Application of Infra-Red Technology
to Control Vehicle Movement
in a Platoon of Cars

by

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1. Introduction

High traffic volumes in urban arterials and in short range intercity traffic have created problems which are mainly associated with the safe and efficient movement of a platoon of vehicles. The car following situation in high traffic densities is rather sensitive to disturbances and rear end collisions are the most frequent type of accidents on urban freeways and expressways. For the Ford and John Lodge Expressways 62 percent and 55 percent respectively of the accidents have been reported to be caused by rear end collisions. Ohio's rural freeways show the following distribution of accident types; which most likely can be influenced by controlling the spacing of vehicles travelling in a platoon.

<table>
<thead>
<tr>
<th>Accident Type</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rear end collisions</td>
<td>25.2%</td>
</tr>
<tr>
<td>Stopped and stopping vehicles</td>
<td>10.9%</td>
</tr>
<tr>
<td>Total</td>
<td>36.1%</td>
</tr>
</tbody>
</table>

Thus about half of all accidents occurring on urban expressways and about 1/3 of the accidents occurring on rural freeways can be expected to be affected by an Infra-Red longitudinal control system. The aim of such a system is to prevent rear end collision accidents, and to substantially reduce the horrifying toll we are paying human suffering, senseless destruction and loss in manpower for highway traffic. Additional benefits from a longitudinal control system can be expected from increased traffic capacities of highways and reduced journey times during rush hours.
2. Study of Platoon Movement

The violation normally described as "following to closely" does not specify the safe spacing of vehicles but leaves it to the driver not to follow another vehicle more closely than is reasonable and prudent, having due regard for the speed, the traffic, and the condition of the highway. As a rule of thumb, it has been recommended to adjust the distance between vehicles to a length of one car for each increment of 10 mph. in speed of the trailing vehicle.

Although it appears extremely difficult to formulate a reasonable comprehensive theory of risk in traffic this problem can be reduced to two levels of risk for the following situation.

(a) Safe Traffic Flow

Sufficient longitudinal spacing is provided between vehicles travelling in a platoon to enable trailing vehicles to come to a safe stop even if the leading vehicle should come to a sudden stop by colliding with a stationary object in the traffic lane.

The spacing for this condition is

\[ s_A = \tau v + \frac{v^2}{2\mu g} + c \]  \hspace{1cm} (1)

where:

\begin{align*}
  s & = \text{distance between vehicles in feet.} \\
  v & = \text{speed of the following vehicle in feet per second.} \\
  \tau & = \text{reaction time of the driver of the following vehicle in seconds.} \\
  \mu & = \text{coefficient of friction between tire and road surface.} \\
  g & = \text{acceleration of gravity, feet per second per second.} \\
  c & = \text{constant \( \geq \) one car length in feet.}
\end{align*}
This traffic flow will have its maximum value at a speed of

\[ v = \sqrt{2\mu g c} \]  

which is about 19 mph, for normal conditions with a \( c = 20 \) feet and a coefficient of friction \( \mu = 0.6 \).

(b) Marginally Safe Traffic Flow

Sufficient longitudinal spacing is provided between vehicles travelling in a platoon to enable trailing vehicles to come to a safe stop if the lead vehicle should brake suddenly in an emergency. The required spacing for marginally safe flow is:

\[ s_m = v \tau + c \]

The maximum traffic flow for this condition is determined by speed and the reaction time of the driver or the response time of the control system. It has no optimum value but traffic flow increases with raising speed.

Traffic movement on Interstate Highway 71 has been studied and a continuous record of traffic movement was obtained by following a platoon of vehicles in a helicopter and recording their positions at time intervals of 1 second with an aerial camera. Figures 1 and 2 show typical results in the form of vehicle trajectories obtained by plotting distance against time. It can be seen that the spacing of vehicles in time, their distance, and their speed and acceleration or deceleration can be readily obtained from these graphs. Figure 1 shows the undisturbed traffic flow in the northbound center lane of about 1,800 vehicles per hour, at an average speed of 27 mph. Figure 2 shows
Figure 1 - Vehicle Trajectories of Undisturbed Traffic Flow, Northbound Center Lane of I-71, Columbus, Ohio.
the disturbed traffic flow in the northbound traffic lane next to the median. The spacing of vehicles proceeding through this disturbance was measured and the degree of safety was determined considering different safety concepts. These are:

(A) Safe traffic flow

$A_1$ reaction time of driver 0.7 seconds, coefficient of friction ranging from 0.8 at 10 mph. to 0.62 at 60 mph.

