Title
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This paper focuses on what benefits a longitudinal control system can be expected to render to the present highway system. There are three major reasons why longitudinal control should be expected to improve traffic flow and to reduce accidents.

(1) It may permit higher traffic densities with uniform spacing forming an even distribution with increased travel speeds and consequently higher capacity.

(2) It may reduce the rate of rear-end collisions that occur on urban freeways.

(3) It can provide increased stability in traffic flow (shock waves due to human response characteristics are the main cause in limiting traffic capacity on today's freeways.)

Today the increasing severity of the traffic problem could result into a chaotic situation, unless some radical changes are instituted beforehand. One such change, which would be at least a partial solution, is highway automation. Two important questions need to be addressed in order to assess the benefits from highway automation. First if a new technology such as longitudinal control is added to the existing DRIVER-VEHICLE-ROAD complex, will extensive modification of the flow pattern occur? and second, in case of a fully automatic control, what improvement will occur in terms of stability and capacity ?

In the following discussion, we review some implications of increasing the capacity by controlling the speed and spacing of vehicles moving on a roadway. When there is a continuous string of vehicles moving on a road, the capacity C of the roadway length is determined by the flow q which is the reciprocal of the minimum headway between vehicles following each other. For a given spacing between vehicles, this flow increases with velocity, and the standard equation of flow give the relation between capacity, headway, spacing and speed as follows:

$$q: \text{Flow} = 1/h = v/s$$

where, q = capacity
h= headway: time interval between two consecutive vehicles
v= speed: the time rate of change of distance
s= spacing: distance between two consecutive vehicle

Now if there is an attempt to improve q, using some technological developments of longitudinal control systems, it will be useful to analyze the different implications of operating these systems in the DRIVER-VEHICLE-ROAD complex. Any system for longitudinal control must be capable of coping with many different highway situations, mainly congested and inefficient roadways; furthermore, it must be introduced on a gradual basis so that it would be compatible with existing traffic at all stages for different levels of congestion and varying conditions. However, it is not very meaningful to just review the technology of a control system without addressing the fundamental questions of risk or "safety" and flow stability.

Two scenarios of special interest will be discussed. The first is the "brick-wall safety separation" case, in which a safe stopping distance for a following vehicle is provided if the lead vehicle stops instantly in its lane. The second is the " controlled acceleration/deceleration and stopping" case, which assumes that all vehicles travelling in a platoon can accelerate and decelerate identically and simultaneously so that no rear-end collisions will occur in case of braking by any one of them.

Scenario 1 :The Brick-wall Safety Separation Case

Safe car-following requires that vehicles be spaced far apart so as if the leading vehicle stops instantaneously, then the following vehicle should be able to brake to a safe stop. Today, the familiar spacing rule is one car length for every 10 mile-per-hour increment in speed. Thus cars must be spaced much further apart at higher speeds, producing a lower capacity per lane per mile. Obviously, it would be extremely desirable if we could permit closer spacing at higher speeds.

In such safe flow conditions, the minimum spacing consists of two components: one is a distance vr traveled by the following vehicle during time r, the reaction time required by the driver to react to the stopping impulses. The other is the actual braking or stopping distance given by:

$$v^2(c/f) \quad \text{or} \quad v^2/(30f)$$

where f is the coefficient of friction between tire and road surface and c is inversely proportional to the maximum rate of deceleration. If each vehicle allows this spacing, then the traffic flow is

$$q = v/s = v/(d_{min}+L)$$

where L is the average length of a car, and

$$d_{min} = vr + v^2(c/f)$$

or

$$d_{min} = 1.47vr + v^2/30f$$

This traffic flow has its maximum value at $v=[30f]^{0.5}$. It should be noted that the rate of flow is influenced by the PIEV time (perception, intelligence, emotion, volition) or reaction time r and the coefficient of friction f, but the optimum speed v is influenced by the coefficient of friction between tire and pavement.

