Effect of Trucks on the Urban Freeway

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An investigation was made into the effect of trucks or grades or both on urban freeway level of service. The primary parameter used was acceleration noise, a well-known and widely used traffic research parameter. A traffic stream composed of both cars and trucks was examined. A short section of the roadway was considered and the entering and leaving energy of the stream equated. Assumptions concerning the resistance to both motion and acceleration were also developed. For verification of the model developed, aerial time-lapse photographs supplied the bulk of the data. Utilizing 100-ft sections marked off on the freeway shoulder, speeds and accelerations for each vehicle photographed were calculated. From these, macroscopic speed and acceleration noise profiles were determined. The results of the research indicate that acceleration noise definitely increases on a positive grade of a rolling urban freeway. The amount of change is independent of the lane studied, however. Because of a wide variance in the percentage of trucks on the different lanes, the conclusion is that trucks do not affect the overall noise values under the conditions studied. This conclusion was strengthened by microscopic noise values and by an examination of typical time-space diagrams. Finally, conclusions were made concerning the type of parameter needed to ascertain the effect of trucks on the road user.

•THE TRAFFIC ENGINEER of today is currently profiting from an unprecedented 20-year boom in highway transportation. The end of World War II and gasoline rationing, the availability of mass-produced automobiles, and the general increase in living standards initially caused tremendous increases in transportation needs. Centralization of the population into large urban areas accompanied by increased industrial growth in the suburbs, primarily along freeways, has added to the problem of transportation. By the early 1950's cities had begun the development of freeway systems that were designed to provide uninterrupted traffic flow.

The number of automobile and truck trips has increased, and the desires of the motorists have changed. Drivers have begun to press for better driving conditions more in line with their powerful and sophisticated automobiles. The quality of the driving conditions now encountered by a motorist on a particular roadway at a particular time has become important to the traffic engineer, who has termed it "level of service". As a result, means of improving traffic conditions as well as increasing volumes are currently under study.

One factor that is now frequently considered as influencing the quality of traffic flow is the number of trucks or slowly moving vehicles or both in the traffic stream. Studies have been made to determine the influence of trucks on rural highway flow, but to date little work has been devoted to this consideration on urban freeways. The effect of trucks or grades or both on the level of service of urban freeways has not been widely investigated. This paper considers this problem area, in order that future driving conditions encountered by the urban freeway motorist may be understood and predicted.

Many parameters, such as Platt's "level of service index" (1) and Herman's so-called "acceleration noise" (2), have been advanced as a means of measuring the level of service of urban facilities. It is this latter parameter that was primarily used in the analysis reported herein.

By definition, acceleration noise, σ, is the root-mean-square of the acceleration of a vehicle. It has been shown by Dudek (3) that σ may be approximated by use of the formula

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$$\sigma = \left[\frac{(\Delta\mu)^2}{T}\sum\frac{1}{\Delta t}\right]^{1/2} \tag{1}$$

where

$\Delta\mu$ = speed change of a predetermined magnitude,
T = total trip time, and
Δt = time increment required for $\Delta\mu$.

The value of this parameter has been well established by Drew and Keese (4) and Drew and Dudek (5). Because it does measure to some degree the interactions between the driver, the road, and traffic conditions, numerous test runs have been made over various categories of roads both in the United States and abroad. Results of such tests indicate that σ may give a better measure of traffic conditions than travel and stopped times. More specifically, σ has been proven to be an excellent measure of the level of service of freeway flow.

MODEL DEVELOPMENT

Drew and Keese (4) and Drew and Dudek (5) have reported the reliability of considering the traffic stream as a one-dimensional, compressible fluid stream. If this analogy is to be true, the principle of the conservation of energy must be maintained.

The general form of the energy equation may be recalled as

$$\frac{W_1\mu_1^2}{2g} + \frac{W_1P_1}{\gamma} + W_1Z_1 + U_1 = \frac{W_2\mu_2^2}{2g} + \frac{W_2P_2}{\gamma} + W_2Z_2 + U_2 + \text{losses} \tag{2}$$

where the total head at section one equals the total head at section two plus any losses between the sections. The four terms that combine to make up the total energy at a section are the kinetic, pressure, elevation, and internal energies respectively.

In the foot-pound-second system, the units of each of these terms are foot-pounds (ft-lb). If the pressure energy, internal energy, and losses are all considered as a form of internal energy, I, then the units of I must be foot-pounds. Previous research has indicated that σ is a measure of I (5), or $I \approx \sigma$. If I is to be in foot-pounds, then

$$I = \text{foot-pounds} = \phi ML\sigma$$

where

ϕ = dimensionless constant;
M = mass, slugs;
L = length of section, feet; and
σ = acceleration noise, feet per second squared.

Dimensionally, then

$$I = \left(\frac{\text{lb sec}^2}{\text{ft}}\right)\left(\text{feet}\right)\left(\frac{\text{feet}}{\text{sec}^2}\right) = \text{foot-pounds}$$

A change I is then measured as

$$I = \Delta\phi ML\sigma = \left(\frac{W_1P_1}{\gamma} - \frac{W_2P_2}{\gamma}\right) + (U_1 - U_2) - \text{losses}$$

Combining and rearranging yields

$$\Delta\phi ML = (W_2Z_2 - W_1Z_1) + \frac{W_2\mu_2^2}{2g} - \frac{W_1\mu_1^2}{2g} \tag{3}$$

which states that a positive change in internal energy occurs when elevation or kinetic energy increases. If the section is short and traffic continuity is maintained such that $W_1 = W_2$ and $\gamma_1 = \gamma_2$, then we obtain

$$\Delta\phi ML\sigma = W(Z_2 - Z_1) + \frac{W}{2g}(\mu_2^2 - \mu_1^2)$$

or

$$\Delta\phi\frac{W}{g}L\sigma = W(Z_2 - Z_1) + \frac{W}{2g}(\mu_2^2 - \mu_1^2)$$

which yields

$$\Delta\phi\sigma = \frac{g(\Delta Z)}{L} + \frac{(\mu_2^2 - \mu_1^2)}{2L} \tag{4}$$

Because ΔZ is the change in elevation, it is approximately equal to $L\alpha$ (if α is small). By substitution we get

$$\Delta\phi\sigma = \frac{g}{L}(L\alpha) + \frac{(\mu_2^2 - \mu_1^2)}{2L}$$

and

$$\Delta\phi\sigma = g\alpha + \frac{(\mu_2^2 - \mu_1^2)}{2L}$$

If $\beta = 1/\phi$, then

$$\Delta\sigma = \beta\left[g\alpha + \frac{(\mu_2^2 - \mu_1^2)}{2L}\right] \tag{5}$$

This constant β allows flexibility in fitting a change in acceleration noise to a particular roadway and its profile.

If the speeds of the traffic stream as measured at the end points of the section are the same, the second term of Eq. 5 goes to zero and

$$\Delta\sigma = \beta g\alpha = \text{Constant } (\alpha) \tag{6}$$

This states that the change in acceleration noise is directly proportional to the grade under the conditions assumed.

