( \Delta x \) to zero. In this final state the vehicle was traveling at \( V_s \); i.e., the speed of the reference signal.

Note from Figs. 41-43 that after steady state is reached, \( \Delta x \) varies about zero in a periodic manner—anomalous behavior which is due to both vestigial and crosstalk effects. Some random appearing variations of \( \Delta x \) are also available but these are of a very small magnitude.

2. Step Changes in Velocity

In these tests, the response of the controlled vehicle to a near-step change in velocity was examined. The experimental procedure was as follows: As the manually controlled vehicle entered the section of instrumented highway, its speed was slightly less than the initial signal speed of either 15 or 24 ft/sec. The position error was thus increasing per Fig. 44, and when it was zero, at time \( t_0 \), vehicle control was switched to the automatic mode, and the vehicle was required to follow the reference signal. Subsequently, at time \( t_1 \) (after steady-state had been reached) the speed of the signal was increased, by an appropriate change in \( \Delta f \) (see Eqn. (36)), to either 24 or 29 ft/sec, respectively, and the resulting response of the controlled vehicle was obtained.

The data from the two tests conducted are shown in Figs. 44 and 45. In both cases, the initial response \( (t_0 \leq t \leq t_1) \) of the controlled vehicle was similar to that discussed in the last section. Then at \( t=t_1 \), when the signal speed was increased, it is noted that
Fig. 44 - Controlled vehicle position error and velocity response
full-scale conditions—step change from 15 to 24 ft/sec
Fig. 45 - Controlled vehicle position error and velocity response
full-scale conditions—step change from 24 to 29 ft/sec
the vehicle responded in both cases by accelerating so that after some 8 sec, $V > V_s$; subsequently, $v$ approached $V_s$ and $\Delta x$ tended to zero.

Several points should be made here. First, this underdamped response was precisely that expected from the choice of non-optimum parameters for the vehicle controller. The maximum error was considerably greater than that predicted per Eqn. 13 for the more optimum controller parameter choice in Chapter 2, but it was expected for this choice of parameters. Finally, the position-reference signal was again contaminated with a periodic component, which was manifested in the oscillatory behavior of $\Delta x$.

3. Vehicle Starting and Stopping

In these tests, the speed of the reference signal was gradually increased from 0 to a maximum value of either 19 or 28 ft/sec and then decreased to zero, and the controlled vehicle was required to follow the resulting speed-versus-time profile. Thus, the vehicle was initially at standstill ($\Delta f = 0$) and positioned over the lines at a $\theta_d = 0^\circ$ point.

The data from the two cases considered are shown in Figs. 46 and 47. Note that as $\Delta f$ was gradually increased, the reference velocity increased (per Eqn. (36)) and the vehicle dropped behind the reference signal ($\Delta x > 0$). When $\Delta f$ reached a constant value (corresponding to the selected $V_s$), a slight amount of velocity overshoot ($v > V_s$) was present; then vehicle velocity and $V_s$ were the same. When $\Delta f$ was decreased, one can note that the vehicle speed decreased accordingly with a slight lag being present.
Fig. 46 - Controlled vehicle position error and velocity response
full-scale conditions--start and stop, 0 to 19 to 0 ft/sec
Fig. 47 - Controlled vehicle position error and velocity response
full-scale conditions—start and stop, 0 to 28 to 0 ft/sec
Somewhat similar tests were conducted at higher speeds; however, in this case it was necessary to use the entire length of roadway for either acceleration or deceleration. The vehicle's response to a command to accelerate from 0 to 46 ft/sec. is shown in Fig. 48, from which it can be noted that this response is similar to that discussed above. The vehicle's response to a command to decelerate from 46 ft/sec. to 0 ft/sec. is shown in Fig. 49—a response which is again similar to that reported above. It should be noted that the reference signal contained a periodic component in both cases.