$A_2$ reaction time of driver 2.0 seconds, frictional coefficients ranging from 0.71 at 10 mph. to 0.55 at 60 mph.

(B) Marginally safe traffic flow

$B_1$ reaction time of driver 0.7 seconds.

$B_2$ reaction time of driver 2.0 seconds.

(R) Recommendation for safe driving; one car length distance to the leading car per 10 mph. speed increment.

Concepts $A_1$, $A_2$ and $B_1$, $B_2$ can be considered as limits denoting the safety range since it was not possible to consider the variance in reaction time for individual drivers. The degree of safety for each of the five concepts was determined by:

\[
\text{safety factor} = \frac{\text{measured spacing}}{\text{required safe spacing}}
\]

Thus a factor $\delta < 1.0$ indicates an unsafe car following situation in regard to the pertinent concept of safety.

In evaluating the field data it was found that the degree of safety varies continuously as a platoon of cars travels along the freeway. In an initial study about 1,300
different spacing-velocity data were reduced, representing 48 vehicles proceeding through the disturbance (kinematic wave) shown in Figure 2. Table I shows an example of data reduction for Vehicle No. 222.

To obtain some measurement of the degree of safety of platoon movement on a freeway the percentage of unsafe driving time was calculated for each vehicle evaluated by

$$t_{\text{unsafe}} = \frac{\sum (\Delta t)_{\delta < 1.0}}{t_{\text{total}}} \times 100$$  \hspace{1cm} (4)

where:

$t_{\text{unsafe}}$ = unsafe driving time in percent of total observation time.

$(\Delta t)_{\delta < 1.0}$ = period of time with safety factor $\delta < 1.0$ seconds.

$t_{\text{total}}$ = total observation time, seconds.

It was found that inspite of the fact that the different safety concepts and the recommendation for safe driving cover a very wide range, not a single concept was met for the whole observation period. Even the safe spacing for concept B$_1$, which provides for marginal safety at rather ideal conditions with a dry clean surface and an assumed reaction time of 0.7 seconds for all drivers, was not met for about 11% of the total observation time. This result clearly indicates that there is some inherent danger in platoon movement on freeways. Table II shows the percentage of unsafe driving for the different concepts of safety and the recommended safe spacing. The requirements for A$_2$ and B$_2$ with a reaction time of 2.0 seconds
<table>
<thead>
<tr>
<th>Time Interval (sec.)</th>
<th>Velocity (mph.)</th>
<th>Headway (ft.)</th>
<th>Spacing (ft.)</th>
<th>Safe Spacing and Safety Factor</th>
<th>R (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>A₁ s  s Δ</td>
<td>A₂ s  s Δ</td>
<td>B₁ s  s Δ</td>
</tr>
<tr>
<td>22</td>
<td>41.63</td>
<td>70.50</td>
<td>52.75</td>
<td>128.2 0.41</td>
<td>218.7 0.24</td>
</tr>
<tr>
<td>25</td>
<td>44.35</td>
<td>72.74</td>
<td>54.99</td>
<td>143.2 0.38</td>
<td>241.0 0.23</td>
</tr>
<tr>
<td>28</td>
<td>43.61</td>
<td>74.96</td>
<td>57.21</td>
<td>139.0 0.41</td>
<td>234.8 0.24</td>
</tr>
<tr>
<td>31</td>
<td>45.45</td>
<td>67.40</td>
<td>49.65</td>
<td>149.4 0.33</td>
<td>250.4 0.20</td>
</tr>
<tr>
<td>34</td>
<td>38.72</td>
<td>64.44</td>
<td>46.69</td>
<td>112.2 0.42</td>
<td>196.7 0.24</td>
</tr>
<tr>
<td>37</td>
<td>28.80</td>
<td>57.42</td>
<td>39.67</td>
<td>68.0 0.58</td>
<td>127.9 0.31</td>
</tr>
<tr>
<td>40</td>
<td>19.47</td>
<td>62.99</td>
<td>45.24</td>
<td>37.3 1.21</td>
<td>76.5 0.59</td>
</tr>
<tr>
<td>43</td>
<td>20.91</td>
<td>67.25</td>
<td>49.50</td>
<td>40.7 1.21</td>
<td>83.5 0.59</td>
</tr>
</tbody>
</table>

