Variability in Traffic Flow Quality Experienced by Drivers: Evidence from Instrumented Vehicles

Joonho Ko
Graduate Research Assistant
School of Civil & Environmental Engineering
Georgia Institute of Technology
790 Atlantic Drive, Atlanta, GA 30332-0355
404-385-2376
404-385-2376 (Fax)
Joonho.ko@ce.gatech.edu

Randall Guensler, Ph.D.
Professor
School of Civil & Environmental Engineering
Georgia Institute of Technology
790 Atlantic Drive, Atlanta, GA 30332-0355
404-894-0405
404-894-2278 (Fax)
Randall.guensler@ce.gatech.edu

Michael Hunter, Ph.D.
Assistant Professor
School of Civil & Environmental Engineering
Georgia Institute of Technology
790 Atlantic Drive, Atlanta, GA 30332-0355
404-385-1243
404-894-2278 (Fax)
michael.hunter@ce.gatech.edu

Date of submittal: November 16, 2005
Word count: 7,529 words (5,279 words in the manuscript + 2,250 words for figures and tables)

ABSTRACT

Freeway operating conditions are typically evaluated using the level of service (LOS) concept, which is defined according to the macroscopic traffic parameter, density. Although traffic density may provide general estimates of current traffic conditions, this parameter generally fails to communicate the variability in the quality of traffic flow experienced by individual drivers. This variability may be caused by factors that are not effectively being captured by density, such as travel lane, vehicle position within a platoon, characteristics of roadway geometry, etc.

This paper investigates the variability of traffic flow quality as indicated by measurements of speed and acceleration noise (standard deviation of acceleration) using field data obtained from instrumented vehicles equipped with global positioning system (GPS) devices. The microscopic measures observed from individual vehicles are compared with density-based LOS, which are calculated with data from the Atlanta, GA traffic monitoring system. This comparison reveals that under the same LOS condition, drivers may experience significant differences in the quality of traffic flow. In addition, the comparison indicates that drivers under different density based LOS conditions may experience a similar level of traffic flow quality. The variability generally becomes larger as traffic conditions worsen.

INTRODUCTION

Evaluating service quality is important for the planning and operation of freeway systems. Numerous measures have been suggested to describe the service quality on freeways. Among these measures, traffic density has been preferred as it is regarded as an indicator of the degree of freedom to maneuver within a traffic stream and sensitive to a broad range of flows (*1*). Typically traffic flow conditions, based on traffic density, are evaluated using the concept of level of service (LOS). There are six LOS categories, extending from A to F, where each LOS represents a range of operating conditions and the driver's perception of those conditions (*1*).

The HCM LOS concept attempts to utilize the macroscopic traffic flow parameter, density to represent the microscopic performance experienced by the individual driver. However, recent studies point out that an individual driver's LOS cannot be determined solely by density. The variability in traffic flow quality can be affected by localized driving conditions. Factors reflecting a driver's experiences, such as flow, roadway conditions, and other drivers' aggressiveness should be simultaneously considered (*2*, *3*). For example, the leading car in a platoon is likely to drive at that driver's desired speed while the following cars must drive under the constrained conditions set by the car ahead. This phenomenon may impose different levels of traffic flow quality on individual vehicles depending on their relative locations within a traffic stream. In essence, localized traffic flow quality may derive from factors such as traveled lane, lane width, vehicle position within a platoon, truck volumes, roadway geometry, and the presence or absence of roadway design factors that may affect driver behavior or perception (e.g. roadside hazards, bridge abutments, shoulder widths, etc.).

Understanding traffic flow variability, particularly on the microscopic (individual driver/vehicle) level, is important since level of service should be assessed from the perspective of the roadway user. However, the majority of studies on the variability of traffic flow have focused on the macroscopic level using data obtained from fixed-point detectors, rather than on a microscopic level (*4, 5*). Furthermore, microscopic studies conducted to date have been based upon a limited number of test vehicles (*6, 7*). This limitation results in an inability to fully evaluate the variability experienced by real-world drivers. Historically, individual driver based data collection, which involves tracing individual vehicle activity on roadway segments, has been difficult. The Commute Atlanta project, an instrumented vehicle research program funded by the Federal Highway Administration (FHWA) Value Pricing Program and the Georgia Department of Transportation (GDOT), provides an opportunity for investigating such variability with a large data set collected in a real-world context. The Commute Atlanta project monitors second-by-second activity of approximately 500 instrumented vehicles using global positioning system (GPS) devices, enabling researchers to examine the microscopic driving conditions that each participant experiences.

