

MEASURING LEVELS OF SERVICE OF A CITY STREET BY USING ENERGY-MOMENTUM TECHNIQUES

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A traditional speed and delay study can yield extremely useful information for the evaluation of traffic operations and flow. Unfortunately the results are deterministic, and traffic flow is highly stochastic. Energy-momentum theory recognizes this; however, its applications have primarily been for freeways and expressways. This study applies energy-momentum theory to a city street without access control. Little correlation was found between derived acceleration noise and average speed relationships. Traffic flow inhibited by delay is stochastic, yet, because the number of delays increases, the aperiodic nature of delay frequency does not lend itself to the energy-momentum model. Each delay type must be handled separately.

•DELAY encountered on downtown collector and arterial streets during peak travel times can be frustrating. A countless number of papers have addressed this subject. The primary purpose of this report was to test energy-momentum concepts for monitoring levels of service (1) on a collector street that has a number of traffic flow delay components.

The study site was the Euclid Avenue corridor between Maryland Plaza Drive and Clayton Road in St. Louis. The corridor has traffic problems directly related to the intensity of commercial and hospital activity in the area, a common situation. On a more microscopic level, the study segment is 3,600 ft (1100 m) long, has a curb-to-curb width of 36 ft (11 m) including two lanes with parking, and has an estimated capacity of 600 vehicles per hour per direction at level of service C. Components that contribute to vehicle delay along Euclid Avenue include curbside automobile parking turn-over, commercial vehicle loading and unloading, pedestrian interference, bus transit operations, right-of-way restrictions, traffic volume, and type of intersection control. All major intersecting streets except three are controlled by a stop sign. Only Forest Park Parkway, West Pine, and Lindell Boulevard (Figure 1) are signalized, and only the latter two are programmed for synchronization.

Currently two conflicting problems exist. First, the support of the commercial strip by the surrounding community practically demands that Euclid Avenue from Lindell to Forest Park Parkway have further restraints on through traffic to enhance pedestrian and business activity. Second, an excess of through traffic uses Euclid Avenue as a means to travel to and from the Washington University medical complex en route to or from Kingshighway Boulevard (two-way ADT of 46,750) or Forest Park Parkway (two-way ADT of 22,100) (2). The hospital complex is a regional center with more than 8,000 full-time employees (3). If the area grows and develops as it is expected to, the demand for feeder routes like Euclid to and from expressways and principal arterials will increase. As a first step toward the solution of such problems, specific delay components in the traffic flow need to be measured and analyzed.

STUDY PROCEDURE

It seemed appropriate to obtain a continuous record of speeds and speed changes and relate specific changes to particular delays. A standard traffic analyzer was used to

record speed profiles, vehicle running time, and total operating time of a floating car traveling in the left lane. Enough runs were made to ensure a 95 percent confidence interval of achieving representative results (4). Data were taken during three pre-determined peak travel times: 7 to 8 a.m., noon to 1 p.m., and 4:30 to 5:30 p.m. The number of delay complications was greatest during the last period. Speed data were also taken at 2 a.m. when no one else was traveling and the traffic signals were operating on flash. These data were used to determine the mean free speed. Detailed commentary on the causes for delay during each run was tape-recorded. Data were analyzed for the 2 a.m. and p.m. peak travel.

SPEED AND DELAY RECORDS AND SUMMARY

Table 1 gives a typical record of speed and delay for a p.m. peak run on Euclid Avenue. [ΔV stands for the number of 2-mph (3.2-km/h) speed changes used for illustration and comparison.] Data were recorded for both northbound and southbound directions. Statistics (in sec) of the runs were as follows:

<u>Statistic</u>	<u>Northbound</u>	<u>Southbound</u>
Total trip time	303	295
Total stop time	60	56
Total time faster than 10 mph (16 km/h)	150	135
Total time faster than 30 mph (48 km/h)	0	0
Running time	243	239

Table 2 gives delay by type for each direction (5). In both cases, intersection delay due to traffic signals predominated. However, delay due to stop signs was large compared to their frequency of occurrence (twice).