The importance of this model lies in the fact that the weight of the vehicles in the traffic stream does not appear, either microscopically or macroscopically. It can be shown that the change in the velocity of a vehicle on a grade is only dependent on its capability of overcoming the component of the vehicular weight parallel to the grade. If, on short grades such as those encountered on urban freeways the capability of light and heavy vehicles to overcome this grade component is similar, the assumptions pertaining to the acceleration noise model may be met. Field studies were conducted to determine the actual conditions encountered.

CONSIDERATIONS CONCERNING STUDY DESIGN

In determining the scope of this research, various complexities regarding adequate samples were considered. Desirably, several urban freeway grades of varying magnitude and length should be studied. For each of these grades, then, the operating characteristics of trucks would need to be studied. Furthermore, any effect caused by a truck would depend on many variables, such as its weight, power, age, and mechanical condition. In addition, the position of the trucks in the traffic stream and their initial speeds would vary greatly.

All possible combinations of these parameters being possible, the number of conditions under which trucks could be observed was quite large. It was decided, however, to concentrate the study at one freeway site. The grade was to have a magnitude and length such that it would represent a typical grade on an urban freeway with a rolling profile. A number of sites in Houston and Fort Worth, Texas, were considered. In

addition, average values for each of the trucks were assumed. However, both macroscopic and microscopic speed analyses were conducted so that the variability of data resulting from the physical characteristics of the trucks could be examined.

DESCRIPTION OF THE STUDY AREA

The site selected for this study was on the Gulf Freeway in Houston, Texas. This freeway, carrying the designations of Interstate 45 and US-75, runs from the Houston central business district to the southeast, ultimately terminating at Galveston, Texas. The first freeway built in Texas, it has six 12-ft lanes with a 4-ft raised median. Basically an at-grade type, the freeway undulates over each of the major cross streets, causing a so-called "roller coaster" effect.

Because of associated research being carried out at the Telephone Road interchange, the inbound upgrade at this interchange was chosen as the specific study site. Approximately one-third of the study section was on a 1-degree horizontal curve, with the remainder on a tangent. Entry grade to the section was -0.3 percent and the maximum grade encountered within the section was +2.445 percent. A plan-profile of the study section is shown in Figure 1.

DATA COLLECTION AND REDUCTION

After selecting the upgrade to be studied, the nose of the Telephone Road on-ramp (inbound) was selected as a reference point. One hundred-foot stations were measured along the inbound shoulder in the outbound direction and marked with 6-in. pressure-sensitive striping tape. These stations were located as shown in Figure 1.

Continuous time-lapse photography was utilized to obtain data for all phases of this study. Because of the length of the study section, it was determined that these films should be made from an aircraft circling the study area.

Because it was necessary to be able to accurately classify the vehicles in the aerial films, a motion picture camera was mounted on the rooftop of a building adjacent to the inbound Telephone Road off-ramp. By synchronizing watches and using an exact filming schedule, simultaneous films were made from the ground and aerial locations

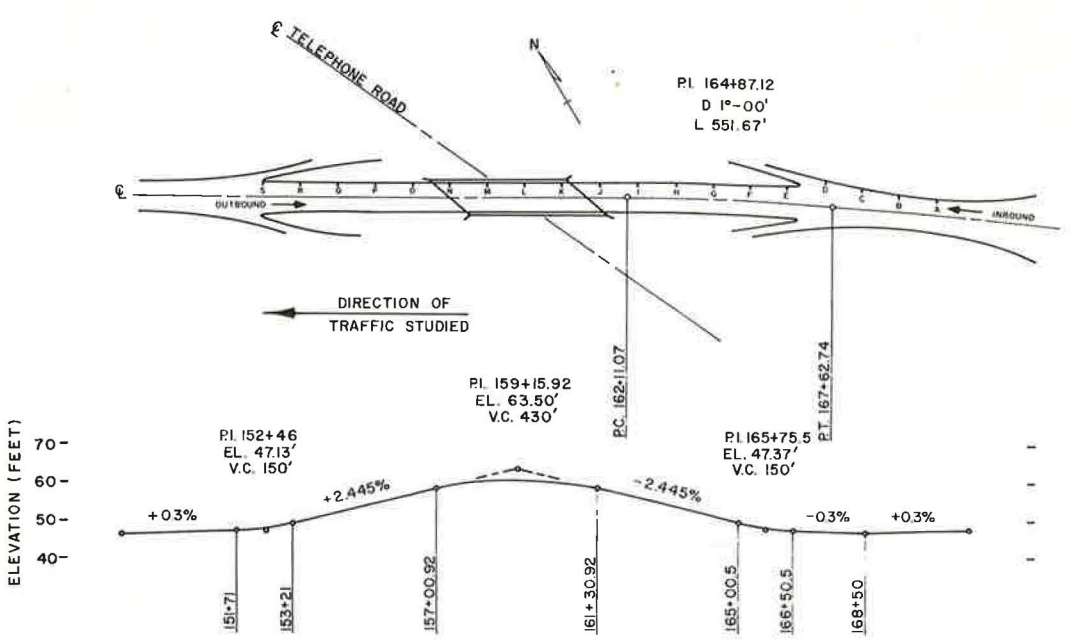

Figure 1. Plan-profile of Gulf Freeway at Telephone Road interchange.

using a 10-frame-per-second filming rate. The ground camera was directed so as to view the right-view quarter of the vehicles so that dual-tired vehicles could be easily classified as trucks.

Analysis of the 35-mm aerial films required a detailed study of every freeway vehicle. Included in each frame as it was photographed was a data board that included a film identification, date, military time clock, and frame counter. By projection of the film on an opaque screen, the location of any particular vehicle with respect to the striped ground stations could be determined. For each vehicle a record was made of the frame number when the front of the vehicle was most nearly opposite each station. As a result, the number of frames required to traverse each 100 ft could be determined. Knowing the film speed in frames per second, speeds and accelerations were computed for each vehicle as it progressed through the study area.

The data were organized and transferred onto IBM punch cards as they were obtained. An edit routine was programmed that checked the cards for errors in logic and key-punching. After editing, all data were analyzed through use of an IBM 7094 computer.

MACROSCOPIC ACCELERATION NOISE PROFILES

Through this analysis, speeds and accelerations of all vehicles passing through the study area were determined for each 100-ft section. For programming ease, particularly in subscripting variables, the letter nomenclature used for the study stations was dropped and the stations were numbered with consecutive odd numbers beginning with 1 at station A. These numbers are hereafter called section numbers.

To show grade correlation with these section numbers, Figure 2 has been included. Figure 2 merely exaggerates the profile as previously shown in Figure 1, and serves as an aid when visualizing the study section. It should be noted that the grade starts about section 9, and the crest of the vertical curve is located near section 23.