The purpose of this study is to investigate the variability of the traffic flow quality experienced by individual drivers within a traffic stream, utilizing the Atlanta freeway system as the test case. The variability is measured using GPS equipment and compared with the density-based LOS as suggested in HCM 2000 and measured by video detection system (VDS) cameras on the system. This research effort should enhance the understanding of how the microscopic traffic flow quality varies within a macroscopic traffic condition. The enhanced understanding may contribute to the development of evaluation systems that better reflect a driver's perceived freeway traffic flow quality, and thus help manage freeway traffic more effectively. With such measures in hand, it may be possible to better utilize the limited resources available for transportation maintenance and system improvements.

PROPOSED TRAFFIC FLOW QUALITY INDEX

Although traffic flow quality is generally considered to be a subjective term, this study uses quantifiable and objective measures for the indices of traffic flow quality: speed and degree of speed variation. Unacceptably low vehicle speeds can significantly decrease the degree of driver satisfaction. Traffic flow that cannot maintain an acceptable level of speed is likely to be described by users as poor traffic flow quality.

However, speed alone cannot fully describe the traffic flow quality experienced by a driver over a roadway segment. Together with speed, the degree of speed variation can also be used as an indicator of the traffic flow quality. Drew and Keese (*8*) suggested that *"…motion in the form of speed and the magnitude and frequency of speed changes is an important measure of level of service from the point of view of the individual driver"*. As illustrated in Figure 1, where two GPS-derived speed and acceleration profiles of freeway driving are plotted, two trips can have the same average speed of 72 mph over the freeway segment, but exhibit significantly different speed variations. The standard deviations of accelerations are 0.79 mph/s and 0.38 mph/s for Trips 1 and 2, respectively. The higher standard deviation equates to more discomfort to drivers because the higher value results from more frequent acceleration and deceleration activities. Hence, the driving conditions of Trip 1 may be considered less desirable than those of Trip 2 in spite of the same average speed or total travel time.

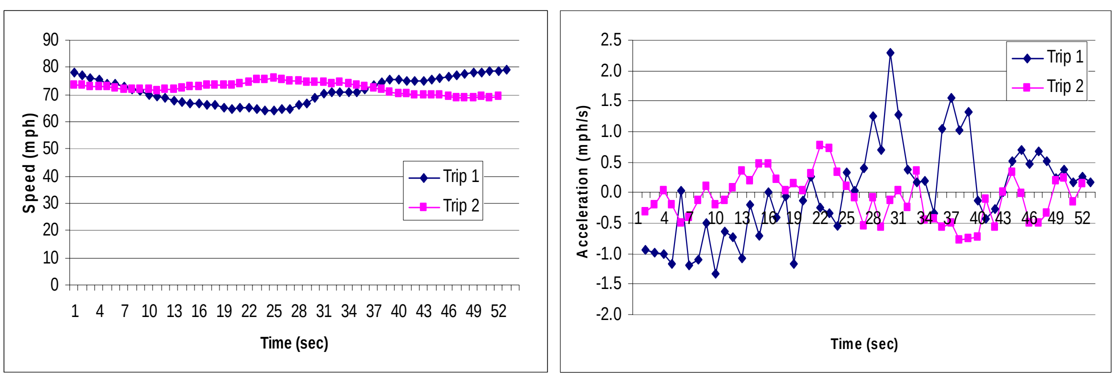


FIGURE 1 Vehicle speed and acceleration profiles obtained from trips with the same average speed

A popular measure for the degree of speed variation is acceleration noise, defined as the standard deviation of acceleration. In fact, acceleration noise was proposed nearly a half century ago as a parameter that might be employed to characterize the driver-car-road complex under various conditions (*9*). Since that time, several researchers have proposed acceleration noise as a possible measure of traffic flow quality (*7, 8, 10, 11*). Based on these previous research results, this study also presumes that acceleration noise is a potential indicator of traffic flow quality experienced by individual drivers and that it should be explicitly considered in establishing a measure of service quality. Consequently, in this study, traffic flow quality will include both average travel speed and acceleration noise.

FIELD DATA EMPLOYED IN THE ANALYSES

Data Collection Location

To examine the variability of traffic flow quality, traffic data were gathered over three basic freeway segments along Interstate 75 southbound (toward downtown) in the metro Atlanta area. A basic freeway segment refers to the portion of freeway excluding entrance and exit ramp areas, such that traffic conditions and roadway characteristics are uniform over the entire segment. Ramp and weaving sections will be considered in future phases of this research effort.

The selected freeway segments have a speed limit of 65 mph, and the numbers of lanes for Segments 1, 2, and 3 are five, six, and seven, respectively. Figure 2 shows the locations of the selected freeway segments.