D. Summary

The various characteristics of the guiding structure and reference signal generator have been measured and correlated with theory. Related position-reference disturbances were measured and a periodic oscillation was found to have a pronounced effect on vehicle performance. In subsequent tests involving both the reference system and a controlled vehicle, the effect of the reference-signal oscillation was reduced by increasing the response time of the vehicle. Random position-reference disturbances were present but their effect was relatively minor in the single-vehicle tests performed. It is also noted that on several occasions during these tests the vehicle's lateral position was sensed either outside the permissible steering regions or outside the assigned slot and excessive demands were made on the vehicle's control—clearly a condition which must be avoided in practice.
Fig. 48 - Controlled vehicle position error and velocity response
full-scale conditions—acceleration, 0 to 46 ft/sec
Fig. 49 - Controlled vehicle position error and velocity response
full-scale conditions—deceleration, 46 to 0 ft/sec
In essence, it can be concluded from these tests that the approach taken to vehicle control is feasible. The controlled vehicle could very accurately track a constant velocity position reference and could respond to small (15-24 ft/sec) velocity-change commands. However, it is equally clear that a great deal of further effort must be expended on this system in order to overcome the problems involved in its use.
CHAPTER V

SUMMARY AND RECOMMENDATIONS

A. Summary

Highway automation appears to be one method of achieving more efficient utilization of existing roadways. Possible advantages of such automation would be higher traffic flow rates, increased safety, reduced demands on the driver and increased comfort. The quality of vehicle longitudinal control has a strong influence on these factors — especially achievable flow rates — and it seems clear that the most precise control would be achieved when each vehicle were given a continuous indication of its longitudinal state as opposed to an indication at only certain discrete times.

Both theoretical and practical aspects of producing a continuous position reference within a synchronous longitudinal guidance system have been discussed. Throughout it has been assumed that each vehicle would track a specified reference, although other modes of operation may be possible. A set of properties was listed for a generalized reference; but only a linearly distributed signal was considered in detail. Using such a reference, steady-state (constant velocity) operation was discussed for variable flow capacity conditions, and two types of velocity-change operations, one involving a constant slot rate and the second a constant slot length, were analyzed to determine their basic properties.
Other CSLG design limitations were related to the dynamic response of the longitudinal controller-propulsion system, and the maximum permitted position deviation within a slot. The longitudinal controller used throughout this work was designed and analyzed by Bender [33]. The response of the controller-propulsion system to unwanted periodic and aperiodic disturbances in the position reference were calculated, and the resulting position and velocity uncertainties associated with a controlled vehicle's state were developed.

A constant phase-difference method of providing a "linear" position reference was developed. This method involved the use of two separate and parallel transmission lines on a roadway section with these lines excited from opposite ends of the section by a phase-shift, single-sideband generator. A vehicle would detect the signal over each line, measure the phase difference between these signals and move so as to keep this phase difference constant. The theoretical requirements of this method for steady-state operation and velocity-change maneuvers were developed. Subsequently, several basic properties of the generator and transmission lines were analyzed, and it was shown that certain aperiodic and periodic anomalies in the phase difference originate in these components. Their effects on controlled-vehicle performance were predicted.

A section of roadway was instrumented with the above lines and a fixed frequency sideband generator. Prior to vehicle testing, thorough measurements of the generator and transmission lines properties were made. For the latter these included experimental
determination of the lateral magnetic field distribution, wavelength, attenuation and crosstalk, while in the former, only the amount of unsuppressed carrier was determined. These measurements substantiated the predicted anomalies in the phase difference, and the related effects were counteracted in the instrumented vehicle by changing the parameters in Bender's longitudinal controller so that a more comfortable ride was achieved.

This choice of parameters increased the response time of the longitudinal controller-propulsion system, and the presence of crosstalk restricted the length of roadway which could be implemented. Thus, the maximum vehicle velocity tested was 46 ft/sec. The vehicle could track the constant phase-difference point at steady-state speeds up to 46 ft/sec and could respond to both gradual and step changes in velocity. Therefore, it was concluded that the method of synchronous guidance presented here was feasible.