s = safe spacing ft.

Table I. Example of Data Reduction for Vehicle No. 222
(car length of preceding vehicle = 17.75 ft.)
<table>
<thead>
<tr>
<th>Criterion of Safety Concept</th>
<th>Average Unsafe Driving Time (percent of total observation time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safe Flow</td>
<td></td>
</tr>
<tr>
<td>A₁  (\tau = 0.7 \text{ sec.}) (\mu = 0.8 \text{ to } 0.62)</td>
<td>69.81%</td>
</tr>
<tr>
<td>A₂  (\tau = 2.0 \text{ sec.}) (\mu = 0.71 \text{ to } 0.55)</td>
<td></td>
</tr>
<tr>
<td>Marginally Safe Flow</td>
<td></td>
</tr>
<tr>
<td>B₁  (\tau = 0.7 \text{ sec.})</td>
<td>10.97%</td>
</tr>
<tr>
<td>Safe Flow</td>
<td></td>
</tr>
<tr>
<td>B₂  (\tau = 2.0 \text{ sec.})</td>
<td>80.28%</td>
</tr>
<tr>
<td>Recommended Spacing</td>
<td></td>
</tr>
<tr>
<td>R  1 car length per 10 mph. speed increment.</td>
<td>37.08%</td>
</tr>
</tbody>
</table>

Table II: Unsafe Driving Time as a Percentage of the Total Observation Time
we were not met for 91% and 80% of the total observation time thus indicating that the somewhat inattentive driver faces a high probability of being involved in a rear end collision if an emergency should occur. The overall results of the study are as follows:

(a) About 90% of the drivers meet the conditions for the rather unrealistic concept $B_1$ - marginal safety at a reaction time of 0.7 seconds.

(b) Only about 60% of the drivers implicitly accept the recommendation for safe spacing, i.e., one car length per 10 mph. increment in speed.

(c) Spacings meeting the unrestricted concept $A_1$ and $A_2$ of safe traffic flow are only maintained by 10% and 30% of the drivers respectively.

(d) There is a distinct minimum in safety for speeds between 30 and 40 mph., i.e., the speed range which occurs most frequently at high traffic volumes.

These results indicate the need for a longitudinal control system which can monitor the safe spacing of vehicles travelling in a platoon, and after studying the possibilities of different media including radar, electromagnetic waves and ultrasonic sound, it was decided that Infra-Red light can provide an inexpensive and reliable solution to the problem.


The means presently available for communication between vehicles are rather limited and not very effective. Three media are in use:

- Lights:
  - Head lights
  - Tail lights
  - Stop or braking lights
  - Turn indicators
Blinking lights for emergencies

Sound: Horn, primarily as a warning device
Signaling: Hand signals

A considerable range of more or less useful information could, in principle, be communicated to a driver-vehicle system; the presence of an unusually congested area ahead, sudden sharp braking of a vehicle several vehicles ahead which may give rise to an unstable transient, the desire of a near-by operator to change lanes, the presence of a gap in an adjoining lane which would allow lane changing safely, headway, velocity and acceleration (deceleration) of vehicles ahead, local mean speed and headway conditions, and even detailed position, velocity and acceleration of each vehicle near the subject.

After extensive studies it was found that differential velocity between successive vehicles and the acceleration (deceleration) pattern of the leading vehicle would be most useful informations to improve traffic safety and to increase traffic capacity and speed safely. The near infra-red was chosen for simple instrumentation and the somewhat superior ability to penetrate fog and haze.