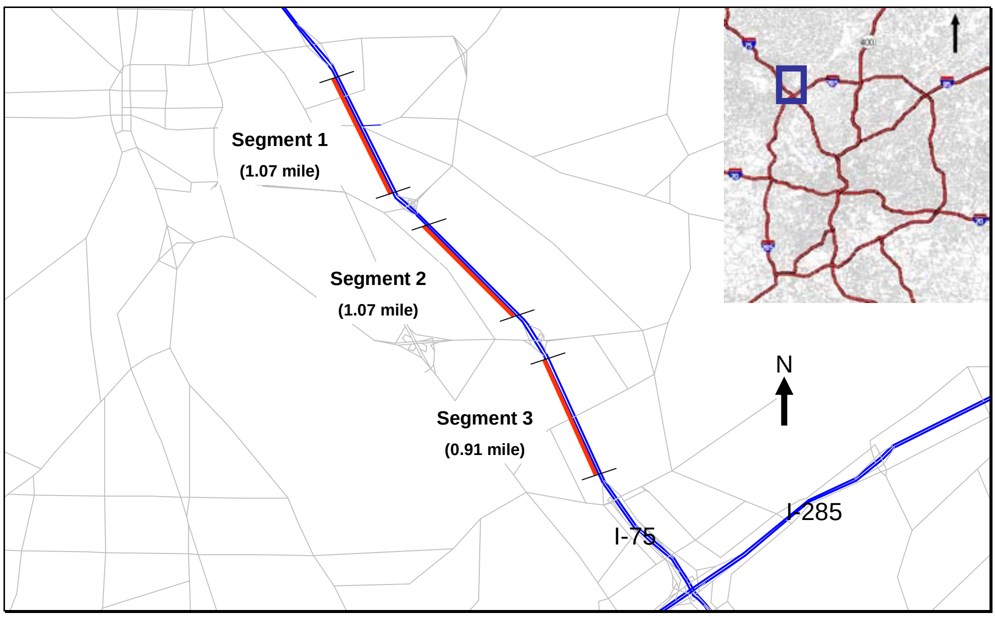


FIGURE 2 Data collection site

Traffic Data

This study employs instrumented vehicle data collected in the Commute Atlanta study and archived Transportation Management Center (TMC) freeway operations records. The Commute Atlanta project has deployed instrumentation in 487 vehicles from 268 households in the 13-county metro Atlanta area and collected second-by-second speed and positional data using GPS devices (*12*). The analyses presented here employ the subset of the Commute Atlanta GPS data collected between October 21 and December 31, 2003 along the study corridor. During this period, Segment 1 carried 247 trips made by 63 different instrumented vehicles, Segment 2 carried 291 trips made by 68 vehicles, and Segment 3 carried 322 trips made by 75 vehicles.

In addition to the instrumented vehicle data, macroscopic traffic data were obtained from the GDOT TMC, which collects and archives traffic data gathered by VDS installed along freeways. The VDS cameras continuously collect traffic volume and speed data for monitored locations, located approximately every 1/3 mile along the freeway. To provide near real-time travel data to the traveling public GDOT updates its traveler information data every few minutes. For archiving purposes the data are aggregated into 15-minute intervals. This 15-minute interval archived data were obtained for the study period. The obtained spot speed and volume data were converted into link-based data by taking the average of the values from the several VDS cameras installed over the selected segments. The speed and volume data were then used for computing traffic density by dividing volume by speed. The density data were then employed for identifying LOS according to HCM 2000 (Exhibit 23-2) criteria.

Instrumented vehicle data were temporally and spatially matched with TMC data. When matching the two data sources temporally, the midpoint of the instrumented vehicle trips over a segment was designated as the reference time. Then, the reference time was compared with the data collection time period of the TMC data. If the reference time is contained in the data collection time period, the two data sources were considered to be matched.

Data Reduction

Based on the 860 trips obtained, the data reduction process sequentially examines the TMC data availability for pairing with the instrumented vehicle trace and GPS data quality to determine when accurate GPS data were collected. After reviewing the availability of TMC data for each instrumented vehicle trip, 32 trips, which accounts for 3.7% of total trips, were identified not to have corresponding TMC data (due to temporary TMC data outages). Then, GPS data quality was examined based on the number of satellites. GPS data points with fewer than four satellites in view were considered as bad data points. This criterion is based on the fact that GPS receivers should track at least four satellites at the same time to obtain an accurate three-dimensional position fix and speed estimate (*13*). Applying this criterion, the values of identified bad data points were replaced with interpolated values using the neighboring data points. This process, however, may not be effective for consecutive bad data points. In addition, data quality may not be acceptable when one trip has many bad data points since trip characteristics become dominated by interpolated values. To avoid this problem, this study adopted a very conservative rule, where trips that had more than two bad data points were screened from the analysis data set. This step resulted in screening of 60 trips (7.0% of total initial trips).