Figure (1) give plots of the headway in seconds vs speed for different reaction times (0,...1.7sec). These values are chosen not as representative of common road properties but rather as extreme case (maximum coefficient of friction), in order that the qualitative features of the trailing vehicle may be exaggerated,

friction coefficient (f)	Speed (mph)							
	10	20	30	40	50	60	70	80
0.2	16.67	666.67	150.00	266.67	416.67	600.00	816.67	1066.67
0.25	13.33	53.33	120.00	213.33	333.33	480.00	653.33	853.33
0.3	11.11	44.44	100.00	177.78	277.78	400.00	544.44	711.11
0.35	9.52	38.10	85.71	152.38	238.10	342.86	466.61	609.52
0.4	8.33	33.33	75.00	133.33	208.33	300.00	408.33	533.33
0.45	7.41	29.63	66.67	118.52	185.19	266.67	362.96	474.07
0.5	6.67	26.67	60.00	106.67	166.67	240.00	326.67	426.67
0.55	6.06	24.24	54.55	96.97	151.52	218.18	296.97	387.88
0.6	5.56	22.22	50.00	88.89	138.89	200.00	272.22	355.56
0.65	5.13	20.51	46.15	82.05	128.21	184.62	251.28	328.21
0.7	4.76	19.05	42.86	76.19	119.05	171.43	233.33	304.76
0.75	4.44	17.78	40.00	71.11	111.11	160.00	217.78	284.44
0.8	4.17	16.67	37.50	66.67	104.17	150.00	204.17	266.67

Table 1. Stopping distances at different speeds

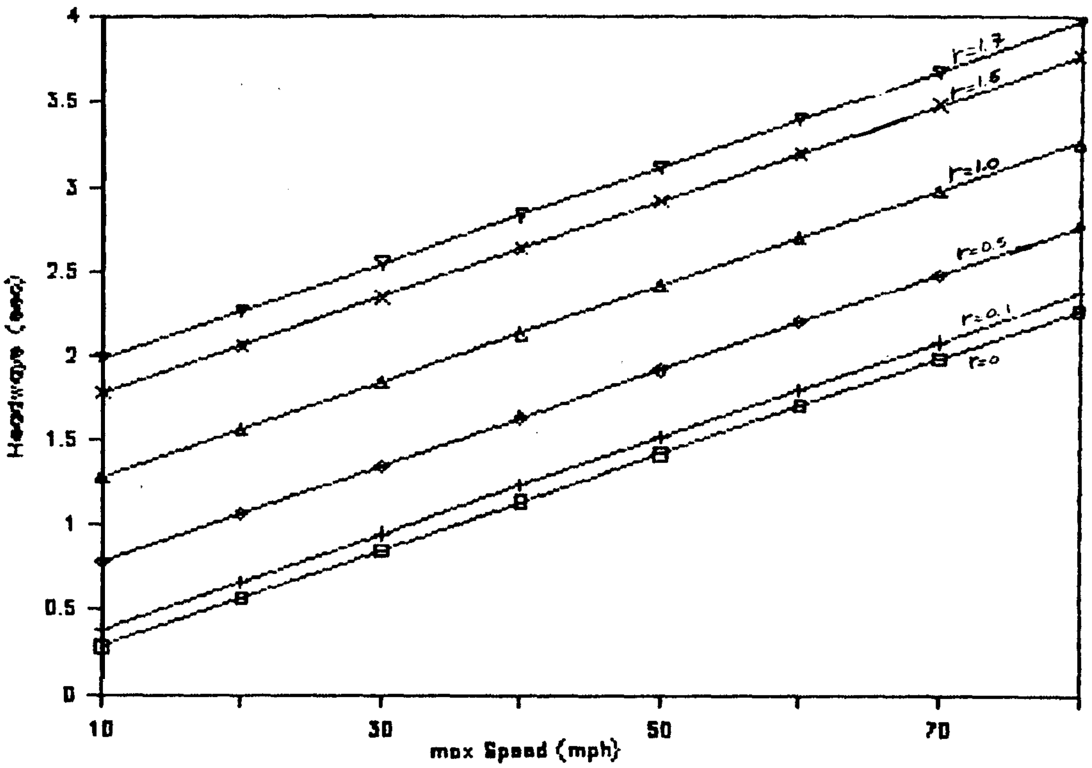

fig.1. Allowable speed at maximum coefficient of friction

From figure (1), it is quite obvious that in order to accept a reduction in headway (or increase in capacity) at speeds more than 50 mph, **a** decrease in reaction time must occur. For example, **a** maximum flow of 2,880 vehicle per hour per lane at a 50 mph will require that the reaction time be reduced to 0.1 seconds from its current value of 1.7 seconds.

These results also tell us that accepting a 33% increase in the capacity at **r=1.5 sec,** but still maintaining the safe distance according to the **"Brick-Wall"** safety requirement, will result in a decrease of velocity from 40 mph to almost 10 mph thus increasing the travel time unrealistically. In view of this situation it seems to be an open question whether the improvement in traffic flow is of greater interest to the individual driver than the trip time. Certainly, from the standpoint of the driver, it would not be desirable to travel at very low speeds so that both the safety and the capacity criterion are fulfilled. A maximum flow of 2,750 vph at a speed of 60 mph can only be obtained with a reaction time of 0.1 seconds, which cannot be realized without some powerful aided control systems, if not totally automated control systems.

