Effect of Trucks on Freeway Flows

ROBERT M. OLIVER, Institute of Transportation and Traffic Engineering, University of California, Berkeley, and
LEONARD NEWMAN, California Division of Highways, Sacramento

This paper reports on a study of the effect of slow vehicles or trucks on flow, density, and travel time characteristics of multiple lane freeways. It is assumed that trucks travel in the outer of two lanes at an average speed that is lower than the average speed of cars. Cars traveling in the outer lane queue behind slower moving trucks until they find suitable passing gaps in the inner lane. The formation and dissipation of these moving queues are discussed as a function of velocity, density, and passing criteria.

• SEVERAL theoretical and experimental studies of the effect of trucks were made on multiple lane roads during the summer months of 1962. The problem originated from the widespread belief that one truck, by virtue of its lower velocity, effectively replaces a large number of cars in the traffic stream. As a result, flow rates of the traffic stream may be reduced and delays may be added to the travel times of those cars unfortunate enough to get caught in queues that form behind the slower moving trucks.

In making mathematical models of the traffic stream, it was decided to study the interactions between two lanes of traffic where cars travel in the same direction in both lanes but at a lower speed in the outer lane than in the inner lane. It was also assumed that trucks traveled slower than cars and only in the outer lane; on overtaking a slow truck in this lane, a car could pass around it, provided there was a sufficiently large gap in the adjacent (inner) lane.

Earlier theoretical studies of the appearance of large gaps in the traffic stream by Weiss and Maradudin (1), Herman and Weiss (2), and Oliver (3) made it possible to calculate the probability that a car, caught behind a truck, could immediately merge into the inner lane and complete his passing maneuver. The major addition to earlier theoretical findings is (a) the introduction of simple speed assumptions for cars and trucks, (b) the experimental verification of these results in terms of freeway grade, and (c) numerical calculations of lane flow rates which would give a desired probability of being able to make an immediate passing maneuver. It was felt that quality of service could be specified in terms of this probability.

An important concept in all of these studies is the formation of blocked and unblocked periods in a traffic stream. Essentially, cars or trucks can be divided into two groups—those which are closer together than some constant (e.g., τ) and those which travel farther apart than this constant. By varying the size of this constant, different fractions of the car population can be included in one group or the other. Figure 1 shows an example of the blocked and unblocked periods in a traffic stream where all cars closer together than some constant amount lie within the shaded or blocked region. In the models, the large gaps or openings in the traffic stream represent those regions where passing and weaving from adjacent lanes can occur. It is even possible to include the wishes of different drivers by constructing several pictures of the traffic stream and assigning a distribution of values to the size of unblocked periods which will be accepted by a large sample of drivers.

Paper sponsored by Committee on Theory of Traffic Flow.

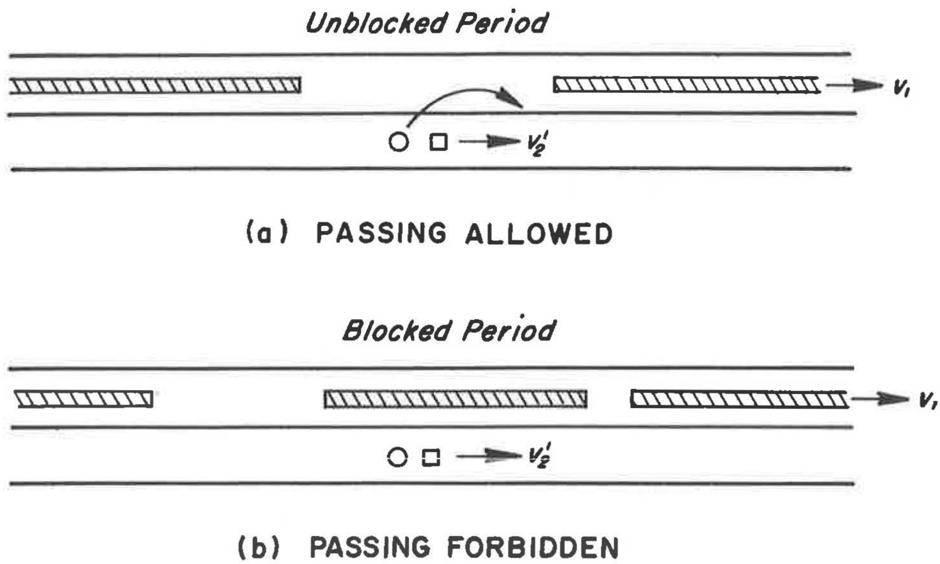

Figure 1. Blocked and unblocked periods.