Utilizing a basic computer program, macroscopic values of accleration noise through each 100-ft study section were determined. A plot of these values by film and lane is shown in Figure 3. A discussion of the analysis of these profiles follows.

Because the acceleration noise model (Eq. 6) indicated a relationship between acceleration noise and grade, a step-down regression was performed with σ as the dependent variable and the first, second, and third powers of distance into the section as independent variables. Nonsignificant variables were eliminated until all remaining variables were significant at the 0.050 level.

Results of this analysis indicated that σ was dependent on location in at least eight of the twelve data sets. Further significance possibly could have been found by using

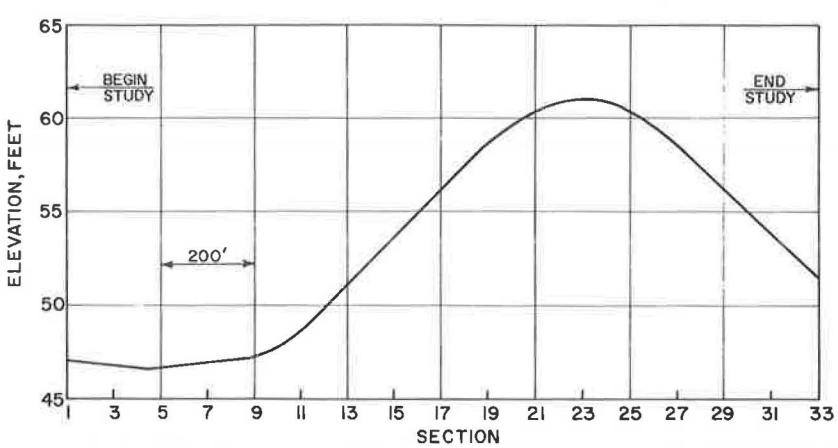

Figure 2. Profile of study area.

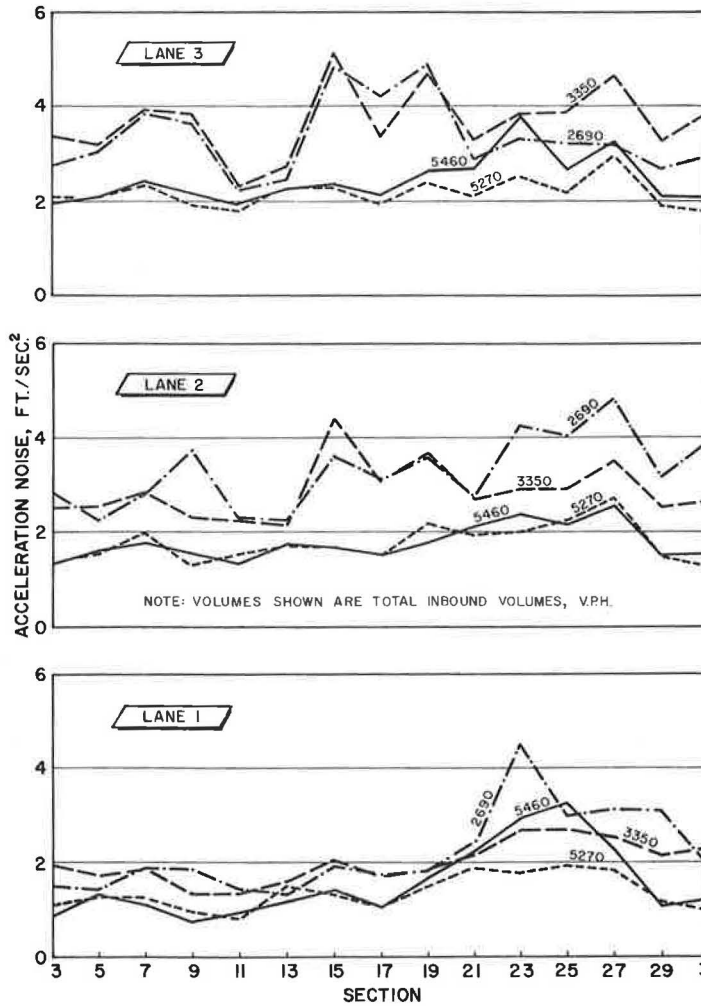

Figure 3. Acceleration noise versus section.

other transformations of the distance such as log x. It was only intended to show the significance of σ on x, however, because it was felt that samples taken on several grades of varying length and slope would be required to determine an empirical relationship of any value.

The model, or $\Delta\sigma$ = Constant (α), indicates that the slope of all of the acceleration noise profiles shown in Figure 3 should be equal. This relationship should be true regardless of the volume or lane considered. Visual examination of the profiles indicates an equality of slopes, especially during the higher flow conditions.

To test the model, a linear regression was made with σ as the dependent variable and distance into the section up to the crest (sections 3 to 23) as the independent variable. Using the F-test for the equality of regression line slopes as outlined by Ostle (6), all acceleration noise profiles were seen to have the same slopes at the 95 percent confidence level. This was true for all volumes taken together, and for the higher flow conditions only. In other words, $\Delta\sigma$ was equal in each noise profile.

MACROSCOPIC SPEED PROFILES

Having thus verified the model, an investigation was made into the assumptions inherent in the model. These assumptions were based on the premise that the speed

characteristics were similar for all vehicles—that is, that trucks had enough reserve power while cruising at normal freeway speeds to overcome the grade component of weight without a decrease in velocity.

By averaging the speeds for all vehicles for each film and lane, speed profiles were developed (Fig. 4). Because speeds were computed by section and all lane changes