Consequently, the data reduction process eliminated 92 trips (10.7% of the initial data). The final data set consisted of 768 instrumented vehicle trips from 73 different real-world vehicles, mainly composed of sedans and SUVs. For the selected trips, average link speeds from the two different data sources were compared as shown in Figure 3, where the average speeds of instrumented vehicles were computed by taking the average of second-by-second GPS speed. The figure suggests that they generally match well ($R^2 = 0.73$). In addition, the cumulative distribution function indicates that about 60% of the trip data have speed differences within ±5 mph and about 85% within ±10 mph. Thus, it is reasonable to state that the data set employed in this study does not significantly deviate from the macroscopic traffic conditions observed on the selected freeway segments.

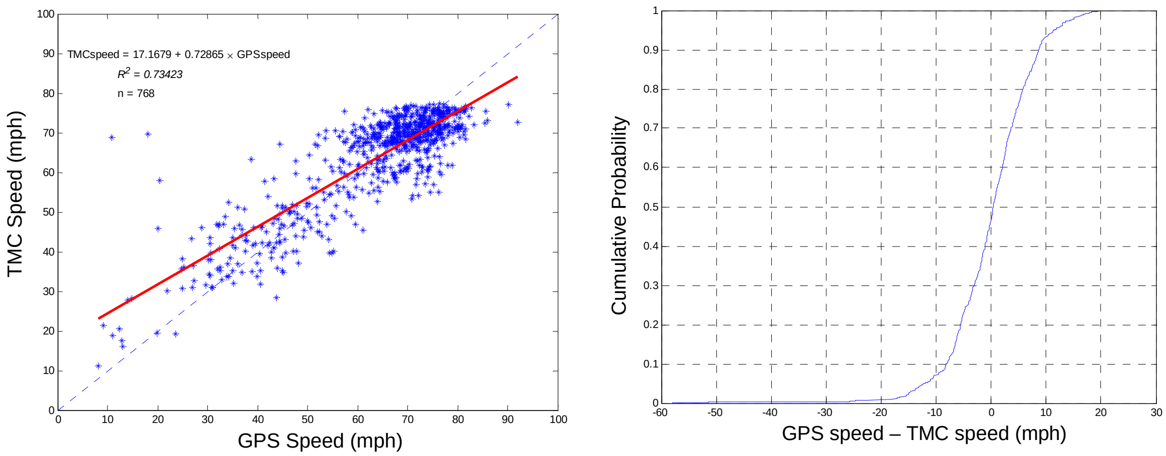


FIGURE 3 Speed comparison and cumulative distribution of the speed difference

TABLE 1 Summary of Selected Data by Segment and LOS

	LOS	Number of trips	Average Travel Speed (mph)	Average Acceleration Noise (mph/s)	Number of GPS data points
Segment 1	A	39	72.9	0.45	2,060
	B	56	70.6	0.46	3,054
	C	61	67.0	0.51	3,509
	D	16	56.6	0.79	1,089
	E	25	44.0	1.07	2,189
	F	23	33.5	1.23	2,643
Segment 2	A	84	74.3	0.31	4,354
	B	84	72.1	0.40	4,487
	C	32	67.0	0.56	1,840
	D	31	53.5	0.85	2,232
	E	22	38.8	1.27	2,186
	F	7	21.8	1.49	1,238
Segment 3	A	88	70.5	0.38	4,088
	B	91	68.3	0.54	4,367
	C	39	64.8	0.66	1,972
	D	24	56.8	0.86	1,385
	E	34	44.2	1.07	2,521
	F	12	29.2	1.34	1,346
Overall	A	211	72.5	0.36	10,503
	B	231	70.2	0.47	11,909
	C	132	66.3	0.57	7,321
	D	71	55.3	0.84	4,706
	E	81	42.6	1.13	6,897
	F	42	30.3	1.31	5,227

Table 1 summarizes the selected data, which shows the trends of decreasing speed and increasing acceleration noise as the degree of congestion increases. In addition, the table indicates that the overall number of trips during periods of LOS D to F is relatively smaller than that of LOS A to C. Note that the smaller number of trips under congested conditions is not a unique phenomenon of this study, as previous studies that deployed probe cars that traveled designated routes by designated drivers also showed similar trends (*14, 15*). In terms of GPS second-by-second data points, however, the differences in data size between LOS ranges are not considerable since the number of GPS data points is proportional to travel time, and thus trips under worse LOS ranges tend to have more data points. In total, the driving time and distance of the selected data amount to 46,563 seconds (approximately 13 hours) and 776 miles, respectively.

DATA ANALYSIS

Traffic Density, GPS Speed and Acceleration Noise

This section outlines the analysis of the observed relationships between traffic density (from within 1 veh/mile/lane to a maximum observed condition of 89 veh/mile/lane) and two traffic flow quality measures, vehicle speed and acceleration noise. In the first step of the analysis, scatter plots shown in Figure 4(a) were developed. Results of the scatter plots indicate that individual drivers' speeds are reasonably well correlated with density (R^2 = 0.67), where speed decreases as density increases. Acceleration noise has a tendency to increase with congestion level. This phenomenon is consistent with expectation that drivers are often forced to adjust their speeds to surrounding traffic conditions, and thus congestion inevitably incurs a higher acceleration noise.