B. Recommendations

Recommendations given here are restricted to possible methods of improving the constant phase-difference technique so that it might ultimately become a practical technique for achieving CSLG of automated vehicles. These methods respectively address the problems of crosstalk, attenuation, allowable steering regions and reference-signal generation.

The most prevalent problem with this approach was crosstalk. Its degrading effect severely limited the length of instrumented
roadway and resulted in either an oscillatory vehicle response or very "loose" vehicle control, with the latter depending on controller parameters selected. One possible method of reducing crosstalk would be a two-frequency approach in which the roadway system produced sinusoidal signals \((1/2)f_0\) and \((f_0-\Delta f)\) and the vehicle system would double the \((1/2)f_0\) signal before making the phase measurement. Hence, crosstalk could be eliminated via frequency selective components. Two considerations would be the phase shifts associated with the frequency selective components (phase shifts should be fixed once the circuits were properly tuned) and the inflexibility inherent in a discrete frequency system.

The maximum usable transmission-line length is determined by crosstalk and attenuation. As attenuation enhances the effect of crosstalk, it clearly must be minimized. Ideally, something similar to the "W-line transmission waveguide" proposed by Koffman, et. al. [43], could be imbedded into the highway and a similar configuration with two conductors for balanced operation is shown in Fig. 50. Such a scheme would doubtless result in greatly reduced attenuation and increased bandwidth, but aside from being expensive, it may be difficult to find a suitable dielectric cover material and to provide proper water drainage. Ultimately a transmission waveguide may be essential, but for evaluation purposes, attenuation could be reduced by lowering the operating frequency per Fig. 34.

In any practical system no abrupt half slot-length changes should occur in the position reference due to steering errors. The
Fig. 50 - A high-quality transmission line
structure in Fig. 50 appears to be one possible solution to this problem. With balanced currents in the conductors only one phase angle would be possible in a lateral-vertical plane over the structure, i.e., no phase discontinuities would be present. Interestingly, the two-frequency approach could be implemented on one transmission line if suitable multiplexers were used on either end, and thus only one expensive transmission line would be required.

Carrier suppression in the phase-shift single-sideband generator could readily be improved by using improved balanced modulators and/or by lowering the operating frequency. In a practical system improvements would be necessary since the resulting phase-difference oscillation in the present system would be unacceptable. Additionally, a more reliable method of generating the two quadrature low-frequency (Δf) sine waves must be found. Wear problems associated with the resolver potentiometer would preclude its use in a practical system. The required signals could possibly be obtained from synchronized digital-to-analog converters whose outputs would be quantized approximations of the sine and cosine.
APPENDIX A

PRINCIPLES OF SINGLE SIDEBAND GENERATION

The frequency spectrum of an amplitude-modulated signal is shown in Fig. 51, where the signal is shown as being comprised of a carrier with upper and lower sidebands. From a communications standpoint, all of the desired information is contained in a single sideband, and the carrier and other sideband are detrimental as these represent wasted power, inefficient spectrum usage, and an increase in noise.

A filtering single sideband modulator would eliminate the carrier in a balanced modulator and the undesired sideband by filtering. The resulting frequency spectrum is shown in Fig. 52 where it is noted that the filter must have sufficiently sharp characteristics to eliminate the upper sideband while leaving the lower sideband virtually unaffected, i.e., filter selectivity must be sufficient to discriminate frequencies less than $2f_L$ (Hz) apart, where $f_L$ is the lowest modulating frequency.