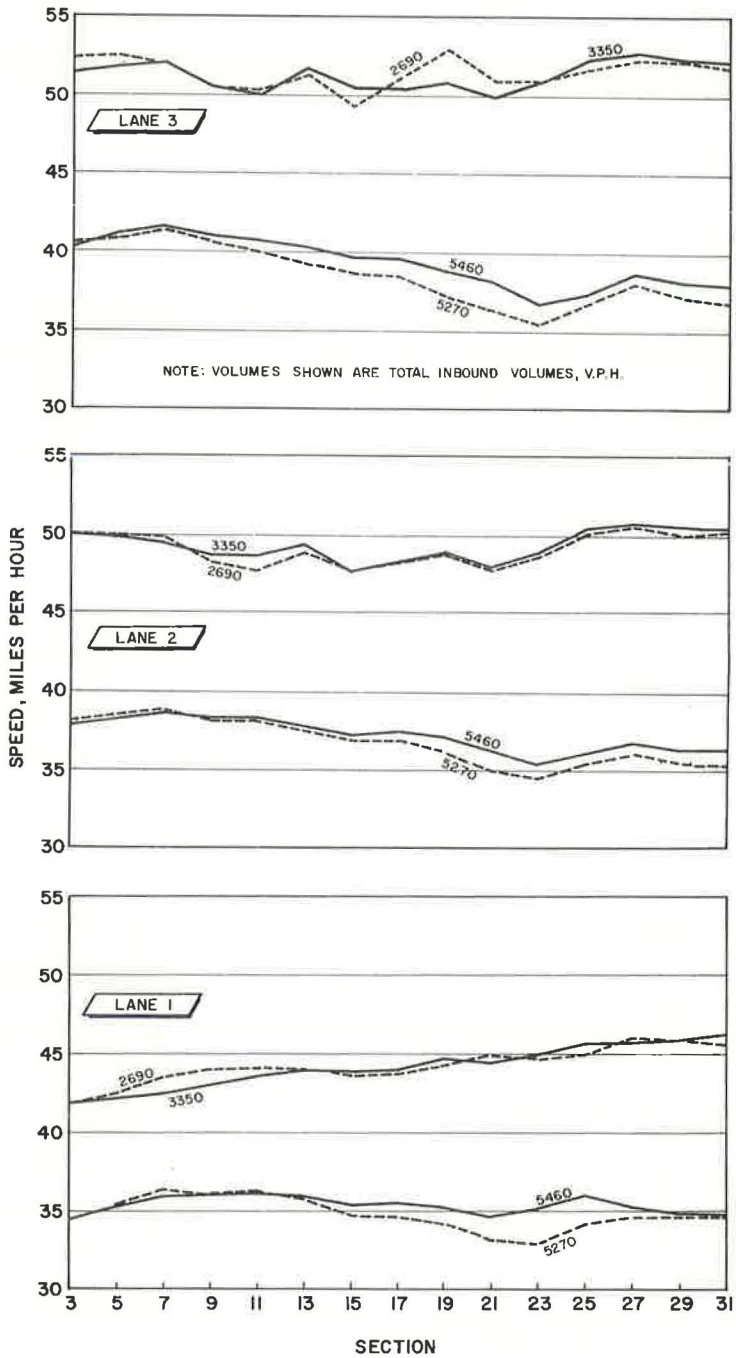

Figure 4. Average speed profile by lane.

considered, this figure reflects all vehicular speeds except those during the 100-ft section in which each lane change took place.

As shown on the speed profiles, all lane speeds tended to decrease during the peak flow periods. However, lane 1, with the higher truck percentage, shows a decrease of only some 2 mph on the grade, whereas lanes 2 and 3 decrease approximately 3 and 5 mph respectively.

Off-peak data showed little, if any, change in overall speed for vehicles on the grade for lanes 2 and 3. Lane 1, however, indicated a definite speed increase obvious through the entire study area. A leveling off of the lane 1 speeds appeared to be taking place on the downgrade, but was not pronounced enough for identification. It was concluded at this point that speed decrements on the grade, if any, were of less magnitude for the lane 1 traffic stream.

Truck volumes and percentages were also calculated for each of the data sets. As expected, truck volumes were higher in lane 1 than in lanes 2 and 3. Lane 1 truck percentages ranged from 4.5 to 10.0, whereas lane 3 ranged from 0.6 to 3.1. Thus, speed decrements were judged not to accompany the lane with the highest percentage of truck flow.

MICROSCOPIC SPEED AND ACCELERATION NOISE PROFILES

Because regression analyses indicated some increase in σ as vehicles traverse the study section up to and across the crest of the grade, a cause for this increase was sought. As an aid in examining the individual vehicular contributions to the noise parameters, two additional programs were developed.

The first of these determined the space and time headways of each vehicle as it entered the study area, as well as the 5-min flow rate in which it was operating. This program also determined σ for each vehicle over the 1,600-ft study section. By studying this output, changes in the magnitude of σ before and after tractor-trailer trucks were noted.

To determine the influence of these particular trucks on the stream, the program was modified to output speed and acceleration profiles of each truck. Examination of these profiles revealed a finding that indicated the validity of the assumptions made in model development. Virtually all tractor-trailer vehicles maintained or increased their speed as they passed through the study area, and no deceleration was found that could be attributed to the grade. This fact, examined in light of the accuracy of the data as previously discussed, was not in keeping with average results for average trucks as reported in the 1965 Highway Capacity Manual (7). The Manual indicates that an average truck on a multilane freeway grade of 2½ percent loses about 3 mph within 500 ft at an initial speed of 40 mph. However, the magnitude of this expected loss in speed is admittedly small, and could be lost very easily in the variability of the available data.

At this point, a time-space diagram of each traffic stream under study was machine-plotted. Each truck, tractor-trailer and otherwise, was identified on these plots, and the speed profile studied. At this point, it was conceded that, for the grade in question and under the traffic volumes filmed, trucks were able to maintain (or increase) their speeds so that the traffic stream should not be disrupted because of their speed characteristics.

As mentioned, however, some variation in the magnitude of σ before and after tractor-trailer trucks (and other trucks as well) was noticed. After determining from the time-space plots queues of vehicles before and after trucks, an average value of σ for each queue was determined. In order for the computed noise values to represent the effect of the trucks, not all of the trucks were analyzed in this manner. For example, if a truck was constrained by the vehicle in front of it, the average noise for the queue following the truck would not be a true reflection of the truck effect, but the effect of some other vehicle. Two such computation are given in Table 1. The results of some additional comparisons are given in Table 2. Note that, in each instant, σ was relatively high for the queue preceding the truck and low for the queue following. In most instances σ was lowest for the truck, indicating a smooth speed profile throughout the study area.

TABLE 1

TABULATION OF ACCELERATION NOISE BEFORE AND AFTER TYPICAL TRACTOR-TRAILER TRUCKS

Lane Data	Lane Rate of Flow	σ for Queued Vehicles	Average σ for Queue
Tractor-trailer truck			
Film 1, lane 1	1,740	2.35	2.46 before truck, 1.69 after truck
		2.23	
		2.93	
		2.33	
		1.03	
		1.64	
		0.16	
		0.50	
		2.65	
		1.93	
		2.10	
		1.66	
Film 1, lane 2	2,364	7.44	5.78 before truck, 2.38 after truck
		6.18	
		3.73	
		2.04	
		3.66	
		2.09	
		1.98	
		2.83	
		1.63	
		2.10	

TABLE 2

ADDITIONAL AVERAGE VALUES OF σ FOR QUEUED VEHICLES BEFORE AND AFTER TRUCKS

Film	Lane	σ, Queue Before Truck	σ, Queue After Truck
1	1	3.01	0.89
1	1	2.82	2.39
1	1	2.94	2.22
2	2	2.12	1.62
2	2	3.38	2.35
3	1	4.10	2.13
3	2	4.52	2.91
4	2	5.48	2.91

TIME-SPACE DIAGRAMS

After completing the microscopic analyses, time-space diagrams for all data were studied in detail. Sections were then isolated that illustrated some facet of the operational characteristics or problems encountered in the research. No attempt was made to weight one type of situation more than another. Four diagrams illustrating points of interest are included herein.