Two infra-red systems were developed, the self contained and the source-sensor system and the latter was built as a prototype and has been tested over 1,000 miles of freeway driving.

3.1 The Infra-red Source-Sensor System

It has been mentioned that the near infra-red region of the spectrum was chosen because of its superior transmission in fog compared with the visible region
and because ordinary glass optical systems could be used.

The source for this system, which is placed at the rear of the preceding vehicle, is a pulsed infra-red beam with the pulse frequency being a function of the vehicle speed. The light presently used is a 4-1/2 inch sealed beam lamp with a maximum rated initial candle power of 35,000. A Wratten No. 87C filter is used in front of the source to eliminate the visible light which could be a traffic hazard. The pulsing of the source is provided by a rotating three blade disc in front of the lamp. This disc is coupled to the output of a differential gear. One input to the differential gear is coupled to a constant speed motor and the other input is coupled to the rear wheel of the vehicle through a flexible shaft. By this arrangement the chopping rate varies from about 40 c.p.s. (vehicle backing up) to about 150 c.p.s. at a velocity of 100 mph. Pulsing the source within the above cycle range was chosen as a simple inexpensive and reliable means to provide an output which is a function of the vehicle speed and to provide a distinct signal from a stopped vehicle which is discernible from other I-R sources. The frequency range was chosen as being convenient for demonstrating the principle, a higher frequency which can be modulated appears to be desirable, and can be obtained with a xenon gas discharge tube or a gallium arsenide junction laser.

The sensor unit has been designed to detect the signal from the preceding vehicle and convert it to speed. This signal is then compared with the speed of the following vehicle. The speed of the trailing vehicle minus the speed of the leading vehicle is displayed on a meter, calibrated in miles per hour, in the trailing ve-
hicle. Once the trailing vehicle is close enough for the detector to lock onto the leading vehicle the driver of the following vehicle is always aware of whether he is travelling slower, faster, or at the same speed as the leading vehicle. The response time of the system is made less than the human reaction time, and it can be expected that safety in the car following situation can be improved considerably if suitable arrangements are made for the control of the trailing vehicle.

An additional safe guard against following too closely has been developed by measuring the intensity of the signal from the preceeding vehicle to determine the distance between vehicles. Figure 3 shows the meter deflection at different separation distances. It can be seen that for the setting shown, the meter is rather sensitive at a range below 300 feet. The sensitivity of the distance measuring circuit varies with weather conditions, and it is left to the driver of the following vehicle to adjust the sensitivity of this distance measuring instrument for a spacing which he considers safe. Predetermined energy level or meter deflection will then actuate a danger signal and/or close the throttle automatically and initiate braking if the trailing vehicle gets to close to the leading vehicle.

This method is not very accurate and the error is estimated to be $\pm 12\%$, mainly due to aberrations in the optical system used with the detector. It, however, was felt that the longitudinal control system must be inexpensive and reliable. Setting and measuring the energy level of the pulsed signal is an effective and simple means to control minimum spacing which appears to be compatible with the driving task in the car following situation, since the performance of the unaided driver is rather poor.
Figure 3 - A Typical Measured Calibration Curve for Distance Measuring Circuit.
The circuit diagram for the sensor is shown in Figure 4. The detector shown is a RCA type SQ 2516 photo junction cell. The cell is sensitive in the region of 3,000 to 19,000 angstroms with the peak sensitivity at 15,000 angstrom, i.e. in the near infra-red as desired. The meter reads directly the differential speed between the following vehicle and the leading vehicle thus providing the driver of the trailing vehicle with the "approach rate" if his speed should be higher than the speed of the leading vehicle.

Photographs of the sensor unit mounted below the front bumper of the following vehicle and the source mounted in the rear window of the leading vehicle are shown in Figure 5 and Figure 6 respectively.

It appears that the taillights of motor vehicles could be used as sources for the system with small modifications, and introducing the source sensor system therefore will not be very costly nor will it cause great difficulties in modifying vehicles. It, however, must be realized that the system can only make a significant contribution to traffic safety if all vehicles are equipped with I-R sources compatible with the system. The introduction of such a system will not be possible without changing the present motor vehicle laws and the vehicle code.