In addition, 95% confidence interval bands (assuming normal distributions) were constructed as shown in Figure 4(b). The appropriateness of the normality assumption was tested by applying the one-sample Kolmogorov-Smirnov test (*16*). The test results showed that an application of the normal confidence interval is not inappropriate since the distributions of speed and acceleration noise for each LOS do not significantly deviate from normal distribution except LOS A (*p*-values of 0.04 for both speed and acceleration noise) and LOS C (*p*-values of 0.02 for both speed and acceleration noise) ranges at the level of 0.05.

The confidence intervals suggested that drivers experience different levels of speed within a same density-based LOS range and that the range of individual drivers' speeds under LOS A to B is about 25 mph, with the range increasing as traffic conditions become worse. This situation is more apparent for acceleration noise, for which variation is wider than that of vehicle speed for the given plot scales. The confidence intervals, thus, reveal that the variation under the worse LOS ranges tends to increase. In addition, Figure 4(b) suggests that speed and acceleration noise have a non-linear relationship with LOS as implied by the steeper slopes for the LOS below C. This observation may be related to the notion that LOS D is the level at which speeds begin to notably decline with increasing flows (*1*), reflecting the greater instability of traffic flow in the lower LOS range.

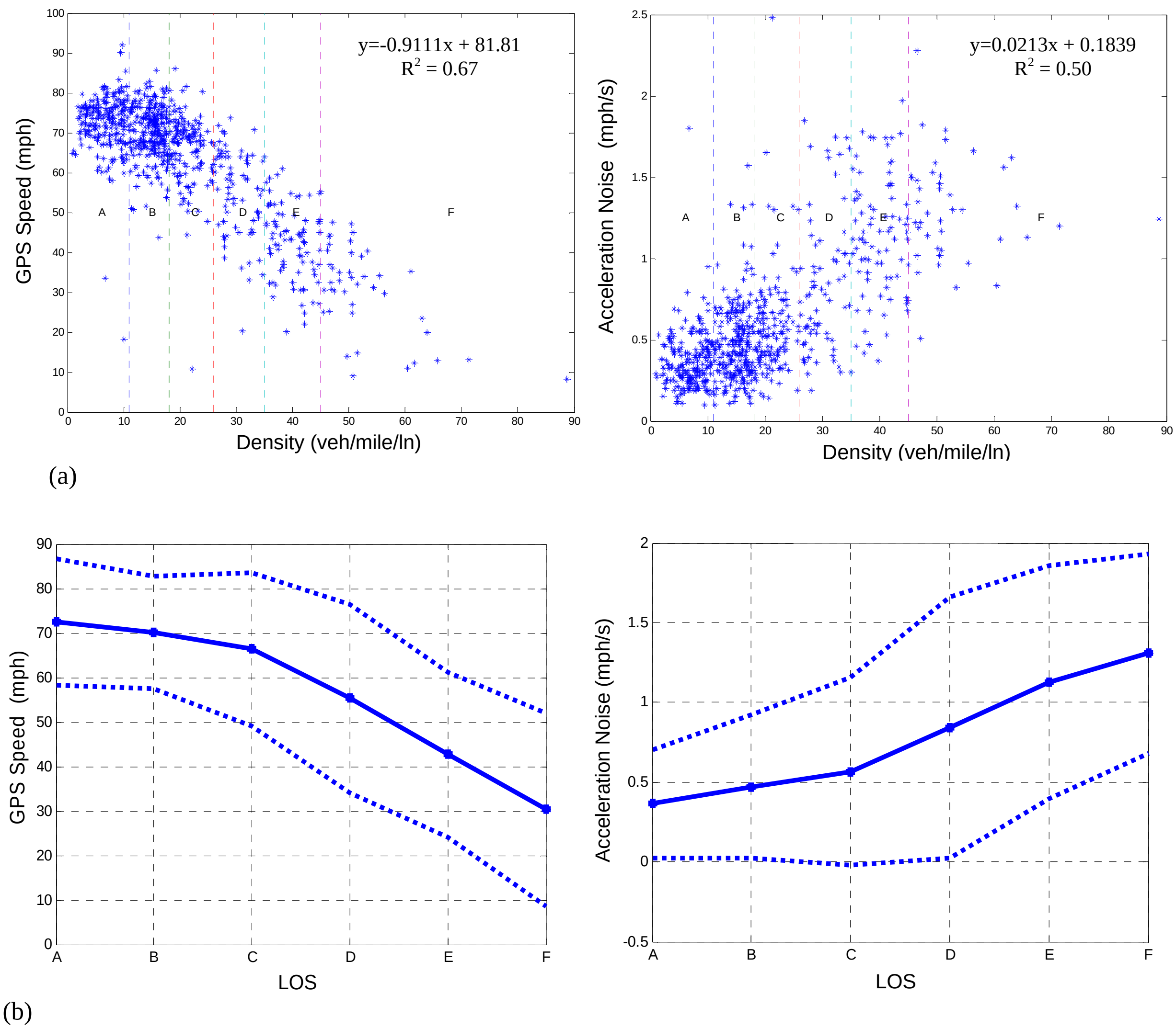


FIGURE 4 Relationships between density and GPS speed and acceleration noise: (a) scatter plots; (b) 95% confidence intervals