The findings reported in this paper are primarily concerned with the probability that a single test car will or will not be able to find passing opportunity at an arbitrary point in time. There seems to be fairly general agreement that the probability of being blocked (i.e., not being able to make a passing maneuver) is directly related to acceptable flow rates along the highway. In some cases the probability of being blocked offers a quantitative measure of service of the highway. As more refined mathematical models are developed and experiments strengthen or refute earlier findings, changes can be expected in the specific conclusions obtained in this paper.

RELATIVE VELOCITY VS GRADE

The average speed of cars relative to trucks enters as an important parameter in the mathematical models. Fairly simple expressions were also found for relative velocity in terms of freeway grade. Assuming v_1 and v_2 ($v_1 > v_2$) are the constant speeds of cars in lane 1 (inner) and lane 2 (outer), if the truck velocity in lane 2 is v_2', the velocity of cars in lane 1 relative to trucks in lane 2 is $v_1 - v_2'$. The parameter

$$K_1 = \frac{v_1 - v_2'}{v_1} \tag{1}$$

measures this relative velocity as a percentage of lane 1 car speeds. In particular, the flow rate of cars in the inner lane measured by an observer moving with the truck is

$$\alpha_1 = K_1 \lambda_1 = \lambda_1 \frac{v_1 - v_2'}{v_1} \tag{2}$$

in which λ_1 is the flow rate in lane 1 measured by a fixed observer.

Experimental measurements of the parameter K_1 (Fig. 2) showed that it was a linear function of grade γ (i.e., $K_1 = a + b\gamma$), and for a large group of California data it was found that