An explanation of these diagrams is in order. Vehicles in the particular lane being illustrated are plotted by a solid line. If a vehicle changed lanes, the plot is dashed when it is in the adjacent lane. Disappearance of a vehicle indicates that a vehicle moved two lanes over from the lane being plotted. For example, a vehicle starting out in lane 1, then changing to lanes 2 and 3 is, on a lane 1 plot, plotted as a solid line, dashed, then blank. No attempt was made to separate lane changes on lane 2 plots, with dashed lines indicating changes to or from lanes 1 and 3.

Figure 5 shows perhaps the most common idea of the behavior of trucks on grades. Each of the tractor-trailer units shown was traveling at a speed less than that desired by most of the cars in the stream. As a result, large gaps appeared before these vehicles at the crest of the grade. Behind the trucks, vehicle headways tended to decrease, with some changing of lanes evident.

Note that the speed of each truck was virtually constant. In fact, slight increases in speed (as measured by the slope of the line) were evident. An additional point of interest is that the second truck driver actually had no opportunity to increase his speed because of the preceding car. Therefore, while the queued vehicles behind the truck

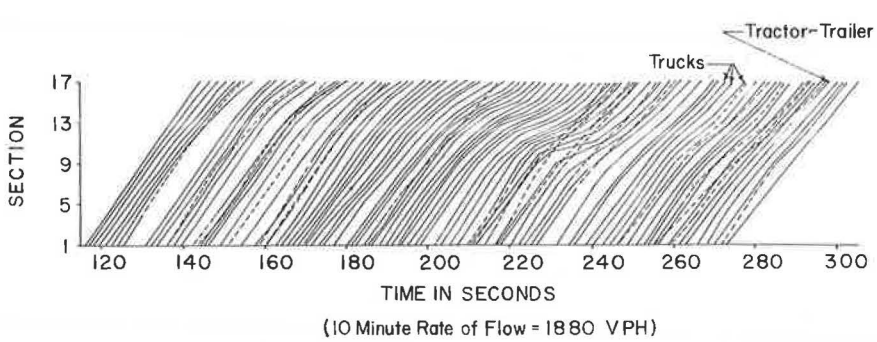

Figure 5. Time-space diagram from film 2, lane 2.

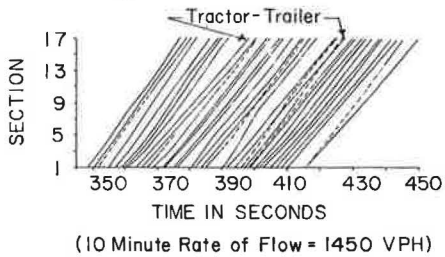

Figure 6. Time-space diagram, lane 1 (350-450 sec).

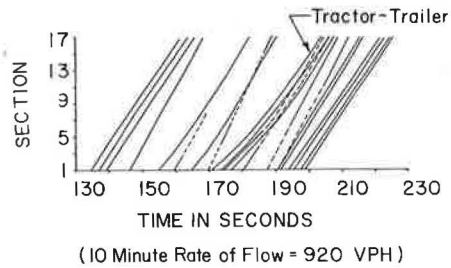

Figure 7. Time-space diagram, lane 1 (130-230 sec).

were being hampered by "that truck", the actual problem vehicle was a slower moving car.

Several shock waves were evidenced as the data were being analyzed. One of the more serious ones is shown in Figure 6. The origin of this shock wave is not known, but it is seen to begin or back into the study area at the upper left of the plot. Prolonged by a heavy flow rate, the wave eventually caused rapid decelerations near the crest of the hill. A 5-sec gap decreased the intensity of the shock wave, which was dampened even more by three trucks moving through the system. The passage of a tractor-trailer unit, however, removed virtually all traces of the disturbance. It is not evident in the plot as shown, but flow after this remained smooth and stable.

The time-space diagram for the tractor-trailer unit shown in Figure 7 is familiar to those personnel engaged in ramp control research on the Gulf Freeway. Ramp and acceleration lane designs on this facility are such that many vehicles are forced to enter the freeway at greatly reduced speeds. Furthermore, for this roller-coaster-type design, on-ramps are in many instances located just prior to upgrades and vehicles are forced to accelerate up to freeway speeds while on the grade. The acceleration capabilities of many loaded trucks thus cause profiles as shown in Figure 7.

Even though this vehicle had the capability of accelerating from 22 mph up to 42 mph through the section, severe conditions might have resulted if this had occurred during the peak flow period. A car obviously would have been able to accelerate more rapidly, causing less disturbance. In this case, lane changes and large headways caused this particular truck to present no operational problems.

Consideration of the problems caused by slow-moving vehicles of any type suggested that Figure 8 should be included. Vehicle A was a car that maintained a speed less than

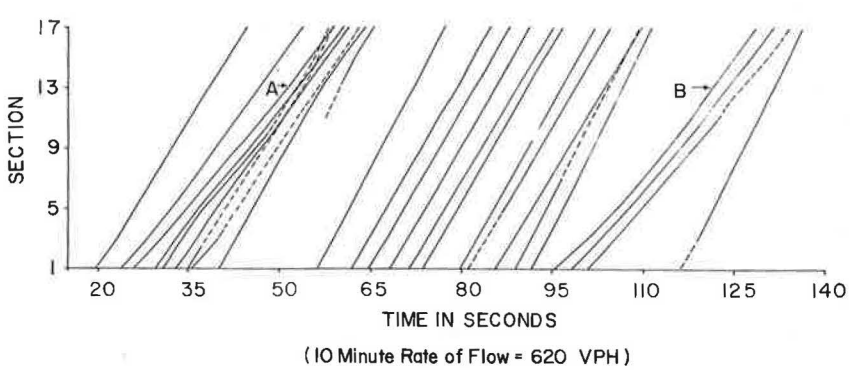

Figure 8. Time-space diagram from film 4, lane 1.

the prevailing lane speed. As can be seen, three lane changes resulted as well as a slowing down of at least four other cars. No indication is evident that the vehicle was forced to this speed. Vehicle B was a tractor-trailer unit that was also traveling slower than the prevailing lane speed. In this instance, B caused no problems, but had it been in the position of A, quite similar conditions to those described above would probably have occurred.

DISCUSSION OF RESULTS

As motorists drive over a given section or roadway, their vehicular speeds are subject to considerable variation. Not only will the speeds between vehicles vary, but each driver will vary his speed as he progresses. Although all the reasons for these speed differences are not known, it has been recognized that they may be physical or psychological, tangible or intangible (8).

When driving at a speed suited to the driver's mood and the surrounding traffic conditions, particularly on a level freeway, the instinctive feeling of many motorists when approaching a grade may be to press down on the accelerator. Although no research was conducted in specially equipped vehicles capable of detecting this movement, many persons have stated to the author that this typifies their actions.

The results of this type of driving action were observed repeatedly while studying in detail the time-space profiles of well over 3,000 vehicles. As observed from the time-space plots, many trucks appeared to be decelerating while moving up the grade, but in reality the vehicles immediately around the trucks were slightly accelerating. In most instances the speed of the trucks was quite steady as they passed through the section.