Since $f_L \approx 0$ for the vehicle-guidance application of interest here, the filtering method would not be applicable, and it would be necessary to use another approach — that of phase-shift single-sideband modulation — such as is shown in Fig. 53. The balanced modulator outputs ($X_1$ and $X_2$) as depicted here are
Fig. 51 - Frequency spectrum of an amplitude modulated signal

Fig. 52 - Filtering single-sideband modulation
Fig. 53 - Phase-shift single sideband modulator
\[ X_1 = \frac{a_1 b_1}{2} \left\{ \cos[(\omega_0 - \Delta \omega)t] - \cos[(\omega_1 + \Delta \omega)t] \right\} + c_1 \sin \omega_0 t \]

and

\[ X_2 = \frac{a_2 b_2}{2} \left\{ \cos[(\omega_0 - \Delta \omega)t + \Psi_0] - \cos[(\omega_0 + \Delta \omega)t + \Psi_0] \right\} + c_2 \sin[\omega_0 t + \Psi_0] \]

where \( \Psi_0 \) and \( \Psi_\Delta \) are phase shifts. It should be noted that additional harmonics due to nonlinearities are neglected; however, incomplete carrier suppression is simulated by including the \( c_1, c_2 \) terms.

The sum of these outputs is

\[ Y = \cos[(\omega_0 - \Delta \omega)t] \left\{ \frac{a_1 b_1}{2} + \frac{a_2 b_2}{2} \cos(\Psi_0 + \Psi_\Delta) \right\} - \frac{a_2 b_2}{2} \sin[(\omega_0 - \Delta \omega)t] \sin(\Psi_0 + \Psi_\Delta) \]

(lower sideband)

\[ - \cos[(\omega_0 + \Delta \omega)t] \left\{ \frac{a_1 b_1}{2} + \frac{a_2 b_2}{2} \cos(\Psi_0 + \Psi_\Delta) \right\} + \frac{a_2 b_2}{2} \sin[(\omega_0 + \Delta \omega)t] \sin(\Psi_0 + \Psi_\Delta) \]

(upper sideband)

\[ + \sqrt{c_1^2 + c_2^2 - 2c_1c_2 \cos \Psi_0} \sin[\omega_0 t + \sin^{-1}\left\{ \frac{c_1 \sin \Psi_0}{\sqrt{c_1^2 + c_2^2 - 2c_1c_2 \cos \Psi_0}} \right\}] \]

(carrier).

Assuming \( c_1 \) and \( c_2 \) to be negligible,

\[ a_1 b_1 = a_2 b_2 \quad \text{and} \quad \Psi_0 = 90^\circ = \Psi_\Delta \]
then

\[ Y = a_t b_1 \cos[(\omega_0 - \Delta \omega)t] \]

which is the desired output. If

\[ Y = X_1 - X_2 \]

then \( Y \) would be the upper sideband.

Five adjustments are necessary to properly align such a modulator -- carrier adjustments on each balanced modulator (to minimize \( c_1 \) and \( c_2 \)), phase adjustments on each generator so that

\[ \gamma_0 = 90^\circ = \gamma_\Delta, \]

and an adjustment controlling the relative output levels of the balanced modulators \( (a_1 b_1 = a_2 b_2) \). An observation of the amplitude of \( Y \) can give an indication of the frequency components present, i.e., an oscillation of frequency \( \Delta f \) indicates the presence of a carrier and an oscillation of \( 2 \Delta f \) usually indicates insufficient sideband suppression. Generally

\[ Y = a_T \cos[(\omega_0 - \Delta \omega)t + \gamma_\Delta] + b_T \cos[(\omega_0 + \Delta \omega)t + \gamma_b] + c_T \cos[\omega_0 t + \gamma_c] \]

(A-1)

where

\[ a_T \gg c_T > b_T \]

and only the upper sideband and carrier need be considered.