$$K_1 = 0.30 + 0.075\gamma \tag{3}$$

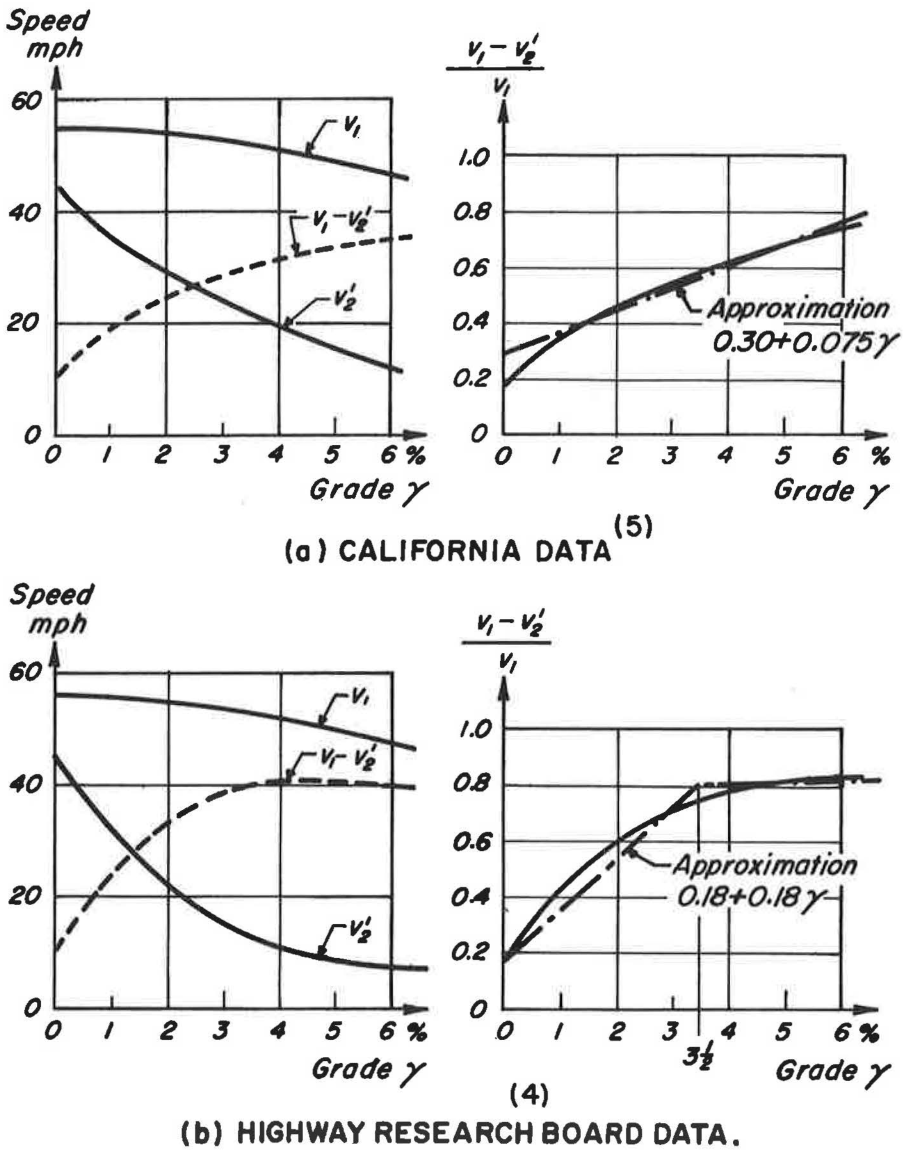

Figure 2. Vehicle speeds on grades: (a) California data (5), (b) Highway Research Board data (4).

Substituting Eq. 3 into Eq. 2

$$\alpha_1 = 0.30\lambda_1 + 0.075\gamma\lambda_1 \tag{4}$$

PROBABILITY OF IMMEDIATE PASSING

Simple expressions having been found for relative flow rates in terms of grade, equations that relate the probability of being blocked to the relative flow rates can now be found. If τ is the minimum passing headway required by a car in lane 2, a(t) is the probability density distribution of headways between cars traveling at speed v_1 in lane 1, and ν is the average headway, it can be shown that

$$U(\tau) = \nu^{-1} \int_{\tau}^{\infty} \int_{t}^{\infty} a(t)\, dt \qquad (5)$$

is the probability of not being blocked; i.e., the probability that a single test car can immediately pass around a slower moving truck in lane 2. If the specific assumption is introduced that intervehicle headways have a translated exponential distribution

$$\begin{aligned} a(t) &= 0 & 0 \le t \le \Delta \\ &= \frac{\alpha_1 e^{-\frac{\alpha_1(t-\Delta)}{1-\alpha_1\Delta}}}{1-\alpha_1\Delta} & \Delta < t \end{aligned} \qquad (6)$$

in which Δ is the minimum headway between cars, Eq. 5 gives

$$U(\tau) = (1 - \alpha_1\Delta)\, e^{-\frac{\alpha_1(\tau-\Delta)}{1-\alpha_1\Delta}} \qquad \Delta < \tau \qquad (7)$$

when the minimum acceptable passing gap is greater than the minimum headway, Δ, between cars. In the case of Poisson traffic in lane 1, $\Delta = 0$ and $U(\tau) = e^{-\alpha_1 \tau}$ which is simply the probability that the spacing from any point to the next car is greater than τ.

Eq. 7 can also be expressed in terms of the grade by substituting Eqs. 1 and 2 for K_1 and α_1:

$$U(\tau) = (1 - K_1 \lambda_1 \Delta)\, e^{-\frac{K_1 \lambda_1 (\tau-\Delta)}{1 - K_1 \lambda_1 \Delta}} \qquad (8)$$

As the flow rate of cars in lane 1 increases, the probability of finding an acceptable gap between cars (i.e., an unblocked period) becomes smaller. As the flow rate λ_1 approaches $(K_1 \Delta)^{-1}$ cars are spaced more regularly and closer to one another; as a result the probability of finding an opening approaches zero.