This is a rather serious shortcoming, since it cannot be left to the individual driver to equip his vehicle with the necessary instruments if he desires the additional driving convenience and safety. An attempt was made therefore to develop a self-contained I-R control system for longitudinal spacing which can be introduced without compelling other drivers to equip their vehicles with the I-R source.
Figure 4 - Circuitry for Infra-Red Speed and Distance Sensor.
Figure 5 - Lens Mount and Detector Mounted on Following Vehicle.
Figure 6 - Source for Source-Sensor System in Proceeding Vehicle.
3.2 The Self Contained Infra-Red Control System

An infra-red source-sensor unit is mounted on the front bumper of the vehicle which emits a frequency modulated I-R signal in the direction of travel. Gallium arsenide junction lasers or xenon gas discharge tubes appear to be very suitable for this task. The emitted signal is reflected to the source by the lead car which, for this purpose, has been equipped with a rear license plate having the properties of a corner reflector. The reflected signal is picked up by a sensor and processed in the usual way to determine differential velocity and distance between the two vehicles. The source-sensor system can be introduced without difficulties in the states where new license plates are issued every year. Some preliminary investigations on the range and the capacity of such a system have shown of sufficient magnitude and reliability. Encouraging results, however, have been obtained with reflectorized license plates.

The self contained I-R system will be much more expensive than the source sensor system and since no field tests in highway driving have been carried out, the question whether an automatic tracking system will be necessary in the car following situation cannot be answered yet. Indications are that a tracking distance of about 200 feet can be obtained with an angular field of view of 2 degrees on a 2 degree curve if the source sensor unit is coupled to the steering mechanism. This range will not suffice for high speed traffic and automatic tracking will be necessary which will further increase the cost of the system considerably.
4. Discussion and Conclusions

The I-R sensing and communication systems have been developed with the ultimate goal to provide fully automatic traffic control for urban and rural freeways, and to eliminate some of the most common hazards in freeway driving. Such a system may not yet be acceptable by the public, and a step by step introduction through the following stages appears to be desirable:

(a) Providing the driver with additional useful information to improve his capacity for safe driving.

(b) Providing a semi-automatic control process for the car following situation in high density traffic.

(c) Providing a fully automatic process which will control the steering and spacing of vehicles on freeways.

The I-R source-sensor system appears to be capable to perform these tasks if it is coupled with a suitable lane coding and vehicle guidance system. Some research on the coding and guidance system has been carried out, but the available space does not permit to report on the system. Theoretical investigations of a system which is controlled by sensing differential speed between vehicles traveling in a platoon have shown that the marginally safe spacing of vehicles will then be

\[ s = 2tv + s_j \]  \hspace{1cm} (5)

where:

\[ s \] = spacing between vehicles in feet.

\[ t \] = response time in seconds.
\[ v \quad = \quad \text{speed of the trailing vehicle in feet per second.} \]

\[ s_j \quad = \quad \text{spacing of cars in a traffic jam condition.} \]

The safe traffic capacity per traffic lane will then be well over 3,000 vehicles per hour at a speed of 40 mph. and a response time of the control system of 0.4 seconds. At the present, rather unsafe conditions, comparable figures would be 2,000 vehicles per lane per hour at a speed of about 35 mph. With the vehicle spacing determined by (5) the differential velocity control system will be stable and disturbances will be attenuated.

Investigations on present driving conditions on urban freeways indicate that about 50 percent of the drivers do not adhere to the safe driving recommendation of one car length headway per 10 mph increment in speed. This means that almost every second driver is a potential candidate for a rear end collision if an emergency should occur. So far no investigations were made in rain or when the road surface was wet or covered with snow. It almost certainly can be expected, however, that a reduced degree of safety will prevail in adverse weather conditions or with a slippery road surface.

The investigations carried out so far clearly indicate that the infra-red system for longitudinal control which might progress through the stages of driver aid, to semi-automatic and fully automatic, will pay dividends, and that it can contribute an important step forward to improve high density traffic flow and traffic safety on urban freeways.
REFERENCES


