Rear-End Collisions Reduced: A Large-Scale Experiment under Natural Conditions

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THE FACT that it is possible to design automotive equipment to prevent the occurrence of automobile collisions has been greatly overshadowed by attempts to design automotive equipment to protect occupants during a crash (1).* The extensive on-road testing of a deceleration warning light system reported here indicates that a reduction of 60% in the number of rear-end collisions is possible.

PROBLEM

The problem of the reduction of rear-end collisions and the concurrent elimination of the "shock wave" phenomenon on super highways may be considered as follows: Two cars are driving down the highway at 60 mph one behind the other separated by two car lengths (40 ft). Suddenly at time zero the first driver applies the brakes on his car as hard as he can and continues to apply his brakes until his car comes to a stop about 5 s later. What can the second driver do and what does he see? Fig. 1 accurately diagrams the alternatives.

The figure shows the distance traveled by either car starting the instant the lead car driver applies his brakes and continuing for the next 5 s. In this particular example the lead car is decelerating at 19.3 ft/s^2.

The solid curve in Fig. 1, the trajectory of the lead car, tells the position of the lead car at any instant. Notice that after 5 s it has gone 200 ft. Now for this particular example, the second car is 40 ft behind (approximately two car lengths) and traveling initially at the same speed, which is shown by the slope of the dashed curve A being the same as the slope of the solid curve at time zero. If the driver of the second car does not apply his brakes, he will follow the straight dashed curve A. Curve A intersects the smooth curve about 2 s after the lead driver slammed on his brakes. This means that the second car driver, by not applying his brakes, runs into the back of the first car after 2 s and after traveling 140 ft. Curve A is one extreme case, while curve B is the other extreme case. In curve B the driver of the second car, by some pre-arranged signal, slams on his brakes at the same time as the first driver. In this case the second car follows the identical curve as the first car and thus comes to a stop 40 ft behind the lead car, which is the same separation after the cars have stopped as there was at the beginning of the braking. In order to do this, the second car's driver must apply his brakes at exactly the same instant as the first car and equal the deceleration of the lead car for the same period of time as the lead

A deceleration warning light system installed on taxicabs in San Francisco for 12.3 million miles of normal on-road driving reduced the rear-end collision rate by 60.6% compared to the rate for a concurrent control group of cabs which traveled 7.2 million miles. Comparing the experimental group with the concurrent control group revealed that the warning light prevented 5.4 collisions per million miles, 1.02 cab driver injuries per million miles, and $643 of taxicab damage per million miles. An amber light was center mounted on the rear of several hundred taxicabs and was designed to communicate information about the taxi's deceleration to following drivers.
The amount of time that the following driver has to make his car match the deceleration or be less than the deceleration of the lead vehicle and still come to a controlled stop behind that vehicle is called the critical time interval. It depends on the common speed of the cars and their separation distance. It is also the time it takes the second car to travel the distance between the cars after the lead car applies the brakes. Fig. 2 gives the critical time interval for any vehicle separation for approximately one-half car length per 10 mph gives a critical time interval of 3/4 s. Fortunately, this critical time interval is longer than the driver’s response time, provided the driver is given adequate warning by a deceleration warning system mounted on the lead vehicle. The average response time is about 1/2 s and at best 1/3 s for a driver to remove his foot from the gas and place it on the brake pedal with the required pressure.

Response times such as these are obtained only by what is known in psychology as a conditioned reflex. For example, if a bell is rung slowly, then the driver has plenty of time to move his foot onto the brake, but if a bell is rung furiously the driver will react very quickly, particularly after he is conditioned to the stimulus by a couple of near misses with disaster. Bell ringing is a poor stimulus, but a stoplight which does essentially the same thing can be a very effective stimulus for the driver.