Confidence Region Analysis

The previous section investigated the variability in one dimension since the relationships were examined for speed and acceleration noise, separately. However, in order to have a more complete understanding of the complexity of the relationships, the measures should be observed in unison. This approach can be implemented using confidence ellipses, a multivariate statistical analysis. In the technique, the confidence region for the mean μ of a *p*-dimensional normal population can be derived from:

$$P\left[n(\bar{x}-\mu)' S^{-1} (\bar{x}-\mu) \le \frac{p(n-1)}{(n-p)} F_{p,n-p}(\alpha) \right] = 1-\alpha \, ,$$

where *n*, $\bar{x}$, and S are sample size, a vector of sample mean, and covariance matrix, respectively (*17*). Thus, a *100(1-α)%* confidence region for the mean μ of a *p*-dimensional normal population is the set determined by all μ such that:

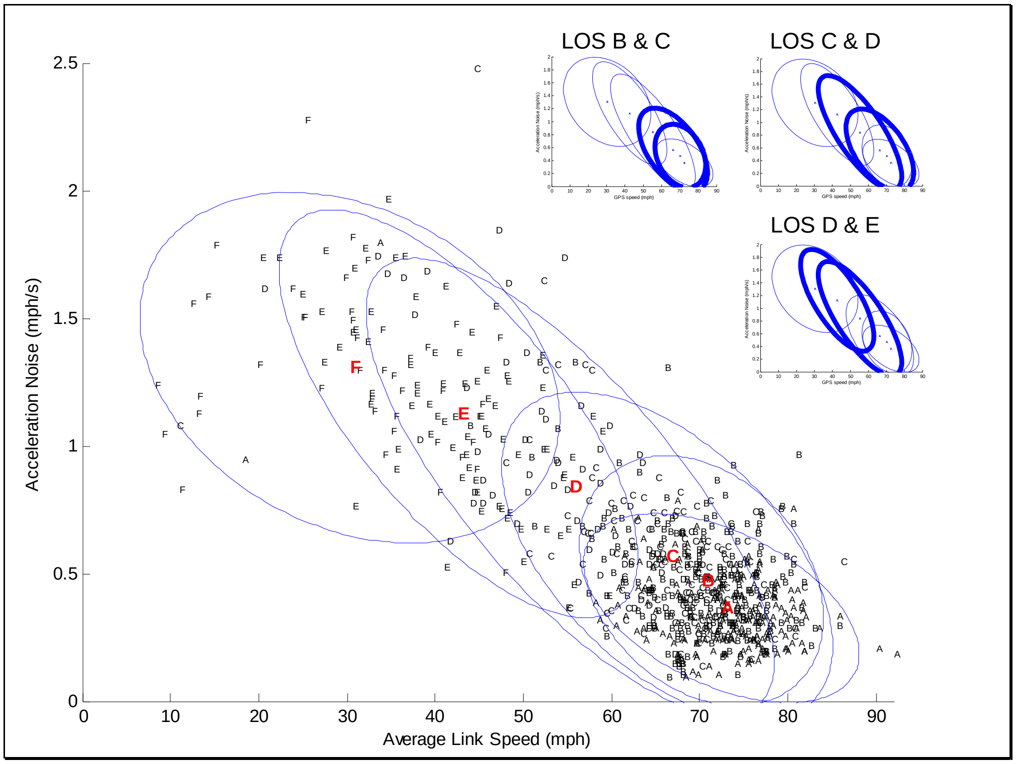
$$n(\bar{x}-\mu)' S^{-1}(\bar{x}-\mu) \leq \frac{p(n-1)}{(n-p)} F_{p,n-p}(\alpha) .$$

The six confidence regions are illustrated in Figure 5(a), where each data point representing one trip is marked by a letter indicating HCM density based LOS and the centroids of the confidence regions are marked by larger bold letters. The relative locations of the centroids indicate that the traffic flow quality measures are reasonably related to density-based LOS in an average meaning. The centroid locations also indicate that LOS A-to-C are closer together compared to D-to-F, which is expected, as free flow speed may be maintained under A-to-C conditions and thus perceivable traffic flow quality under these conditions are likely to be similar.