It will be recalled that in the derivation of Eq. 6 an assumption was made concerning the speed of vehicles. Certain terms were eliminated by the assumption that the speed of the traffic stream was relatively constant up the grade. This finding relating to the truck speeds indicates that this simplifying assumption is a reasonable one. The reason for this maintenance of speed appears obvious. Trucks operating on an urban freeway under average stable flow conditions are not operating at maximum power. The excess power available to each driver is therefore available to overcome the increased gradient resistance, thus resulting in no appreciable speed changes.

This finding was further substantiated by a study of the macroscopic speed profiles shown in Figure 4. The overall speed changes were not great, but they were slightly positive under off-peak conditions. Where motorists drive in peak periods with more attention given to the traffic around them and, in general, disregarding the roadway profile and its relationship to the flat, surrounding terrain, speeds were seen to decrease slightly. From these speed profiles it is seen that, if the automobile driver has sufficient headway as he sees a grade approaching, he tends to compensate for an expected speed loss, thus at least maintaining his speed. To fully verify this occurrence, additional data collected from other grades would be necessary.

Many, if not most, freeway drivers presuppose that trucks cause undesirable disturbances in the traffic stream. Because acceleration noise measures speed disturbances, any such action by trucks should result in an increase in this parameter. Furthermore, because the outer lane carries the highest percentage of trucks, this influence should be noted most in that lane. In analyzing the acceleration noise profiles shown in Figure 3, however, the most obvious feature is the stability of lane 1 flow compared to lanes 2 and 3. Noise values in lane 1 under widely varying volumes are relatively the same, with a general increasing trend as the crest of the grade (section 23) is reached. Volume levels do not separate these profiles into high and low volume groups, and large fluctuations in the profiles are noticeably absent.

Lanes 2 and 3, however, do not follow this trend in that the lower volume profiles are higher in magnitude. Large fluctuations in σ are also apparent at the lower volumes, reflecting again the desires of the driver to compensate for grade by accelerating, rather than by maintaining a constant speed over the grade.

Volume segregations on the lane 2 and 3 profiles are to be expected. For the inbound volumes of 5,460 and 5,270 vph (vehicles per hour), the speed profiles

in Figure 4 range between 35 and 40 mph. On the other hand, speeds from 48 to 52 mph are noted for volumes of 3,350 and 2,690. As derived and confirmed by Drew and Dudek (5), minimum acceleration noise occurs at about 40 mph; thus, further proof of the validity of these data is offered.

It has been shown by regression analysis that σ was dependent on distance into the section. As can be seen from Figure 3, this dependence is quite apparent for peak period flow. From values of approximately 1.0 for lane 1, 1.4 for lane 2, and 2.0 for lane 3, σ increased smoothly up to average values of 2.5, 2.7, and 3.0 ft/sec^2 respectively.

Truck percentages were determined to be quite small for lane 3 during the peak flow period. In fact, during the two filming periods in the peak, no tractor-trailer units were observed in this lane, and a total of only three vehicles classified as trucks were observed. The increase in acceleration noise, particularly on this lane, is therefore seen to reflect the characteristic noise of a stream of cars passing over a grade.

A study of the change in acceleration noise for each of the three lanes indicated that the change in σ was equivalent for the three lanes. Because the truck percentages over the lanes varied widely, the validity of Eq. 6 is proved, and, thus, the change in acceleration noise is a function of the grade and not of the percentage of trucks operating in the lane.

One word of caution must be included at this point to prevent incorrect conclusions concerning the effect of trucks. Although it is true that the vehicles directly behind the trucks tended to have low values of σ, those in front had high values of σ. Macroscopically, the change in σ, or $\Delta\sigma$, was shown to be the same in all lanes. Thus, although trucks did not improve the flow, they did not cause an increase in the average value of $\Delta\sigma$.

Again referring to Figure 3, the acceleration noise appears to be higher in lanes that had the lower truck percentages. This can be attributed to the fact that the left-hand lanes are conventionally used as passing lanes, and the passing maneuver will involve accelerations and decelerations, thus increasing σ. Therefore, the author concludes that the effect of the trucks should be given by the change in σ, and not its magnitude.

Trucks and Automobile Drivers

The author has been offered several suggestions by his colleagues as a result of the findings presented herein. Perhaps the most striking is one offered in jest. This proposal was that a large fleet of trucks might someday be stationed at the outskirts of a city near the freeway. If no heavy vehicles were observed during the morning peak flow period, trucks would be arbitrarily injected into the traffic stream in order to improve the level of service. Obviously this is a major extrapolation of the data presented herein. However, if conditions of flow are much better behind trucks, and if trucks do maintain a more constant speed, the question of "What's the problem?" is surely in order. After studying all the time-space diagrams in this research, several hypotheses are offered that might answer this question in part.

In those diagrams vehicles were seen to pass trucks on the grade even though the trucks were maintaining the average speed of the lane. Other vehicles tended to queue up behind trucks, awaiting their chance to pass and move to a position where they evidently felt more free to "jockey" for speed and position. In other words, automobile drivers were not content to drive behind a truck, which probably would have ensured them of a smoother journey.

Perhaps one reason for this driver feeling is the fume problem experienced when behind certain diesel-powered vehicles. An even better reason put forth by many drivers is that the restricted sight distance is annoying and dangerous. Much of the answer, however, possibly relates to the vagaries of man, who has always tended to be capricious when placed in a man-made environment such as the automobile and the traffic stream. Uncertainties surrounding the "monstrous" truck—"Will he swerve?" "Will he tip over?" and the like—all cause the average motorist to avoid it as if it were the plague.

This type of psychological thinking was also observed by Podesta (9). He stated that, from his observations, large trucks seemed to be a "rather important cause of disturbance for automobile drivers". Although he had no data to verify his comments, he surmised that this disturbing effect was due to noise and fumes, restriction of sight distance, and sensitivity of trucks to grade changes. Because the data presented herein do not support this latter supposition under conditions of short, low grades, his comments relative to the motorist's irritations have become even more important.

Of course, instances do occur where slow-moving trucks enter the freeway just prior to grades and cause a problem. At times of operational breakdowns when flow becomes unstable, the accelerating capability of some trucks is also a problem. As pointed out, however, slow-moving cars also present the "moving bottleneck" problem. Evidently drivers remember the problem trucks much longer than the problem cars, and drive accordingly.

CONCLUSIONS

Before drawing any conclusions from this research, the author would again like to emphasize the limitations of the study. The data were all collected at a single freeway site, and thus no variations due to location of the facility or varying geometric features were obtained. It is felt, however, that the grade at this site represents the average magnitude and length of grade encountered on a rolling freeway. Because of this, results are considered applicable to many similar grades on various roller-coaster-type freeways.