What essentially happens now is that the driver of the following car sees the lead car rapidly dip nose downward under severe braking conditions. This rapid dipping causes the following driver to apply his brakes more intensely. Some vehicles such as tractor-trailer trucks, however, do not dip. Also, if the following driver blinks, lights a cigarette, looks at a road sign, etc., the dip will be missed, providing the lead vehicle does dip. If the dip is missed, the following driver must wait for his eye to detect a significant change in the separation distance and, furthermore, the separation distance must change rapidly enough to attract his attention. The average driver takes a little over 1 s to perceive the changing
separation distances and increased closure speeds. No driver is average all the time, however, and if a driver has had a drink, a cigarette, a long hard day of work, etc., the change in separation distance and closure velocity must be larger than normal before he will react. Thus his response will be significantly delayed beyond 1 s and he must exceed the deceleration of the lead vehicle, if possible, or run off the road to avoid hitting it. In most cases the following car can exceed the deceleration of the lead vehicle and still stop. If it cannot, a rear-end collision results.

If there are a number of cars in single file, it is occasionally observed that if the first car decelerates slightly, the fourth or fifth car may be involved in a rear-end collision. A wave of crashes travels up a crowded freeway and can involve many cars. The first car need not decelerate maximally in order to cause this phenomenon, because most of the drivers in the line do not react within the critical time interval. Therefore, each driver must slightly exceed the deceleration of the car immediately in front. Eventually one vehicle will have to exceed the decelerating capability of his vehicle. Not being able to exceed this capability, his car will slam into the car ahead. This process may repeat itself several cars behind those involved in the original accident. People also overreact to the braking of a lead vehicle and unnecessarily exceed its deceleration because, at present, they cannot tell how hard the lead vehicle is braking. In sum, although the stimuli now available to a driver work amazingly well, the number of rear-end collisions and the shock wave on freeways can be reduced by utilizing a better stimulus than dipping, change in separation, and rate of change in separation to alert the driver to how hard the lead car is braking. All that is needed for the driver to make the right response at the appropriate moment in order to obtain a significant (60%) reduction in rear-end collisions is the correct information at the right time.

Since motor vehicle accidents account for more deaths in the United States for the age group of 1-44 years than such better known causes as cancer and heart disease (2), considerable national attention is now understandably focused on the problems raised by motor vehicle use. This paper reports that the enhancement of the following driver's response by the use on motor vehicles of a stoplight which positively meets certain theoretically derived requisites significantly reduces auto collisions. These requisites include: first, the instantaneous degree of deceleration of the lead vehicle regardless of vehicle separation; second, the stationary on-road position of the lead vehicle, thereby signaling the possibility of dangerous high closure velocities. In addition, the stoplight must be compatible with the nervous system; capable of attracting the attention of the following driver and evoking involuntary, rapid, reflexive-type response; and congruous with existing signal systems. Not discussed in this paper are some practical requirements which have been met in developing an actual instrument, such as applicability to all vehicles and brake systems, exceptional reliability so that reflexive responses are reinforced, and low cost.

**HUMAN VISUAL PERCEPTION**

Present knowledge of the mechanism of human visual perception can be inferred from psychological experiments on man and neurophysiological experiments on animals other than man. The human data will be considered prior to those from lower animals. Of primary interest, for present purposes, is the neural reaction to a simple visual display which may vary in intensity, area, and contrast, and change with time, either in intensity, area, pulsation frequency, or contrast.

The intensity relationship has been studied in many experiments concerned with estimation of brightness as it varies with the luminance. For relatively steady states, the estimate is usually found to be a negatively accelerated function of intensity of illumination; Stevens and Galenter (3) find that a power function with an exponent, 0 $< \delta < 1$, less than one, closely approximates the data.

For a given illumination early experiments by Pieron (4) found that brightness is similarly a function of area of stimulation, larger areas yielding increased estimates of brightness according to a power function with the exponent $\delta$ less than 1.

Contrast effects are by definition the effects that result when luminance differences exist within the visual field. For maximum contrast between two points, Brown and Mueller (5) demonstrate that the luminance difference should be as large as possible between the two points and the separation distance as small as possible. Burnham, et al. (6) show that the brightness of an object surrounded by a dark field increases as the contrast increases.