Recent experiments by Herman and Weiss (2) have shown that not all drivers will use the same minimum gap. In fact, the density distribution of minimum acceptable gaps can also be represented by a translated exponential function

$$\begin{aligned} g(\tau) &= 0 & 0 < \tau < T \\ &= (\nu_g - T)^{-1}\, e^{-\frac{\tau - T}{\nu_g - T}} & T \le \tau \end{aligned} \qquad (9)$$

in which ν_g is the average value of the distribution and T is the smallest gap acceptable by any driver on the road. Typical values for the flow rates these are T = 2 sec and ν_g = 5 sec.

Multiplying $g(\tau)$ by $U(\tau)$ and integrating overall values of τ gives the unconditional probability that an arbitrary driver will not be blocked by the adjacent stream. The mathematical result is

$$P_0 = \Pr\,(\text{not being blocked})$$

$$= \int_{T}^{\infty} (1 - \alpha_1 \Delta)(\nu_g - T)^{-1}\, e^{-\frac{\alpha_1(\tau-\Delta)}{1-\alpha_1\Delta}}\, e^{-\frac{\tau - T}{\nu_g - T}}\, d\tau$$

$$= (1 - \alpha_1\Delta)^2 \left[(1 + \alpha_1 (\nu_g - T - \Delta)\right]^{-1} e^{-\frac{\alpha_1 (T - \Delta)}{1 - \alpha_1 \Delta}} \tag{10}$$

The exponential term is similar to Eq. 7, obtained for constant gap acceptance criteria. As the relative flow rate increases, the denominator of the exponent decreases while the numerator increases; because of the negative sign in the exponent, the right-hand term becomes smaller.

The first factor in Eq. 10 can be rewritten in the form

$$\frac{(1 - \alpha_1 \Delta)^2}{1 + \alpha_1 (\nu_g - T - \Delta)} = \frac{\alpha_1}{(\alpha_1^{-1} - \Delta) + (\nu_g - T)} \cdot \frac{1 - \alpha_1 \Delta}{\alpha_1} \tag{11}$$