However, if one looks at these results in a more realistic way, taking into account natural limitations such as road friction properties and car limitations imposed by available power, braking and steering performance, an average reaction time of 0.8 seconds appears to be more reasonable and desirable. If this reaction time could conceivably be made with a driver-aided control, then only 2,000 vph would be achieved at maximum speed of 45 mph. Thus, it is obvious that longitudinal control at these conditions will hardly bring any improvement in traffic capacity. On the other hand, by providing a more uniform response time to changes, this may reduce the generation and propagation of kinematic disturbances thus increase the stability of traffic flow.

It should be noted that human efficiency in controlling vehicles in high-density traffic is not outstanding. Increased capacity, which is usually attained by operating at high speeds with small spacings, cannot be safely maintained with individual driver control of vehicles. When a car-following control strategy is used, the danger of instability within a platoon of cars exists. That is, under certain conditions, perturbations in the velocity of a lead car can lead to propagation of kinematic disturbances within the platoon of cars following that lead car. If one can remove or effectively reduce the vehicle operating responsibility from the individual driver, then increased safety of operation and convenience may be attained. Furthermore, by providing a more uniform controlling scheme through the whole platoon, this may reduce the generation and propagation of kinematic disturbances and shock waves due to the instability of flow. It may be feasible that the whole problem of longitudinal control would be simplified by controlling the whole string of vehicles as an ensemble and not on the individual base. However this approach must be considered further to determine whether acceptable fail-safe system behavior can be achieved.

Scenario 2 : Controlled Acceleration/Deceleration and Stopping

Now if one looks at conditions where vehicles are travelling in a platoon, assuming that the trailing vehicle will duplicate the same behavior pattern as of the leading vehicle after a certain reaction time r, it is necessary that a continuous communication linkage between vehicles is available. The entire stream of vehicles would accelerate or decelerate simultaneously like a train, maintaining a constant spacing between vehicles. In case of an emergency stop, where the leading vehicle is forced to brake, a trailing vehicle has the capability to duplicate the deceleration profile of the lead car and stops after some lag time, which allows the driver to hit his brakes and lock the wheels. Thus all vehicles will come to stop after an original time lag, the reaction time. Assuming that there will be no rear-end collisions, the spacing of vehicles is