An important qualification needs to be made with respect to visibility as a function of intensity, area, and contrast, and this concerns the rate of change over time. For example, Riggs, et al. (7) report that a stimulus of constant intensity...
At some subfusional pulse frequencies, brightness of pulses appears greater than brightness of steady illumination at fusion frequency—enhancement is maximum in neighborhood of 10 pulses/s. Three curves represent three different light-to-darkness ratios: A = 1/1, B = 7/2, C = 8/1 (Bartley (8)).

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S - S₀ = CP^γ
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where:

- $S =$ pulse frequency less than 10 cps
- $S₀ =$ minimum pulse frequency of 1 cps
- $C$ and $γ =$ constants where $γ = 1/6, γ > 1$
- $P =$ reported brightness above minimum frequency

**ELECTROPHYSIOLOGY OF PERCEPTION** - The facts of visual perception are rooted in the neurophysiology of receptor cells and transmission systems in the nervous system. Fortunately, there are many parallels to human perception in the magnitude of electrophysiological responses from single cells or cortical areas. For example, practically identical curves to those reported by Bartley (8) in Fig. 3 are obtained by electrophysiology in nerve cells of the visual cortex of a cat as reported by Reidemiester and Grüsser (9) (Fig. 4). The curves in Fig. 4 show the relationship of light pulse frequency to neural discharge frequency where peak repetition rate occurred near 10 flashes/s and fusion occurred near 20 cps with 46 fc of illumination. Furthermore, there are also some relationships from neurophysiological data which are not now available in human data that permit a mathematical formulation of the perceptual consequences of some aspects of strength of stimulation. For example, Ratliff (10) has found that the instantaneous frequency of discharge of the eye of Limulus is a function of the intensity of illumination for steady-state
conditions and the rate of change of intensity during dynamic conditions. Hartline and Graham (11) also demonstrate that the magnitudes of Limulus correspond approximately to the power laws. In fact, the aforementioned dynamic and magnitude relationships appear to be characteristic of nerve cells in general (12) where they have been found for kinesthetic cells by Mountcastle (13) and Boyd and Roberts (14), in muscle spindle by Katz (15), and in motoneurons by Hodgkin (16). Mathematically the magnitude relationship can be written as

\[
\alpha (I - I_0)^\delta_s + \beta \left( \frac{dI}{dt} - \frac{dI_0}{dt} \right)^\delta_d = x(t) + \gamma \frac{dx}{dt}
\]

(2)

where:

- \(x(t)\) = instantaneous firing rate of cell in impulses/s
- \(I\) = intensity of illumination in candlepower
- \(I_0\) = threshold intensity
- \(\frac{dI}{dt}\) = rate of change of intensity
- \(\frac{dI_0}{dt}\) = rate threshold
- \(\alpha\) and \(\beta\) = proportionality constants
- \(\delta_s\) and \(\delta_d\) = static and dynamic magnitude constants, respectively, with values less than one

The constants \(\delta_s\) and \(\delta_d\) describe the characteristic negatively accelerating output magnitude of nerve cells to input magnitude.

Retinal cells in man synapse in the lateral geniculate, thalamus, and visual cortex (Bishop and Clare (17)) and with other cells which in turn behave as receptor cells by transmitting information computed from inputs received from all retinal receptor cells. Cells in the lateral geniculate of a cat respond to the amount of contrast surrounding an image; cells in the visual cortex respond when lights turn off; and cells in the visual cortex respond to orientation of slits of light (light gradients or edges) as well as direction of movement and length (Hubel and Wiesel (18)). Transient phenomena for these cells in the cat are similar to those nerve cells which have been described by Baumgartner (19). Therefore, if an image of any object has an edge (uniform light gradient or slit) of length \(l_1\), then the output of a cortical cell measuring the length and rate of change of length is described by:

\[
x(t) = \alpha (l_1 - l_{10})^\delta_s + \beta \left( \frac{dl_1}{dt} - \frac{dl_{10}}{dt} \right)^\delta_d
\]

(3)

where:

- \(l_{10}\) and \(\frac{dl_{10}}{dt}\) = threshold values
- \(l = zero for simplicity

In other words, the strength of the stimulus increases the response of the cortical cell (visibility) when the object is against a dark background or is made brighter than the background; if the object is moved spatially; if the object is increased in size; and if the object is flickered temporarily. Eqs. 2 and 3 summarize these relationships on the basis of the electrophysiological data; it is inferred that the same form of function holds for human perception. Note that the parameters have not been quantitatively specified; because it is the form of the function that is inferred, the presumption is that the quantitative parameters can be determined empirically.