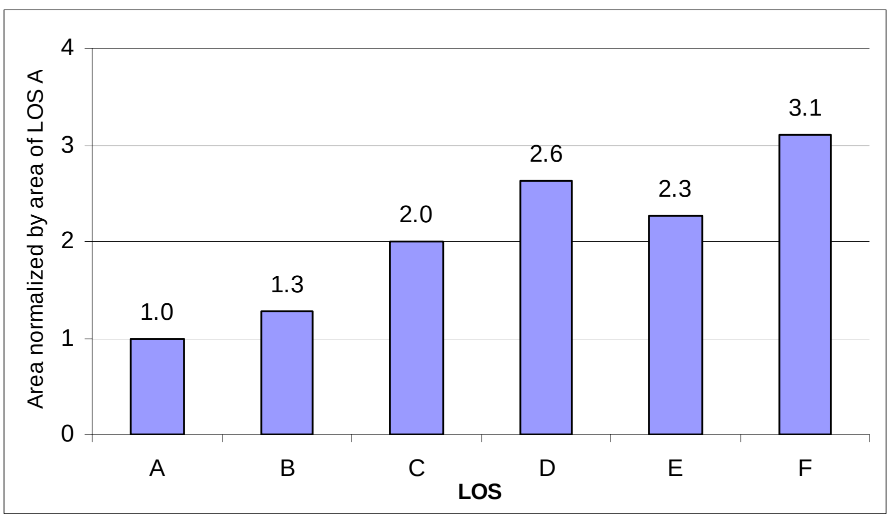
The confidence regions illustrate two aspects of the variability in traffic flow quality experienced by individual drivers. First, drivers may experience the same level of traffic flow quality under different density-based LOS ranges. For example, at a speed of 70 mph and acceleration noise of 0.5 mph/s, density based LOS A through D are all seen to occur. Second, individual drivers may experience significantly different levels of traffic flow quality under the same density-based LOS condition. For example, among the drivers who traversed the segments under a density-based LOS D condition (based on the TMC15-minute aggregate measurements), some drivers experienced the same traffic flow quality as vehicles in the density based LOS A, while others experienced the same conditions as drivers in density based LOS F conditions.

One interesting finding is that the sensitivity of acceleration noise to traffic flow conditions is greater than that of speed under LOS A-to-C. For example, when speed and acceleration noise for a trip are 65 mph and 1.0 mph/s respectively, speed is not enough to distinguish among the LOS conditions while acceleration noise can indicate that the traffic conditions at the time of driving were more likely LOS C or D. In other words, although average travel speed may not be significantly different within the range of A-to-C (as also seen in the HCM methodology), drivers may experience different levels of speed variation. This observation can be associated with the insensitivity of average speed to traffic conditions under a free-flow regime and a potential applicability of acceleration noise to measurement of level of service. This finding also supports the use of acceleration noise as an indicator of traffic flow quality that may not be fully explained by using speed alone.

The variability represented in Figure 5(a) can be quantified by computing the confidence regions areas. The areas were numerically calculated by dividing a whole ellipse into smaller pieces. Figure 5(b) compares the areas of confidence regions for each LOS. As expected, the worse LOS has the wider variation in general except for LOS D which has a greater variation than LOS E. The greater variation of LOS D may be because it is located at the transition point where traffic flow changes from free-flow to forced-flow conditions and thus various traffic conditions are likely to be observed under this range. LOS A has the smallest variation, while LOS F experiences about three times the variation of LOS A. The large variation in LOS D to F implies the instability of traffic conditions under these ranges.



(a)



(b)

FIGURE 5 Confidence regions and areas: (a) 90% confidence regions for speed and acceleration noise by LOS; (b) normalized areas of the regions

The proportion of overlap area was computed to quantitatively examine the variability between density based LOS ranges. The results are summarized in Table 2, where the values represent the percentage of each confidence region that overlaps another. For example, 0.88 in the cell of A (row) and B (column) means that 88% of LOS A confidence region is overlapped with LOS B, while 0.69 in the cell B and A indicates that 69% of LOS B confidence region is overlapped with LOS A. The table indicates that the traffic flow quality of a vehicle classified in density based LOS A conditions may also be observed in LOS B (69%), C (46%), D (25%), and E (5%). More interestingly, LOS D considerably overlaps with all other LOS confidence regions, which is suggestive of its unstable or dynamic traffic flow characteristics. In practice, the understanding of such variability is important because it provides information about the degree of uncertainties behind the density-based LOS system. In this sense, Table 2 suggests an approach to quantifying the uncertainties.