$$s = 1.47vr + L$$

and the traffic flow is

$$q = v/s = v/(1.47vr + L)$$

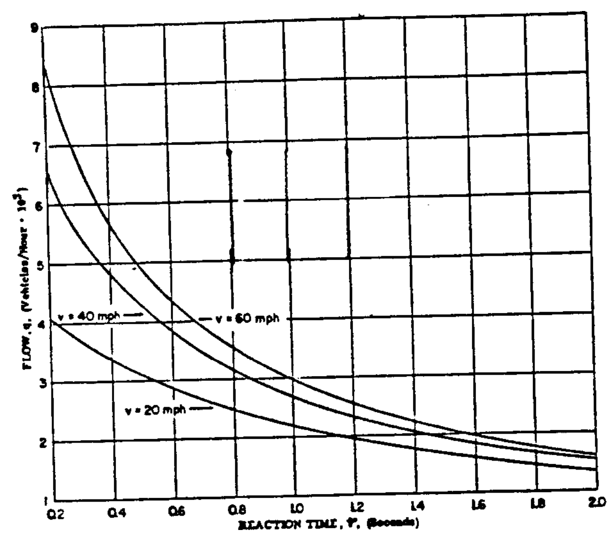

fig.2. __flow as a function of reaction time at various speeds__

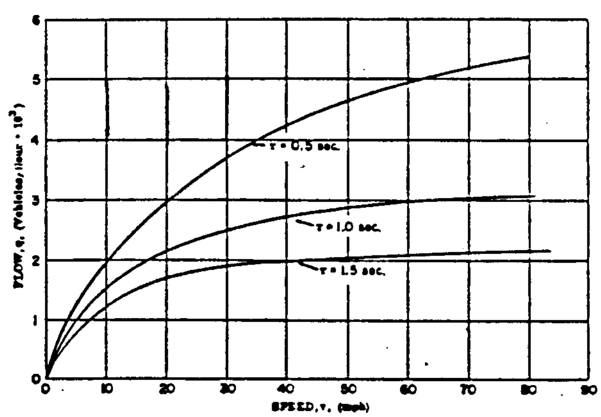

fig.3. __flow as a function Of speed for various reaction times__

Figure (2) and figure (3) show the influence of speed and reaction time on the flow **q.For example,** for vehicles travelling at a speed of 40 mph, a substantial gain in traffic flow of 75% may be obtained if a reaction time r is reduced from 1.5 seconds to 0.7 seconds: whereas, for vehicles exceeding 50 mph, an increase in traffic flow appears to be rather small if a reaction time r is reduced from 1.5 sec to 1.0 seconds. These results suggest that in order to obtain more substantial traffic flow, one may have to reduce reaction times to nearly the order of 0.5 seconds, which cannot be attained without giving the driver additional assistance by a suitable longitudinal control system. An adoption of very short reaction times, in the range of milliseconds, appears to be very appealing from a capacity point of view, however, it may have to require a fully automatic control system. If this is the case, the spacings of vehicles being

$$s = 1.47vr + L$$

can be reduced to few feet, and traffic flow would still be maintained even at high densities and reasonable speed. Thus the traffic flow will then be in the range of 10,000 vehicles per hour per lane. This figure is only mentioned to show the possibilities of having such a control, but it is still at this time an engineering judgement, which leads to say that tremendous research and development effort will be necessary before a satisfactory automatic system is in operation. This effort must involve not only vehicle and roadway control studies, but also an intensive investigation of the present driver-vehicle complex so that proper specification of the future control system components can be selected to interface with the present status.

Capacity Trend

The practical importance of these scenarios and conditions with respect to the feasibility of automation and longitudinal control show that the spacing-speed relation depends a great deal on the driving environment. A typical speed-capacity curve is shown in figure (4). If cars could be operated bumper to bumper, with some type of automatic system and no lags in the speed response, then capacity would continuously increase with speed, as shown by the straight curve.

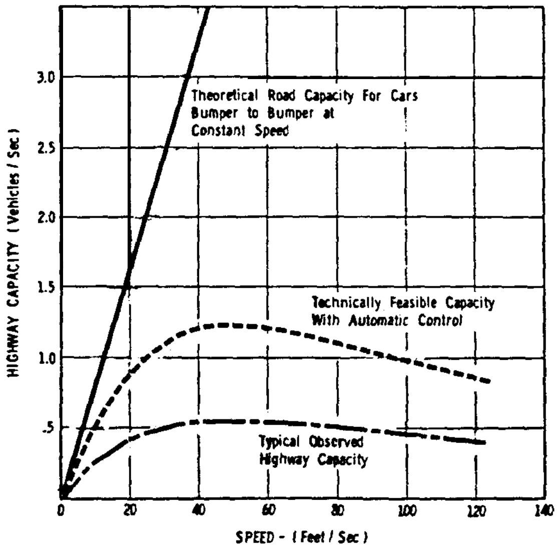

fig.4. speed - capacity curve

The difference between these curves evidently illustrates the maximum attainable capacity improvement. As a follow up to the second scenario, if an automatic control were to be implemented, then this must be self adaptable to the existing road properties and driving condition. Provided that this control becomes technically feasible, then capacity can be doubled as illustrated in figure (4). However, before the implementation of such a scheme would be feasible, some important questions should be investigated further. Such questions as how to control a stream of vehicles in case of an emergency situation and how to provide a stable **safe** flow with only the machine response time (of the vehicle control system) must be considered.

Conclusion

The foregoing discussion has served to indicate that a longitudinal control system, which might progress through the stages of driver aid to fully automatic, can contribute an important step forward to improve traffic and safety on our urban freeways. Summarizing, one may state that maximizing the lane capacity by enabling safe vehicle operation at short spacings may not be achievable by a driver aided controller unless creating the conditions needed for introducing a completely automated control system. This preliminary theoretical investigation suggests that application of spacing control on vehicles travelling in a platoon may not be effective as to improve traffic flow. A reduction in the driver's reaction time may lead to cause unpleasant rides and high accelerations which will endanger the traffic flow. The adoption of a control permitting a duplicate regime of acceleration, deceleration and stopping through the entire stream without any lag time or change in operaton variation could lead to obtain uniform spacing, eliminate rear-end collisions and increase the stability of flow with a potential increase in capacity.

Near future improvements in traffic flow can be achieved provided that a research program is launched to analyze the factors influencing its operation and the development of control system components to improve driver perception and vehicle reaction time. Ultimately, some automatic control systems seem both feasible and desirable for limited vehicle operation.