ACCELERATION NOISE CALCULATIONS

The acceleration noise parameter σ , defined as the standard deviation of changes in vehicular speed, was calculated by using Jones and Potts approximation (1) with the conversion factor of 1.465 for converting miles per hour to feet per second:

$$\sigma = \left[\frac{(1.465)^2 (\Delta V)^2}{T} \sum_{i=0}^T 1/\Delta T_i \right]^{1/2}$$

where

- ΔV = 2-mph (3.2-km/h) speed change,
- ΔT_i = running time of vehicle for each speed change, and
- T = total running time of vehicle.

This equation was calculated for both northbound and southbound vehicles over defined road segments as shown in Figure 1.

Three components of acceleration noise were defined. Case one took into account the natural roadway noise, neglecting signal control, and vehicle interaction. This component was studied in two sections governed by the stop-controlled intersection at Laclede Avenue. Mean free speeds were determined at this stage. Case two in Figure

Figure 1. Acceleration noise versus distance.

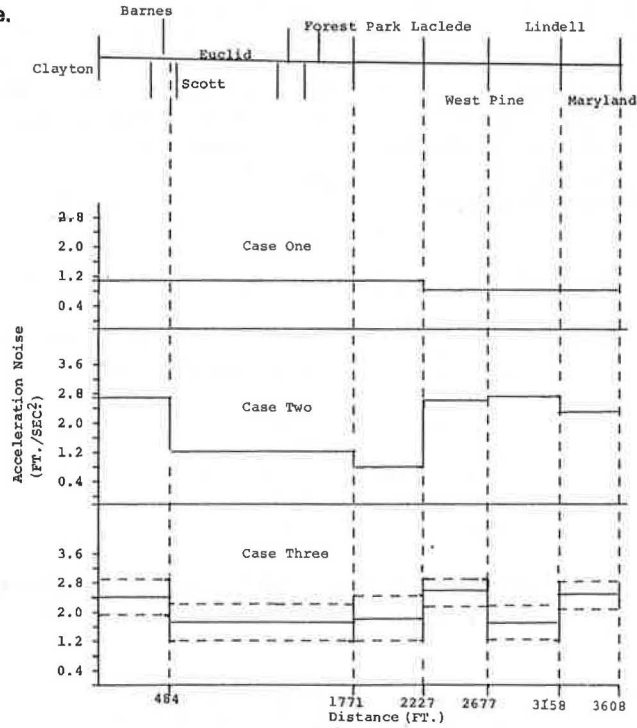


Table 1. Typical speed and delay record.

Start Intersection	Stop Intersection	Delay	Duration (sec)	Total ΔV	Estimated Running Time (sec)
Mayland Plaza	Lindell	Pedestrians	7	25	39
		Signal	36		
Lindell	West Pine	None, made light		10	18
West Pine	Laclede	Midblock	4		
		Crossing	10	29	54
Laclede	Forest Park	None, made light		9	24
Forest Park	Scott	Midblock	4		
		Unloading	15	50	78
		Crossing	15		
Scott	Clayton Road	None		22	30
Clayton Road	Barnes Plaza	Pedestrians	6	24	33
Barnes	Forest Park	Crossing	12	27	63
Forest Park	Laclede	Crossing	12	23	27
Laclede	West Pine	Midblock	4	26	36
		Signal	12		
		Crossing	15		
West Pine	Lindell	None, made light		11	18
Lindell	Maryland Plaza	Crossing	39	26	62
		Pedestrian	20		
		Unloading	15		

Table 2. Percentage of intersection and midblock delay.

Delay	Northbound	Southbound
Intersection		
Signal	54	65
Stop sign	21	5
Pedestrian	11	6
Turning movement	3	5
Total	89	85
Midblock		
Loading-unloading	5	8
Block	3	4
Parking	3	3
Total	11	15

1 was also summarized from the mean free speed runs, and it took into consideration the combined effects of vehicle operations due to stop sign and signal control. Case three showed the effects of all delay components. Because the case two data were within the range of case three data (a majority of delay caused by signal control), case two and case three data were grouped so as to make 95 percent confidence intervals about the average (horizontal dashed lines in Figure 1) meaningful. Table 3 gives a summary of acceleration noise data. Table 4 gives additional information on case three data and the symbols used in Figures 3, 4, 5, and 6.