If it is desired to study the effects of inadequate carrier suppression, only the relative amplitudes \( a_T \) and \( c_T \) are important and the angles \( \gamma_a \) and \( \gamma_b \) can be neglected: thus

\[ Y = a_T \cos[(\omega_0 - \Delta \omega)t] + c_T \cos(\omega_0 t). \]  

(A-2)
Magnetic Field Pattern for a Parallel-Planar Wire System

A listing of a Fortran program designed to determine the magnetic fields in a lateral-vertical plane above a system comprised of any number of parallel-planar wires in a homogeneous medium, with each wire carrying currents of the same frequency but of independently specified amplitudes and phases, is contained in this appendix. Following Magnusson [36] the magnitudes and phases of the horizontal and vertical components of the resulting magnetic field are calculated at a large number of observation points in the lateral-vertical plane (see Fig. 54). The position of each observation point is specified by horizontal and vertical coordinates, X and Y respectively, with X=0, Y=0 being the position of the first wire. (X, Y and other quantities used in this appendix should not be confused with identical notations used elsewhere).

The symbols used in the program are:

- \( H(K) \) = spacing from first wire to K wire, \( H(1) = 0 \)
- \( \text{TH}(K) \) = phase of current in the K wire
- \( A(K) \) = amplitude of current in K wire
- \( C(K) = A(K)e^{j \text{TH}(K)} \), complex current (calculated from \( \text{TH}(K) \) & \( A(K) \))
- \( R(K) \) = distance from K wire to a specified observation point
- \( HX \) = horizontal (X) component of magnetic field
- \( HY \) = vertical (Y) component of magnetic field
Fig. 5.4 - Cross section of a parallel planar wire system
MAGHX = magnitude of horizontal magnetic field component at a specified observation point; i.e., MAGHX(X(I),Y(J))

MAGHY = magnitude of vertical magnetic field component at a specified observation point; i.e., MAGHY(X(I),Y(J))

ANGHX = angle of horizontal magnetic field component at a specified observation point; i.e., ANGHX(X(I),Y(J))

ANGHY = angle of vertical magnetic field component at a specified observation point; i.e., ANGHy(X(I),Y(J))

X1,Y1 = initial observation point

X2,Y2 = final observation point

DEX,DEY = amount by which X and Y are incremented prior to each calculation

NPS = number of wires used.

The program is shown in its entirety on the next page.

For calculation of the fields above a balanced two-wire transmission line, such as was described in Chapter 2, the following assignments were made:

NPS = 2
A(1) = 1.0 = A(2)
TH(1) = 0°
TH(2) = 180°
H(2) = 1.0 in
X1 = -3.0 in
Y1 = .25 in
X2 = 4.0 in
Y2 = 2.5 in
DIMENSION H(50), TH(50), R(50), C(50), A(50)
COMPLEX C, HX, HY, HFX, HFY
REAL MAGHX, MAGHY
INTEGER T, U
PI = 3.14159
TPI = 2. * PI
READ(5,15) NPS
15 FORMAT(2X, I3)
READ(5, 71) X1, X2, Y1, Y2, DEY
7 FORMAT(17F10.5)
DO AGO M = 1, 4
....
DO 50 L = 1, NPS
READ(5, 71) TH(L), A(L), H(L)
50 CONTINUE
T = 1 + (Y2 - Y1) / DEY
DO 200 J = 1, T
Y = Y1 + (J - 1) * DEY
WRITE(6, 8)
8 FORMAT(/ 8X, 14X, 1HY, 14X, 5HMAGHX, 10X, 5HANGHX, 10X, 5HMAGHY, 10X, 15HANGHY)
U = 1 + (X2 - X1) / DEY
DO 100 I = 1, U
X = X1 + (I - 1) * DEX
Y = CT * Y
DO 300 K = 1, NPS
R(K) = SQRT((X - H(K))**2 + Y**2)
300 CONTINUE
HFX = C(K) * Y / (TPI * (R(K)**2))
HY = HFX / CT
WRITE(6, 10) X, Y, MAGHX, ANGHX, MAGHY, ANGHY
10 FORMAT(6F15.8)
WRITE(6, 10) X, Y, MAGHX, ANGHX, MAGHY, ANGHY
END
DEX = .01 in
DEY = .25 in