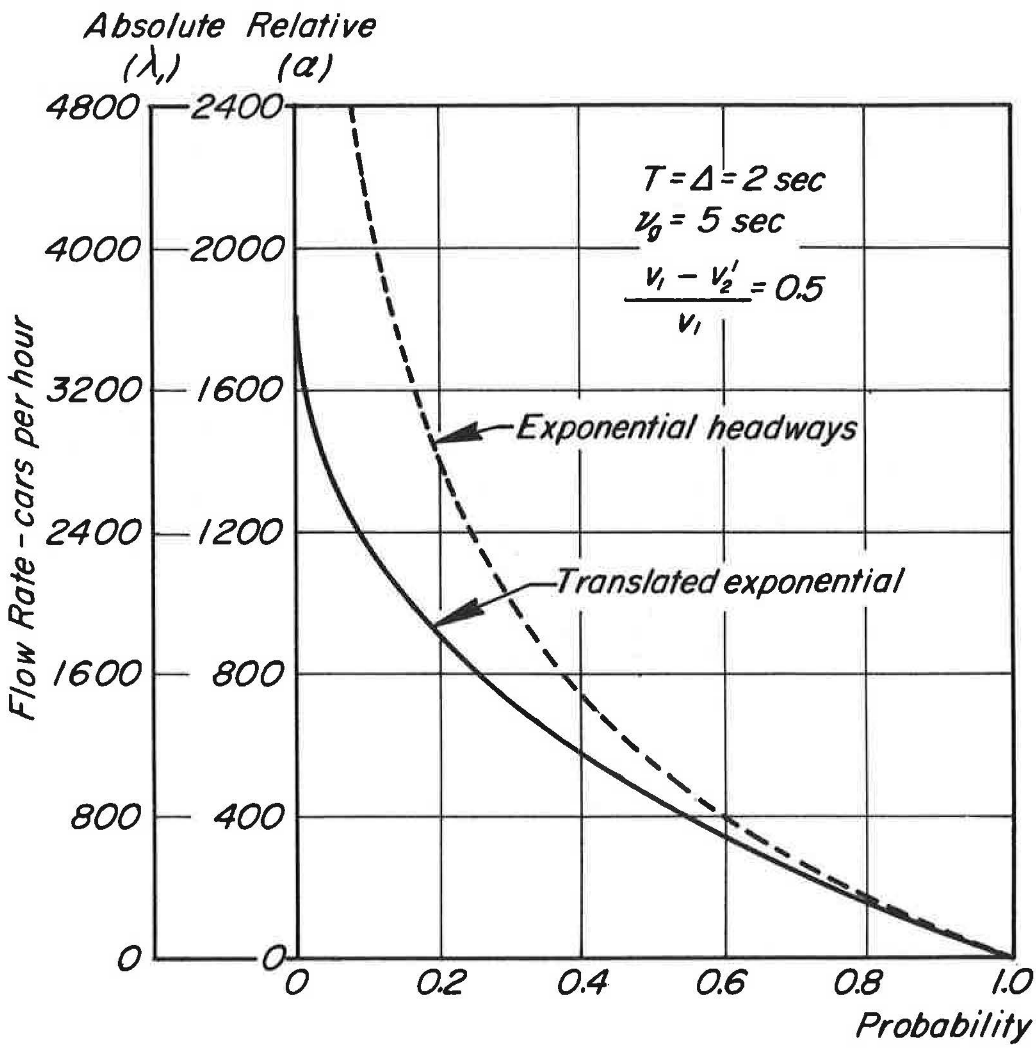

Figure 3. Flow rate vs probability of zero wait.

Because α^{-1} (>Δ) is the average relative headway between cars and ν_g (>T) is average desired gap, the fraction is always positive. As average spacings become larger than the minimum values, the variability of the distributions also increases, and the probability of zero wait decreases. The interpretation of this result is clear: as the driver demand for large gaps increases or as their supply in the traffic stream decreases, the probability of being blocked increases.

Experimental curves for low flow rates would probably lie below the solid line in Figure 3. For example, a flow rate of 400 vehicles per hour in the inner lane (measured by a fixed observer) gives about a 20 percent chance that a test vehicle in the outer lane is blocked behind a truck and must wait before passing can begin. In actual practice, this probability may be lower because vehicles may see the truck long before the passing maneuver takes place. An experienced driver in the test vehicle, on seeing the slower-moving truck, would move over into the inner lane before he became blocked. Thus, the probability of being blocked should also include the important effect of lane changing, which anticipates being blocked.

Again, the situations described only consider the probability of immediate passing for a single car that arrives behind a truck. Even when the possibility of queue formation behind the truck is included, it is still possible that this probability, P_0, represents the probability of not being trapped in the queue. If both lanes are traveling in the same direction, the service mechanism of the queue may be one known as last-come, first-serve. This explains the way in which cars at the tail of the moving queue get the first opportunity to use large openings in the adjacent lane and thereby preempt the service of earlier cars which have been waiting for gaps to appear.

On the other hand, if a first-come, first-serve priority mechanism which guaranteed the more democratic policy that the earliest cars in line get the first opportunity to pass were insisted on, the probability of immediate passing would be the product (i.e., the joint probability) of P_0 and the probability that, on arrival, the test car finds an empty queue behind the truck.

Some of the restrictions imposed on lane changing will be relazed in future works and the effects of queues in the outer lane will also be included.

REFERENCES

1. Weiss, G. H., and Maradudin, A. A., "Some Problems in Traffic Delay." Operations Research, 10:1.
2. Herman, R., and Weiss, G. "Comments on the Highway Crossing Problem." Operations Research, 9:6.
3. Oliver, R. M., "Distribution of Gaps and Blocks in a Traffic Stream." Operations Research, 10:2 (1961).
4. Huff, T. S., and Scrivner, F. H., "Simplified Climbing-Lane Design Theory and Road-Test Results." HRB Bull. 104, 1-11 (1955).
5. California State Division of Highways, Traffic Bulletin 2 (1961).