SUMMARY OF ENERGY-MOMENTUM CONCEPTS USED

In the energy-momentum approach for measuring roadway levels of service (1), the total energy of the stream T equals the kinetic energy E plus the internal energy I where

$$\begin{aligned} I &= \sigma, \text{ the acceleration noise,} \\ E &= \alpha k u^2, \\ k &= \text{vehicle concentration in vehicles/mile (km),} \\ u &= \text{speed of vehicles, and} \\ \alpha &= \text{an empirical constant.} \end{aligned}$$

The energy can be evaluated for any length of road. Boundary conditions help define the relationship between acceleration noise and E . In general the equation for E is

$$E = \alpha k u_r^2 \left[1 - 2 \left(\frac{k}{k_j} \right)^{(N+1)/2} + \left(\frac{k}{k_j} \right)^{N+1} \right]$$

for $N > -1$.

As I approaches 0, E approaches a maximum, which equals T . Theoretically T then equals $\alpha k_j (u_r)^2$. For the case of $N = 1$ in the above equation, E can be reduced to

$$E = \frac{4}{27} \alpha k_j u_r^2$$

In the other extreme, as E approaches 0, I approaches a maximum σ_{max} . Because energy is neither lost nor gained but merely transferred from one form to another,

$$\sigma_{max} = T = \frac{4}{27} \alpha k_j u_r^2$$

for $N = 1$, or

$$\alpha = \frac{27}{4} \frac{\sigma_{max}}{k_j u_r^2} = 1/\text{capacity of the roadway}$$

$T = E + I$ now becomes

$$\sigma_{max} = \alpha k u^2 + \sigma$$

or

Table 3. Acceleration noise summary data.

Case	Section	Running Time (sec)	ΔV	Average Speed (fps)	σ
One	Maryland Plaza to Laclede	58.0	19	24.0	1.01
	Laclede to Scott (Barnes)	69.4	24	25.1	1.15
Two	Maryland Plaza to Lindell	29.1	17	15.4	2.29
	Lindell to West Pine	24.4	19	19.7	2.66
	West Pine to Laclede	24.5	20	18.4	2.55
	Laclede to Forest Park	24.7	12	18.5	0.99
	Forest Park to Barnes (Scott)	40.5	11	31.8	1.33
	Barnes (Scott) to Clayton	30.0	24	16.2	2.51
Three	Maryland Plaza to Lindell			15.1	
	Lindell to West Pine			22.8	
	West Pine to Laclede			16.3	
	Laclede to Forest Park			16.7	
	Forest Park to Barnes (Scott)			23.4	
	Barnes (Scott) to Clayton			16.2	

Note: 1 fps = 0.3 m/s.

Table 4. Additional acceleration noise summary data.

Section	σ Average	95 Percent Confidence Limits	Segment Symbol
Maryland Plaza to Lindell	2.39	2.39 ± 0.42	○
Lindell to West Pine	1.66	1.66 ± 0.62	□
West Pine to Laclede	2.54	2.54 ± 0.32	△
Laclede to Forest Park	2.03	2.03 ± 0.58	●
Forest Park to Barnes (Scott)	1.90	1.90 ± 0.50	■
Barnes (Scott) to Clayton	2.39	2.39 ± 0.40	▲

Figure 2. General shape of acceleration noise versus freeway speed curve.

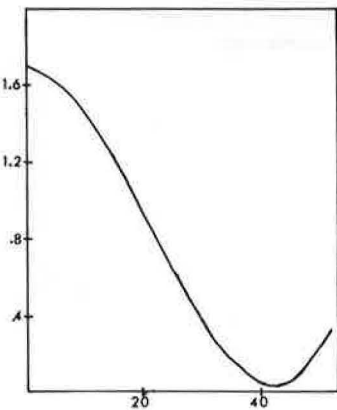


Figure 3. Acceleration noise versus speed for all cases.