With these limitations in mind, the following findings may be listed:

1. During conditions of light flow, i.e., excluding peak periods, automobiles tend to accelerate up moderate urban freeway grades. Trucks tend to maintain a constant speed on these grades so long as they are not constrained by other vehicles.
2. Conventional acceleration noise increases on a grade. Furthermore, the increase in acceleration noise is independent of the percentage of trucks in the traffic stream. Because this parameter has been related to the jerkiness of flow in a traffic stream, an increase in σ is undesirable. It is concluded, then, that urban freeway grades are undesirable from a level of service standpoint.
3. The acceleration noise of a truck and vehicles immediately following the truck are appreciably less than corresponding values for other vehicles. Furthermore, trucks tend to stabilize flow and suppress shock waves because of the driving characteristics of truck operators.
4. Poorly designed ramps and acceleration lanes, particularly those located just prior to an upgrade, present special geometric problems. Slowly accelerating vehicles often cause undesirable operations, possibly resulting in a breakdown of stream flow.
5. The parameter called acceleration noise, although useful in grade computations as shown in the third finding, is not adequate to measure the effect of trucks on level of service. Some quantified value reflecting the many vagaries of human nature would be required, necessitating a human factors research study.

The following recommendations are offered as a logical follow-up to these findings:

1. Research efforts should be continued in studies relating to stable flow operating conditions. Because trucks in general do not cause serious problems as long as stable flow conditions are maintained, this recomendation appears to be an obvious requirement.
2. The design and location of freeway entry points must be considered not only from the level of service encountered at the merge area, but also from the level of service to be expected downstream. For example, inadequate acceleration lanes should never be built and marginal ones never located just upstream of a positive grade.
3. Research should be considered that would allow a quantification of the dependency of $\Delta\sigma$ on grade. This would necessarily entail research involving several grades of varying magnitude and length on different freeways.
4. Indications are that the physical effects of trucks under stable flow conditions, as measured by acceleration noise, are not disruptive to the flow conditions. It is recognized, however, that this is not the belief of the general driving public. Thus,

future research studies attempting to quantify the effect of trucks on the traffic stream should consider including a human factor analysis of automobile drivers.

5. Consideration should be given to depressed (or elevated) freeways from a level of service point of view. We should consider not only certain aesthetic principles such as noise and view, but also the operational problems on the proposed freeway itself. In addition to operational advantages already claimed for depressed profiles, this study indicates that the overall level of service would be improved by removing the "roller coaster" effect of present designs.

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Discussion

JOHN J. HAYNES, University of Texas at Arlington—The author has carried out an interesting research study involving an approach that is unique. The study actually centers around the attempt to utilize acceleration noise as a possible means of identifying the effect of trucks on freeway traffic flow. Acceleration noise has been used in studies to identify the level of service of freeway flow. However, it is doubtful that this paramater is an "excellent one" in this respect. As outlined in the 1965 Highway Capacity Manual, the level of service is identified by freedom to maneuver, by speeds that can be attained, and, most graphically, by the density of the traffic stream itself.

The mathematical relationship that was to be utilized in this research states that the change in acceleration noise is directly proportional to the highway grade, and is derived utilizing several simplifications including the assumption that the density of the traffic stream will not change and that the speeds of the traffic stream at the end points of a section are equal. Thus, the model indicated that for some specific roadway grade, σ, the change in acceleration noise, $\Delta\sigma$, would be directly proportional to that particular grade and independent of such things as traffic volumes and percentage of trucks.

The study site involved in this research was a single-crest vertical curve on the Gulf Freeway with a plus $2\frac{1}{2}$ percent grade of about $\frac{1}{8}$ mile followed by a minus $2\frac{1}{2}$ percent grade of equal length. This research did not include a study of several urban

freeway grades of varying magnitude and length, and thus the validity of the model, $\Delta\sigma = K\alpha$, was not evaluated.

It was not stated just how many individual vehicles were traced for the purposes of this study nor was an error analysis discussed concerning the study methods involving both recorded actuations from pressure-sensitive striping tape and continuous time-lapse photography from a circling aircraft. Because this was a study of the change in acceleration, any small errors in the estimation of the successive positions of the vehicles would magnify the periodic estimates of acceleration and, even to a greater extent, the sucessive changes in acceleration.

The author analyzed the data and found, in a majority of the cases, that there was a rather significant relationship between acceleration noise and the distance into this particular test section. This was true for the combined data for all volumes as well as for higher flow conditions only. In other words, the change in acceleration noise was comparable in each noise profile regardless of the flow quantity. It would be constructive to determine just how much of the variability in acceleration noise was accounted for by the distance and how much was accounted for by the slope.

The author gave considerable attention to the operating characteristics of trucks on this singular test section. This section involved a plus grade of approximately 2½ percent for a distance of approximately 650 ft. According to data published in "A Policy on Geometric Design of Rural Highways" a heavily loaded truck with a very poor weight to horsepower ratio of 400 lb per horsepower would be expected to lose only 4 mph in negotiating this particular test section. Most of the trucks observed in this study doubtless were not heavily loaded. One should expect a speed reduction of only 1 mph when averaging all the trucks observed regardless of size or load.

When studying the microscopic speed profiles, the author has determined that there was a speed reduction of 2 or 3 mph on the grade during peak flow periods in lanes 1 and 2 and a slightly greater speed reduction in lane 3. He makes the point that lane 1 contains a higher percentage of trucks than lanes 2 or 3. During the off-peak periods, the speed in lane 1, with the higher truck percentages, seemed to have increased slightly through the section while the speeds in lanes 2 and 3 either decreased slightly or remained virtually constant. The differences in these speed profiles were very slight and the percentage of trucks ranged from 5 percent to 10 percent in lane 1 and ranged down to less than 1 percent in lane 3. The author has stated that "speed decrements were judged not to accompany the lane with the highest percentage of truck flow". It might also be stated that the average speeds in lane 1 were always lower than in lane 2 or lane 3.

In a microscopic speed and acceleration noise study, the author pointed out that the acceleration noise of the vehicles following tractor-trailer trucks was noted and compared to the acceleration noise for the vehicles in advance of such trucks. As has been determined previously, the acceleration noise for a queued vehicle was less than for a free-moving vehicle. This paper did not, however, explain the criteria used in identifying the vehicles "following" a tractor-trailer truck and how the differentiation was made between those following one truck and those leading a subsequent truck. By whatever definition the author used, he did find that the acceleration noise was relatively high for the vehicles preceding trucks and low for the queue following trucks.

Analysis of time-space traces of successive vehicles through the study sections led to several conclusions, one of which concerned the hypothesis that the passage of a tractor-trailer unit removed the traces of a disturbance, or shock wave, in the flow pattern. From a careful study of these data, it may be observed that this disturbance had disappeared two or three vehicles prior to the passage of this tractor-trailer. It is difficult to conclude that the passage of the tractor-trailer unit was responsible for this observed dampening or smoothing effect. In another example, it was pointed out that the trace of a tractor-trailer unit moving in the traffic stream showed that it was actually not holding up traffic, but was, in fact, being held up by a slow-moving vehicle in front of it. It can be noticed, however, that a car did weave from an adjacent lane into the gap between this truck and the vehicle leading it.