**REACTION TIME**

Reaction time (RT) is defined as the time required for the human subject to get the overt response started. Principally RT depends on the magnitude of the change in the strength of the stimulus which is given by Woodworth and Schlosberg (20) as the change in the algebraic combination of intensity, area, contrast, and the corresponding rates of change. In all cases, if the change in the stimulus carries the correct information as well as increasing in magnitude, RT decreases and approaches a finite limit. Fig. 5 from Steinman (21) shows that the limit is quickly approached, thus eliminating the need for very bright lights of high stimulus strengths above a given level; however, Woodworth and Schlosberg (20) point out that besides stimulus strength, RT quickens when motivation (punishment, fear) increases or the subject is given prior warning or practice. Finally, in the usual RT experiments the subject has no other duty to perform except that of starting promptly. If, however, the correct response is to analog track an input stimulus as in following a target with minimum delay, then RT becomes slower. Searle and Taylor (22) show RT in one particular experiment to be 0.250 s and the primary movement and convergence to take an additional equivalent time of 0.250 s, resulting in a recognition and response time of 0.500 s. As a general rule, twice RT is the time required to initiate and converge on target. Woodworth and Schlosberg (20) point out that the fastest measured mean RT for man is in the neighborhood of 0.170 s when visually stimulated.

**HIGHWAY REQUIREMENTS ON DRIVERS' REACTIONS**

If drivers are to avoid collisions with decelerating lead vehicles or stationary vehicles in the traffic lane, they must respond appropriately within a given time interval. The response
The time interval is defined here as the recognition and response time interval, $\Delta t_{rr}$; and since matching decelerations over time involves analog tracking, the magnitude of $\Delta t_{rr}$ equals at best twice RT. On the other hand, the maximum amount of time which can pass from the instant that the lead vehicle initiates deceleration, $t_0$, before the following driver must react by achieving equal or greater deceleration (if possible) is defined as the critical time interval, $\Delta t_c$. The critical time interval is given mathematically by the equation,

$$\Delta t_c = \frac{X(t_0)}{V(t_0)},$$

where:

- $X(t_0) = \text{initial separation distance}$
- $V(t_0) = \text{common vehicular velocity (Fig. 2)}$

It can be seen from Fig. 2, for example, that the rule of thumb of 1/2 car length (10 ft) vehicular separation for each 10 mph of velocity gives $\Delta t_c = 0.7$ s. If, as is evidenced by the current accident rate, $\Delta t_{rr}$ is often greater than $\Delta t_c$, then the following car must exceed the deceleration of the lead vehicle, and, if it cannot, an accident occurs. Multiple car collisions are similarly caused. On the other hand, if $\Delta t_{rr}$ is much less than $\Delta t_c$, the following driver may take advantage of the initial separation distance, $X(t_0)$, and decelerate at a lesser rate than the lead vehicle. This advantage can lead to as much as a 20% reduction in necessary deceleration for each consecutive vehicle, thereby damping the multiple car collision shock wave.

In sum,

$$2RT = \Delta t_{rr} < \Delta t_c$$

gives the preferred conditions which at present are not the conditions under which vehicles are being operated.

**THEORETICAL RELATIONSHIP BETWEEN CHARACTERISTICS OF HUMAN SYSTEM AND HIGHWAY REQUIREMENTS**

What are the principal stimuli observed by the following driver and why do accidents occur? The stoplight system presently in widespread use on motor vehicles conveys no information as to the rate at which the lead vehicle is coming to a stop. The stoplight is merely illuminated upon application of the brakes and appears the same whether the driver is riding the brake, coming to a crash stop, or stopped in the traffic lane. Thus the driver must rely on his perception of the change in closure and of the rate of change of vehicular closure which often is inadequate to permit him to respond in time when deceleration or closure velocities are unexpected.