The data obtained from this case are plotted in Figs. 26 and 27.
APPENDIX C
EXPERIMENTAL EQUIPMENT

The equipment used to implement the constant phase-difference CSLG system is discussed here. Individual units belong to either the roadway system or the vehicle system (Fig. 3), with a block diagram of the former shown in Fig. 55a. The guiding structure consisted of two parallel two-wire transmission lines 1600 ft long separated by 7 ft-2 in. Each line consisted of two standard #14 AWG wires spaced 9 in apart. These lines were connected to the reference signal generator via matching units (Fig. 55b) which provided the necessary impedance matching and current balancing.

The reference-signal generator (Figs. 15b and 21) included two power amplifiers (Heath DX-35 transmitters), a phase-shift single-sideband generator, a Δf generator (a servo-motor resolver-pot combination), and the required power supplies. A complete schematic of the single-sideband generator is shown in Fig. 56. A section of the transmission line, one matching unit and the coaxial cable (between this unit and a DX-35 located in the van barely visible under the bridge) are shown in Fig. 57.

The instrumentation located in the test vehicle consisted of the following:

a) Signal-detection probes,

b) Preamplifiers,
Guiding Structure

Roadway nomenclature (ft north or south of center)

Coaxial cable

Heath DX-35 Transmitter

Phase-shift single-sideband generator (see Fig. C-2)

Heath DX-35 Transmitter

Portable 60 Hz power source 1500 watts (Onan)

DC Power Supply Δf generator (servomotor-resolver-pot)

reference signal generator

a. - Total Roadway System

Coax to Transmitter

two-wire transmission line on highway

taps adjusted for balanced currents, capacitors adjusted for minimum SWR

b. - Matching Unit Schematic

Fig 55 - Experimental Roadway System
**Fig. 56** — Schematic of phase-shift single-sideband generator
Fig. 57 - Components of roadway system
c) A vector voltmeter for processing of the detected signals,
d) An Analog computer, and
e) Electrohydraulic control systems.

The signals from the two transmission lines were sensed by two probes—one over each line. Each probe (Fig. 58b) consisted of a coil wound on a small ferrite cylinder (pickup), a variable shunt capacitor and a balun coil. The balun coil was necessary to prevent signal pick-up in the coaxial cable leading to the preamplifiers, and the entire assembly, balun and coax included, was tuned to resonance at the single frequency used (3.734 MHz). In Fig. 59a the probes are shown positioned over the inside wire of each transmission line.

The detected signals were amplified, by Ameco preamplifiers, to assure signal levels above the minimum threshold of the position detector—a Hewlett Packard model 8405A vector voltmeter—whose output was a voltage proportional to the phase difference between the two amplified signals. This voltage was proportional to the vehicle's position error. A block diagram of these components is shown in Fig. 58a, and a corresponding photograph, with the preamplifiers taped to the hood of the vehicle and the vector voltmeter visible through the windshield, is shown in Fig. 59a.

The position error voltage was fed to the vehicle controller which consisted of analog compensation elements, electrohydraulic control systems (for control of the throttle valve and brake-line pressure), and the instrumented vehicle so connected that the block
vehicle velocity

Channel A

Δf indicator

strip chart recorder
Clevite model 2D-2

Hewlett Packard model 8405 A
vector voltmeter

$v_y$ or position error

to longitudinal controller

a. CSLG components of the vehicle system

b. - Probe schematic

Fig. 58 - Experimental vehicle system
Fig. 59 - Components of vehicle system
The analog compensation was obtained using the onboard computer shown in Fig. 59b. Note that the vector voltmeter output and recorder are also depicted here.