In connection with the conclusions drawn in Humphreys' paper, the following observations are offered:

1. The author did admit that the study represented only one study site. It is his contention, however, that the study site is representative, or average, of most "roller-coaster-type freeways".

2. This discussant will concede that the study did indicate that automobiles do tend to accelerate slightly up a moderate urban freeway grade of a few hundred feet and that trucks tend to maintain a slightly more constant speed up such a grade, although the difference observed was very slight.

3. The fact that acceleration noise in general increases on a grade does indicate that urban freeway grades are undesirable from a level of service standpoint. This conclusion is supported by other considerations indicating that grades are undesirable.

4. The conclusion that trucks tend to stabilize flow and suppress shock waves because of the driving characteristics of truck operators is subject to question and further study. It is likely that the gaps existing in front of trucks may tend to help dampen possible shock waves.

5. Certainly, the conclusion that "poorly designed ramps and acceleration lanes present special geometric problems" because some "slowly accelerating vehicles often cause undesirable operations" must be correct but is not properly substantiated in this paper.

6. The final conclusion, indicating that acceleration noise is not adequate to measure the effects of trucks on the level of service of freeway flow, is perhaps a valid one.

In many instances, scholarly research brings to light methods that do not work, rather than those that do. The author is to be commended for attempting to evaluate the effect of trucks by the use of acceleration noise as the parameters and should be encouraged to pursue this topic in accordance with his recommendations for future study.

PATRICK J. ATHOL, Expressway Surveillance Project, Oak Park, Illinois—Humphreys addresses the problem of establishing the influence of truck operations on urban freeways. He presents his ideas in two parts, the first attempting to establish acceleration noise in the traffic stream as the measure of truck influence, the second discussing the operation of trucks in terms of individual travel trajectories. The analytical approach is emphasized in the use of acceleration noise in his first part, whereas he handles the effect of slower vehicles in a much more conversational manner.

In terms of general interest, I think the initial analysis falls short of its potential, whereas the second part gets into an area of widespread public interest. In the conclusions, the shortcomings of acceleration noise in identifying the impact of truck performance are presented. The latter part of his work could, I suggest, be considered as one facet of the more general topic of the influence of slower moving vehicles on the traffic stream.

Acceleration noise is chosen as the level of service of operations (2). It reflects the changes in acceleration of the vehicle along its route weighted by the square of the changes. Describing measures as noise is derived from the wide use of this expression in control and communications and relates actual performance with nominal or desired performance. Noise precludes the achievement of the ideal effect.

Helly (9) looked at acceleration noise along city streets, particularly with respect to the influence of traffic signals and congestion. Acceleration noise did reflect, by definition, changes in the acceleration; however, in the case of arterial streets, he found noise alone nondiscriminatory between operations at 3 a.m. and a congested peak period. Both noise values were approximately 2 to 3 ft/sec^2.

On the same section of the Gulf Freeway, Drew presented results of acceleration noise measurements. He concluded that noise at free-flow conditions was highest, diminishing toward maximum flow level, then increasing again in congested traffic.

These changes were proportionately very large, from 0.1 to 1.6 ft/sec^2. Again, acceleration noise by itself tended to be nondiscriminatory between free flow and congestion and needs further specification in speed or similar measurement to establish performance.

From the rudimentary measure of acceleration noise, the attempt was made to relate it to the total internal energy of freeway traffic. The extension of this energy analogy had a confusing result; Drew came to the conclusion that acceleration noise is directly proportional to slope of the grade. Humphreys, from the same concepts, concludes that the change of acceleration noise is proportional to the slope of the grade. The slope of acceleration noise along the grade was tested for difference between lanes, and was found constant. What is not made clear is whether or not these slopes are significantly different from zero. If it is zero, then both ideas agree. Drew's own results infer zero noise on level sections; this of course, as Drew states, must be disagreed with. From the data used in both studies, it appears that neither case is proved; thus, one is alerted to potential contradiction in using the underlying energy analogy.

The energy analogy, as Humphreys used it, assumed no change in kinetic energy, and hence no speed change in the area. In some of his data, speed changes at least of the order of 2 mph within a lane and 8 mph between lanes were presented. The presented speed profile data showed speed changes of 3 ft/sec at speeds of 60 ft/ sec on a 500-ft section.

Following Eq. 5,

$$\Delta\sigma = \beta(0.64 + 0.35)\ \text{ft/sec}^2$$

where 0.35β is the component resulting from the change in kinetic energy. For 3 ft/sec changes in speed at 60 ft/sec, the rate of change of acceleration noise is changed by 50 percent, showing the keen sensitivity of the model. There are, therefore, grounds for concern that the assumptions were not completely substantiated by the data.

In the second discussion, Humphreys is looking at the trajectory of vehicles through a section of highways as illustrated by the time-distance charts. In his charts he really gets to the fundamental point of showing the performance of slower vehicles. Paraphrasing his conclusion, the report says that slower vehicles do influence performance, but not all slower vehicles are trucks. This point, I suspect, would have wide acceptance among operating engineers. Under certain geometrics the majority of slow vehicles will be trucks traveling slowly, i.e., up the long, steep grades, but this is not so on the Houston "roller coaster". In the data presented, it can be seen how slow-moving vehicles encourage lane-changing. Faster moving lanes have to accept lane changes caused by slower vehicles and they are constantly required to adjust, thus creating more acceleration noise. Slower moving traffic behaves in a sense similar to the 35-mph freeway condition in which minimum acceleration noise occurs; all vehicles are constrained to the lower speeds.

The presence of slower moving vehicles does introduce longer headways, which are in a detailed sense low volumes that can help absorb the impact of shock waves. In routine traffic operations, the police in Los Angeles and some other highway departments utilize a system of introducing vehicles into the traffic stream in advance of a problem area. These vehicles slow the stream down to a uniform speed until past the problem. By this action they introduce a large headway and temporarily delay input to diminish the shock wave impact. This action can be used for severe weather conditions where visibility is impaired, such as by fog.

The Gulf Freeway section under study would be difficult to match in other existing areas and, one would hope, never in the future, so the results are limited in future applications. There remains the continuing need to establish the impact of slower vehicles and trucks along urban freeways. The measures must go beyond acceleration noise alone. Other measures that can be included are desired speed (nominal performance), the demands on the driver to gain information, as shown by the work done by Gordon (10), and the control actions taken by the driver in response to his environment.

Other aspects of the influence of trucks is shown by the work of Michaels and Cozan (11) of Northwestern University, and the work of Moskowitz (12) in California. All of these studies present important factors. Humphreys' conjecture into operational areas is certainly stimulating. The slow driver, be he the truck driver or self-assured automibile driver who is convinced that his slow speed is the safest, is a problem, and it is his influence we are trying to establish. Humphreys has reiterated the question, "What is their impact?" and shows us that we are not likely to get a simple answer.

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