The relationship between an object in the real world and the image on the retina is given by the well-known lens law (Ruch and Fulton (24)) and its time derivative:

$$\frac{\delta x}{\delta y} = \frac{\delta y}{\delta x} = \frac{\delta t}{\delta t} = \frac{X}{X^2} \frac{dX}{dt},$$

where:

- $\delta x = \text{length of image, length of any uniform light gradient or edge of image}$
- $\delta y = \text{equivalent length on object and is constant}$
- $X = \text{focal length and is constant}$
- $X_0 = \text{distance of object from lens}$
- $K = \frac{-X}{X_0^2}$

By substituting Eq. 6 into Eq. 3, the relationship between the output of cortical cell, separation, and closure rate is obtained:

$$X(t) = \frac{a}{X_0} + \frac{b}{X_0^2} \frac{dX}{dt}$$

where:

- $a = \alpha K$
- $b = \beta K$
- $\delta_s$ and $\delta_d = 1$ (for simplicity)
- $\gamma = 0$
- $\theta = 0$

Thus Eq. 7 states that the strength of the visual stimulation to the driver depends inversely on the vehicle separation $X_0$, and most important, that the driver's ability to detect closure velocity decreases as the inverse square of the vehicular separation $1/X_0^2$. In other words, the greater the separation distance, the more difficult it is for the human eye to detect closure velocity, simply because of the physical principles governing the operation of the human eye's lens. Furthermore, although it appears that these principles should reduce accidents because as the closure and closure rate increase, the promptness of response increases, this consequence does not presently follow (as evidenced by current accident statistics) because at current highway speeds and/or separations, the appropriate response has to be made before (within 0.7 s) the eye has a chance to recognize large changes in closure and closure speeds.
Thus change in closure rate remains as the primary stimulus change which can attract the attention of the following driver. Parenthetically, a rapid rate of change of environment such as a sudden movement, a loud noise, or a flash of light always attracts attention due to the large transient output of receptors. Because of the lens laws governing perception by the human eye, the closer the two vehicles, the more detectable are changes in the closure velocity, thereby resulting in changes in stimulus strength which cause quicker reaction times. However, since at present there are many other visual stimuli which mask changes in separation and closure rate, RTs are lengthened; unexpected deceleration or high closure velocities give no prior warning, thereby also lengthening reaction times. Large RT means $\Delta t_c$ will be exceeded. Thus, separation distance is not a safety zone. Indeed many accidents occur when the lead car is stationary and initial separation is very large; because, from Newton's laws, stopping distance increases as the square of the closing velocity whereas the detectability of changes in closing velocity decreases with the square of distance. Therefore, when visual conditions are poor and/or decelerations and closing velocities are unexpected, reaction time will be too slow and accidents should be expected.

Parenthetically, the ability of the eye to detect a stopped vehicle in the lane of traffic thus falls off as the square of the separation distance. Many rear-end collisions occur because of this optical phenomena. It was found during the San Francisco test that about one-half of the collisions occurred under these conditions and that about half of those were prevented by having the warning of a 1 cps light pulse, 1200 cp, visible on the back of the car. A higher percentage reduction would have occurred if all cars in San Francisco were equipped. Multiple car accidents occurred where a second car would block the warning light and a third car would hit the second car in the first car. Additionally, if the car was angled more than 5 deg to the approaching traffic, the light pulse visibility was considerably reduced and was thereby rendered ineffective.

AUTOMOTIVE STOPLIGHT DESIGN BASED ON THEORETICAL RELATIONSHIPS

Several proposals have been made to overcome some of the above-mentioned defects by providing a specialized stoplight. One proposal is to increase light intensity proportionally to applied brake pressure; but since observed light intensity depends on separation distance and on atmospheric and lens conditions, only distorted information will be received. Another proposal is to employ flashing stoplights whose frequency is proportional to speed; however, the change in speed is too small to be detectable in $\Delta t_c$ s. Finally, color coding deceleration has been proposed where the color of the stoplight is to change from green to yellow to red as the foot is removed from the gas pedal and applied to the brake; but, aside from color blindness (9% of all men and 0.5% of women, Haas and Graham (25)), the red light presently has many meanings including crash stop as well as the all clear signal of the tail light, therefore no additional information will be available to the following driver than is now available after braking begins.