A Clevite model 2D-2 recorder, shown in Fig. 58a, was used to record the position error, the vehicle velocity and \( \sin(2\pi \Delta ft) \). This latter signal, which was the output of the resolver pot (Fig. 56), was transmitted at 27 MHz from the van to the controlled vehicle. During testing operations, this signal was recorded with the collected data (see Figs. 41 - 45) and subsequently used to compute \( T \) and \( V \).
APPENDIX D
VEHICLE RESPONSE TO A SINUSOIDAL DISTURBANCE

The response of one class of vehicle controller to an unwanted sinusoidal input — representing an unwanted periodic variation of a synchronous reference signal — was derived in Chapter 2 (Eqns. (20) and (21)). This controller's response for typical parameter values (ξ = 0.7, ɔ = 1, and k = 0.3, 0.6, 0.8) are shown in Figs. 11 and 12. Its response for other values of these parameters (see Table III) are presented here in Figs. 60 - 75.

TABLE III
Parameter Values Used

<table>
<thead>
<tr>
<th>ξ</th>
<th>ɔ</th>
<th>k</th>
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<td>4</td>
<td>.3, .6, .8</td>
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<td>8</td>
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</tbody>
</table>
Fig. 60 - Controller magnitude vs frequency for $\xi = .7$, $\zeta = 4.0$
Fig. 61 - Controller phase vs frequency for $f = .7, z = 4.0$
Fig. 62 - Controller magnitude vs frequency for $\xi = 0.7$, $\zeta = 0.0$
Fig. 63 - Controller Phase vs Frequency for $f = 0.7, z = 8.0$
Fig. 64 - Controller magnitude vs frequency for $\xi = 1.0, \zeta = 1.0$.
Fig. 65 - Controller phase vs frequency for $f = 1.0$, $\zeta = 1.0$
Fig. 66 - Controller magnitude vs frequency for $\xi = 1.0$, $\omega_n = 4.0$
Fig. 67 - Controller phase vs frequency for $\xi = 1.0$, $\zeta = 4.0$
Fig. 68 - Controller magnitude vs frequency for $\xi=1.0$, $\zeta=0.0$.
Fig. 69 - Controller phase vs frequency for $f = 1.0$, $\zeta = 8.0$
Fig. 70 - Controller magnitude vs frequency for $\xi = 2.0; \zeta = 1.0$
Fig. 71 - Controller phase vs frequency for $f=2.0$, $\zeta=1.0$
Fig. 72 - Controller magnitude vs frequency for $f = 2.0, \zeta = 4.0$
Fig. 73 - Controller phase vs frequency for $\xi = 2.0$, $\zeta = 4.0$
Fig. 74 - Controller magnitude vs frequency for $s = 2.0$, $\zeta = 8.0$
Fig. 75 - Controller phase vs frequency for $\xi = 2.0$, $\zeta = 8.0$
APPENDIX E
VEHICLE RESPONSE TO A RANDOM DISTURBANCE

The response of one class of vehicle controller to an unwanted random input — representing an unwanted aperiodic variation of a synchronous reference signal — was derived in Chapter 2 (Eqn. (23)). This controller's response for typical parameter values ($S = 0.7$, $\zeta = 1$, and $k = .3, .6, .8$) are shown in Fig. 22. Its response for other values of these parameters (see Table III) are presented here.
Fig. 76 - Variance vs bandwidth for $f = 0.7, \omega = 4.0$
Fig. 77 - Variance vs bandwidth for $\xi = 0.7$, $\zeta = 8.0$
Fig. 78 - Variance vs bandwidth for $\xi = 1.0$, $\zeta = 1.0$
Fig. 79 - Variance vs bandwidth for $\xi = 1.0$, $\zeta = 4.0$
Fig. 80 - Variance vs bandwidth for $\xi = 1.0$, $\tau = 8.0$
Fig. 81 - Variance vs bandwidth for $\zeta = 2.0$, $\tau = 1.0$
Fig. 82 - Variance vs bandwidth for \( f = 2.0, \ \tau = 4.0 \)
Fig. 83 - Variance vs bandwidth for $\phi = 2.0$, $\zeta = 8.0$
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