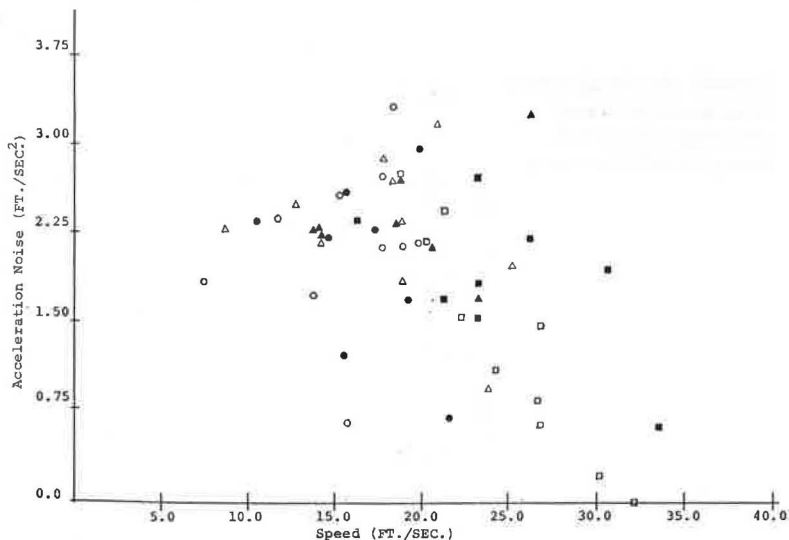


Figure 4. Acceleration noise versus speed for average case three and case one southbound.

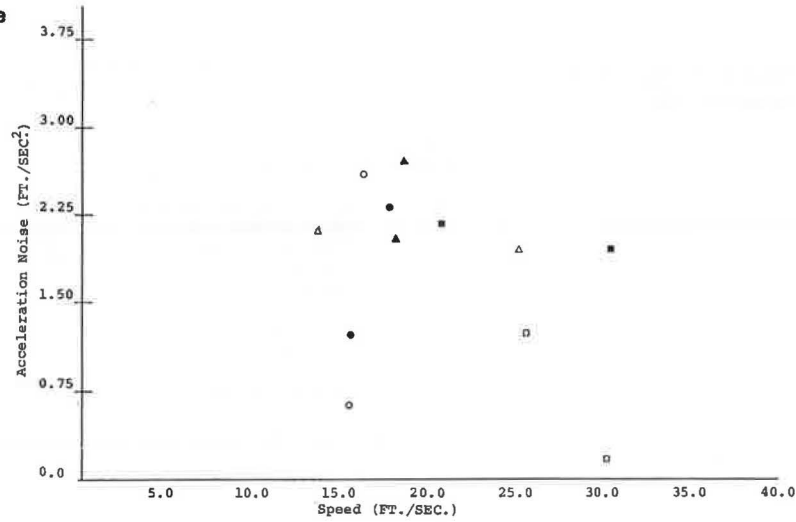


Figure 5. Acceleration noise versus speed for average case three and case one northbound.

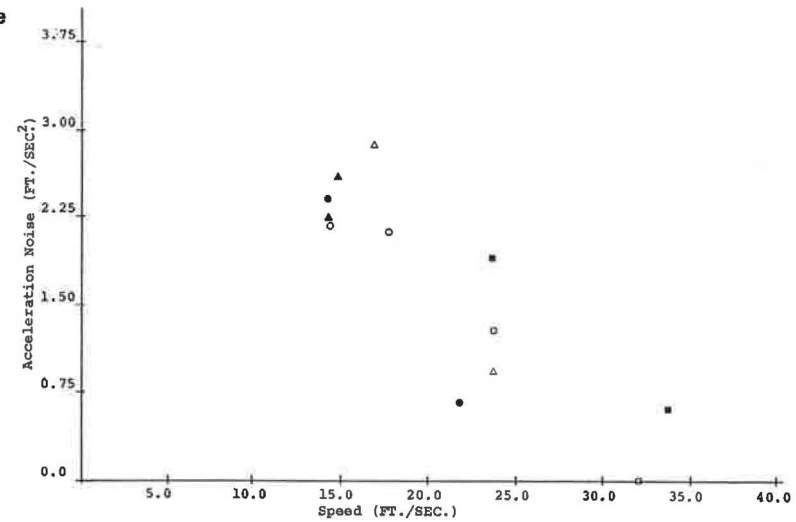
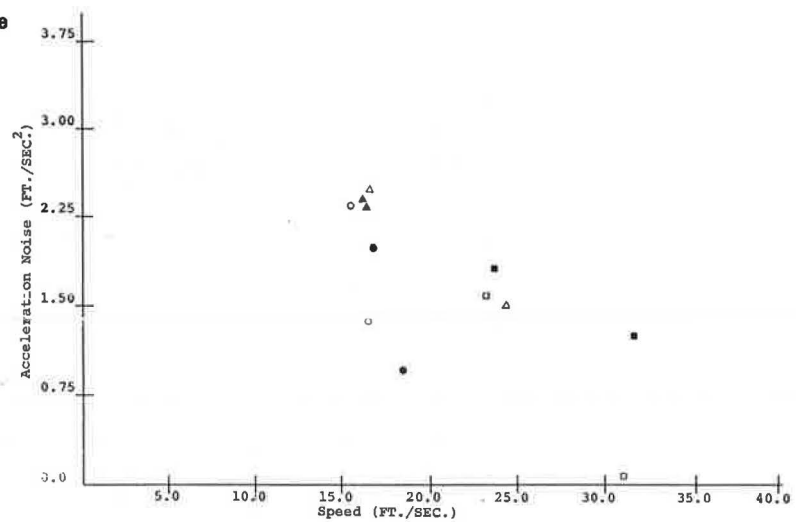