In order to effect recognition and response times, $\Delta t_{fr}$, less than the critical time interval, $\Delta t_c$, as dictated by current highway conditions, it is proposed that advantage be taken of the large neural response generated by a pulsed light which causes focusing of attention. All during the application of the brakes, not only should the stoplights be pulsed at a rate that is a positively accelerating function of the deceleration experienced by the vehicle, but the on-time of any pulse should be a function of deceleration. A redundantly coded system thereby results. Furthermore, it is proposed that the lowest pulse rate be used to signal the stationary condition where the vehicle is stopped in the traffic lane with the driver's foot on the brake, a condition which often occurs when the vehicle is stopped at a stop sign, stoplight, or in preparation for a turn.

The upper frequency limit must, of course, stay below the critical fusion frequency (CFF) of about 16 cps (the same rate as is used in silent movies). Actually peak reported brightness occurs at about 1/2 CFF. It so happens that standard stoplight bulbs (20 fc) work well at 7.6 cps with a 40% on-time current pulse cycle. Because the necessary information is available to the observer in 0.131 s at 7.6 cps, quickest possible reaction times (between 0.175-0.250 s) can result, thereby giving the fastest recognition and response times (between 0.350-0.500 s) and permitting each succeeding driver to stop his car safely without collision and with less deceleration than the car immediately in front. On the other hand, the lowest frequency should be as low as possible to ensure maximum information-carrying capacity and yet still give timely warning. The lowest frequency which signals the least dangerous condition is 1.0 pulse/s with 50% duty cycle, resulting in a leisurely recognition and response time, $\Delta t_{fr}$, of 0.500 s which is less than the $\Delta t_c = 0.70$ s generally required by current highway conditions (see Fig. 2) and equal to maximum time required as measured by Searle and Taylor (22). Furthermore, with a highly directional lens, 1200 cp light pulses produce a very visual discernible warning at 1.0 pulse/s to cars approaching a stopped car in the traffic lane.

The requirement that a positively accelerating relationship exist between pulse frequency and deceleration produces upon subject habituation a linearly increasing perception of danger or, as has been pointed out previously, a linearly increasing cortical potential. If Eq. 1 is substituted into the required relationship between deceleration $g$ and pulse frequency $S$:

$$S - S_0 = Ag^T$$

the desired linearly increasing relationship

$$P = \left(\frac{A}{C}\right)^\delta g$$

results in habituation of the subject to the system. The nu-
Numerical parameters are empirically determined. Normal stops occur in the range 0.1-0.2 g. Crash stops with locked tires on clean, dry pavement for most American cars will create maximum decelerations between 0.5 and 0.6 g. Thus, a frequency bandwidth from 1-7.65 cps gives a 50% increase (clearly visible) for each 0.1 g increase in deceleration up to 0.5 g maximum (Fig. 6).

The shape of the voltage pulse through the filament for the equipment used in the test was square. The percent “on” time decreased linearly from 50% at 0.0 g to 40% at 0.5 g. The peak relative brightness increased from 1.0 at 1200 cp at 0.0 g to 1.6 at 0.5 g. (For further engineering information, see Title 13, Chapter 2, Article 9, California Administrative Code.)

Use of the above system on motor vehicles, where the deceleration of the vehicle is measured by an accelerometer mounted rigidly to the car, theoretically produces involuntary reflexive responses of appropriate speed and magnitude by the following habituated driver because:

1. The tension in muscle fiber increases as the frequency of firing of the motoneuron (Ruch and Fulton (24)).
2. The tension in the muscle accelerates the limb or increases its force on the brake pedal (Sears and Zemansky (23)).
3. The position and rate of change of position of the limbs are fed back (Mountcastle (13), Boyd and Roberts (14)), and inhibit the motoneuron (Ruch and Fulton (24)), thereby completing the feedback control loop and forming a second-order control system which will normally follow the input to the motoneuron (D’azzo and Houpis (26)).
4. Upon habituation to the system, the subject’s synaptic efficacies change (Rushton (27), Eccles (28)) until a direct transmission line from photo receptor to motoneuron exists (Rushton (27)), thereby assuring that the limb system tracks the input from the eye with minimum delay (D’azzo and Houpis (26)).

Thus it is inferred from the evidence presented in this paper that pulse-coded stoplights will enhance the following driver’s response to unexpected decelerations and/or closure velocity in such a manner that his recognition and response time, $\Delta t_{fp}$, will be less than the critical time interval, $\Delta t_{cr}$, dictated by present highway conditions. This inferential conclusion has been verified by the use of prototype instruments on a large-scale experiment conducted in San Francisco in 1972-1973 under the supervision of the California Highway Patrol.

**LARGE-SCALE EXPERIMENT UNDER NATURAL CONDITIONS**

The deceleration warning light system tested was an amber warning light, center mounted on the rear of a vehicle at the same height as existing stoplights, which communicated a component of deceleration initiated by the driver of that vehicle to the driver of a following vehicle by application of the foot brake. A device for measuring deceleration, essentially an inertial pendulum, hence independent of any mechanical adjustments of the car such as brake pedal position, was rigidly attached to the vehicle. The warning light pulsed in a controlled fashion at a rate which varied exponentially with a component of deceleration. A 50% increase in frequency of the light pulses from 1.0 pulse/s to 7.6 pulses/s for each 0.5 g increase in deceleration from 0-0.5 g provides the exponential relationship. For further details, see Title 13, Chapter 2, Article 9, California Administrative Code.

**TEST PROCEDURE** - The experiment was designed to test the collision prevention effectiveness of the deceleration warning light in normal on-road driving conditions rather than in laboratory or off-road driving conditions. A commercial taxicab company, to be referred to as the Cab Co., was invited to participate in the experiment at no cost to themselves other than any inconvenience occasioned by equipping the cabs and operating them so equipped. The Cab Co. was asked to make their San Francisco fleet of 503 cabs available for the experiment for two reasons: first, the San Francisco fleet travels almost 2 million miles per month, thereby enabling testing of the equipment over significant mileage in a relatively short time period, and second, the Cab Co. maintains complete records of cab accidents which were available for the five years prior to 1972, thereby providing a statistical base from which to evaluate the test data. The Cab Co. agreed to complete cooperation with the planned experiment in permitting the deceleration warning lights to be installed on their San Francisco fleet and in making available all their accident and mileage records.

On Mar. 1, 1972, 343 cabs began operation with deceleration warning lights. The remaining 160 cabs were to be traded in on new vehicles and thus were not equipped and served as a concurrent control group. The new vehicles were equipped when delivered to the Cab Co. Later, between June 1 and Aug. 28, 1972, the deceleration warning lights were removed.
from previously equipped cabs in order to equalize the mileage driven by the equipped and nonequipped cabs. This approximately equal monthly mileage was continued through the end of the experiment, Feb. 1, 1973. The changes in proportion of cabs equipped or nonequipped are corrected by expressing all collision rates as collisions per million miles driven. Cab drivers drove cabs equipped with the deceleration warning light or not equipped at the discretion of the dispatcher who disregarded requests by the drivers to drive or not drive the equipped cabs in his dispatching of the cabs. No massive education program on the operation and function of the deceleration warning light system was made prior to the experiment or during the experiment. Limited news coverage at the start of the test provided the only source of public information.

RESULTS

At the end of the reporting period, Jan. 31, 1973, the vehicles equipped with the deceleration warning lights had traveled a total of 12.3 million miles with a rear-end collision rate of 3.51 collisions per million miles (Fig. 7). This is a 60.6% reduction in the rear-end collision rate from the concurrent control group which has 8.91 collisions per million miles over a total of 7.2 million miles. The rate for the concurrent control group is almost identical to the 1971 rate of 8.89 over 21.5 million miles, and near the mean rate of 7.9 for the five years prior to Jan. 1, 1972, computed over 125 million miles from Cab Co. records.