Figure 6. Acceleration noise versus speed for average case three and case one, average of both directions.



$$\sigma = \sigma_{\max} - \alpha k u^2$$

For the case of $N = 1$,

$$k = k_j(1 - u/u_r)$$

where

k_j = jam concentration, and
 u_r = mean free speed.

Substitution gives

$$\sigma = \sigma_{\max} - \alpha k_j u^2 + \alpha k_j u^3 / u_r$$

Figure 2 shows the general shape of this theoretical relationship fitted with data for a freeway section (1). The results of data from cases one, two, and three of Figure 1 are shown in Figures 3, 4, 5, and 6.

EVALUATION OF RESULTS

Examination of Table 2 shows that intersection delay predominated along Euclid Avenue. Delay due to signal control was the most frequent cause. However, the induced shock wave effects brought about by stop sign and midblock delay can halt traffic for a considerable length of time. Such deterministic results hid an inherently stochastic process. Thus, the acceleration noise results were tabulated to bring to light the variations in traffic flow.

Case one illustrated not only the effect on vehicle operations of the roadway, that is, the pavement type and sight distance conditions along intersecting streets, but also the effect of a stop sign. Without it, ΔV would be reduced 50 percent, cutting σ by a third approximately. In case two, σ between Barnes (Scott) and Laclede was very low in comparison with other segments because for that particular run the Forest Park intersection was cleared without delay. This can be interpreted as a simulation of a well-operating, progressively timed signal system. If the corridor had one, σ would be decreased substantially if other stream delays did not inhibit vehicular platooning. It should be pointed out that, even though it appears that a new minimum σ was obtained, the combined effects of σ between Clayton and Laclede for case two were still higher than those of case one. That is not to say that σ_{\min} in case one was an absolute minimum, for it was only the minimum according to the definition of the road segment used.

Case three in Figure 1 contained some very useful results. Maximum dispersion on σ occurs between West Pine and Lindell. Link distance had little to do with it, but intersection control did. As previously mentioned, the Lindell and West Pine intersections are synchronized. The dispersion was the result of the state of the intersections in terms of the number of vehicles waiting to clear before the next platoon desires service. Oftentimes, these two intersections formed bottlenecks because of left-turning traffic. The signals do not have separate left turn indicators. The higher values of σ shown are a direct result of having to stop each time due to stop sign control.

Little correlation exists between Figure 2 and Figures 3, 4, 5, and 6. The energy-momentum theory did not appear to be applicable to a city street with all its stochastic delay components. This may be because the speed ranges in the study were not large enough or the floating car method was not applicable. Although either of these was possible, the biggest factor by far was the aperiodic nature and number of delays en-

countered. For the freeway case, the vehicle stream is most often inhibited by a bottleneck section that induces a shock wave. But this is one type of delay that affects the whole stream in a fairly consistent manner and not the same as the multiple delays encountered on a collector street like Euclid Avenue.

SUMMARY AND CONCLUSIONS

This study set out to examine the use of energy-momentum concepts for measuring levels of service along a city street. The acceleration noise parameter can be extremely useful in pinpointing bottleneck segments when accompanied by accurate speed-delay results. The lack of fit between observed and theoretical results for measuring actual levels of service was due to the number and stochastic nature of the delays found. Through isolation of delays by type, a better fit might be obtained. Realistically speaking, a freeway is the only roadway facility that can exhibit an isolated delay. For the most part as traffic mobility is compromised for traffic accessibility, delays and delay types increase in number and become less independent of one another, producing the scatter shown in Figures 3, 4, 5, and 6.

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