The 10 months for which comparative data are available can be taken as 10 independent experiments. For this purpose the month of April 1972 is excluded because there are no control data for this month. When the rear-end collisions are treated as collisions per million miles within each month, a paired t-test of the differences for equipped and nonequipped cabs is significant ($t = 4.06, df = 8, p = 0.006$).*

A common criticism of social experiments that involve innovative arrangements is that the operators are sensitive to the new arrangements and behave differently owing to the so-called Hawthorne effect (Roethlisberger and Dickson (29)). This criticism does not apply in this study because the collisions are caused by the drivers of the cars that follow the cabs and not by the cab drivers. The fact that the cab driver has not become more cautious because of driving a cab equipped with a safety device is attested by the lack of change in the collisions in which the cab driver runs into the rear-end of a car in front of him. The drivers of equipped cabs produced 7.1 such collisions per million miles and those not equipped produced 8.1 such collisions per million miles. When this difference is tested statistically by the aforementioned procedure, the difference is not significant ($t = 0.65, df = 8, p = 0.52$).

The rate of personal injury to cab drivers in equipped vehicles struck in the rear by other vehicles was 0.65 per million miles, or a 61.1% reduction from the 1.67 rate of the concurrent control group (Table 1). The costs of repairs to the cab vehicles struck in the rear by other vehicles declined from $1041 per million miles for the concurrent control group to $398 per million miles for the deceleration warning light

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*The division of accident rates into units of months is somewhat arbitrary, but to produce a statistical test at all it was necessary to use the data available from the Cab Co. Mileage data are reported monthly rather than by miles to accident, which would permit the use of Poisson statistics.
equipped vehicles, or reduction of 61.8%. Damage figures for the vehicles which collided with cabs are not known. Because the Cab Co. is not at fault, injuries to persons other than the cab driver and collision damage amounts to other vehicles are not included in their records.

The results of the 11 month, 12.3 million mile test of a deceleration warning light system in natural driving conditions reported here indicate that a significant reduction in rear-end collisions and injury resulting therefrom can be achieved. During the experiment, the deceleration warning light prevented rear-end collisions to equipped vehicles by 5.4 collisions per million miles, reduced the number of cab drivers injured from such collisions by 1.02 injured per million miles, and reduced the cost of repairs to cab vehicles struck in the rear by $643 per million miles. These figures do not include the injuries and property damage prevented to the vehicles which ran into the rear of the cabs, nor do they include passenger injuries in the cabs. With the American public driving approximately 1,115,000 million miles each year (National Safety Council (30)), the potential reduction in personal injury and property damage from rear-end collisions is enormous. Thus a human benefit of significant proportions would occur if deceleration warning systems of the type herein described could be adopted by the automotive industry.

This quantitative experiment illustrates that it is possible to achieve results comparable to those obtained in the laboratory, provided cooperation can be had from the agencies, public and private, that are involved. The California Highway Patrol prepared a separate report to the Legislature of the State of California (31) approving the use of this system on all California vehicles. The California Legislature amended the California Vehicle Code to legalize the use of this type of deceleration warning system (Section 25251.1).

SUMMARY

Rear-end collisions and multiple car shock wave phenomena are shown to be caused by the human's inability to detect and track the deceleration of a lead-vehicle with sufficient speed and accuracy. To correct the problem, a stoplight was proposed which signals by frequency pulse and on-time coding the deceleration to the following driver in a nonlinear exponential manner.

An amber light, center mounted on the rear of several hundred San Francisco taxicabs, was designed to communicate information about the taxi's deceleration to following drivers. The light, activated by the use of the brake pedal, pulsed in a controlled fashion at a rate, duty cycle, and intensity which varied exponentially with a component of deceleration. A comparison of an experimental group (with the light for 12.3 million miles) with a control group (without the light for 7.2 million miles) revealed the light prevented 5.4 collisions, 1.02 cab driver injuries, and $643 of taxicab damage per million miles. The rear-end collision rate for the equipped cabs was reduced by 60.6% when compared to the rate for the concurrent control group of cabs.

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REFERENCES