TABLE 2 Proportion of Overlapped Area

LOS	A	B	C	D	E	F
A		0.88	0.93	0.67	0.10	**0.00**
B	0.69		0.99	0.72	0.13	**0.00**
C	0.46	0.63		0.74	0.29	0.06
D	0.25	0.35	0.56		0.57	0.36
E	0.05	0.07	0.25	0.66		0.72
F	**0.00**	**0.00**	0.04	0.31	0.53	

SOME FACTORS FOR THE VARIABILITY

The variability found in the previous section can be attributed by numerous factors such as roadway characteristics, traveling lanes, positions within a platoon, traffic flow dynamics, etc. Although these factors are critical elements in determining the quality of traffic flow, the density-based macroscopic measure has limitations in terms of capturing their full effects. This section discusses whether such factors affect traffic flow quality within a traffic stream.

Roadway

Roadway characteristic effects may be identified by examining the data only within the LOS A condition, since the effects of traffic are negligible in this range. Consequently, the quality of traffic flow can be reasonably assumed to be dominated by roadway effects.

Table 3 shows simultaneous 95% Bonferroni confidence intervals for average speed and acceleration noise obtained from the trips made by eleven drivers commonly found on all the three segments under LOS A condition. The Bonferroni test is an appropriate approach for making multiple comparisons without altering the specified significance level (in this case 5%) (*17*). The use of trips made by such selected drivers was designed to minimize the variance introduced by the driver/vehicle effects. Table 3 indicates that generally, trips made on Segment 2 experienced the best traffic flow quality as suggested by the highest average speed and the lowest acceleration noise while those on Segment 1 experienced the worst. In addition, the confidence intervals in the table suggest that the acceleration noise of Segment 1 is significantly higher than those of Segment 2 at the level of 0.05 although no significant differences in speeds were found along all the segments. This observation is of interest since acceleration noise captured the segment-by-segment differences that might otherwise be overlooked if only speed were considered. This is consistent with the previous finding obtained from the confidence region analysis. Again, the adoption of acceleration noise as an indicator of traffic flow quality appears to be supported.

Table 3 Simultaneous 95% Bonferroni Confidence Intervals for Speed and Acceleration Noise Obtained from Trips Made by Drivers Commonly Found on All Three Segments under LOS A Condition

Segment	Number of Trips	Speed		Acceleration Noise	
		Lower	Upper	Lower	Upper
1	38	70.7	75.0	***0.38***	***0.51***
2	62	73.8	77.0	***0.26***	***0.34***
3	58	70.0	76.4	0.29	0.39

Consequently, the analysis based on the data within the LOS A range implies that the effects of roadway characteristics on the traffic flow quality may exist, although the question about which characteristics of the roadway result in such differences is not explicitly answered here. The answer to the question will be sought in another study which is currently underway by the authors to thoroughly investigate the relationships between vehicle activities and roadway characteristics including the number of lanes, grade, speed limit, segment type (e.g., weaving and basic segment) across major freeway sections in Atlanta.

Vehicle Position

In addition to roadway characteristics, the relative positions of vehicles in a traffic stream (e.g., traveling lanes and positions in a platoon) may affect the perception of traffic flow quality. Unfortunately, the data employed in this study do not provide information on the detailed location of a vehicle in a traffic stream, thus the direct evidences for variability induced by the positional factors cannot be reported in this paper. However, previous research efforts show that the acceleration noise of vehicles far down a platoon is about three times that of the freely moving lead car (*6*) and that traffic flow parameters such as speed, flow, and density may be significantly different lane-by-lane (*5*). These findings may effectively explain the variability of traffic flow quality within a traffic stream due to the vehicle positional factors.

Traffic Flow Dynamics

Another possible factor is the changes in traffic flow within the 15-minute macroscopic data aggregation time interval. As suggested by the areas of confidence regions, the traffic flow dynamics is more apparent in the lower LOS ranges, as shown particularly by the wider scatter patterns observed under LOS D condition.

To examine the existence of the traffic flow dynamics, TMC data collected for one-weekday (November 19, 2003) at one station of northbound GA400 in Atlanta, Georgia were examined in more detail. The station is located near the interchange of GA400 and Interstate 285 where four lanes are present. The selection of a different freeway segment from the ones used in the previous sections was necessary because traffic data aggregated at smaller than 15-minute interval were not available for the I-75 segments (the GA400 data were being collected for a different research project). The data from GA400 are appropriate for this purpose since they were aggregated at 20 second intervals. The traffic data were aggregated by one minute and then aggregated by fifteen minutes to examine the traffic dynamics within every 15-minute interval. Based on the aggregated traffic volume and speed, density was computed by dividing volume by speed and density-based LOS was identified for both 1-minute and 15-minute data.

Figure 6 illustrates one-minute LOS distributions for six 15-minute-based LOS ranges. The figure also provides standard deviations, noted by σ, which was computed by coding LOS A-to-F as numbers 1 to 6, to quantify the degree of dispersion of 1-minute based LOS within a 15-minute LOS range. The distribution pattern and the standard deviations suggest that traffic dynamics exist within 15-minute time intervals and the LOS D range has the greatest dynamics, consistent with the findings in the previous sections.

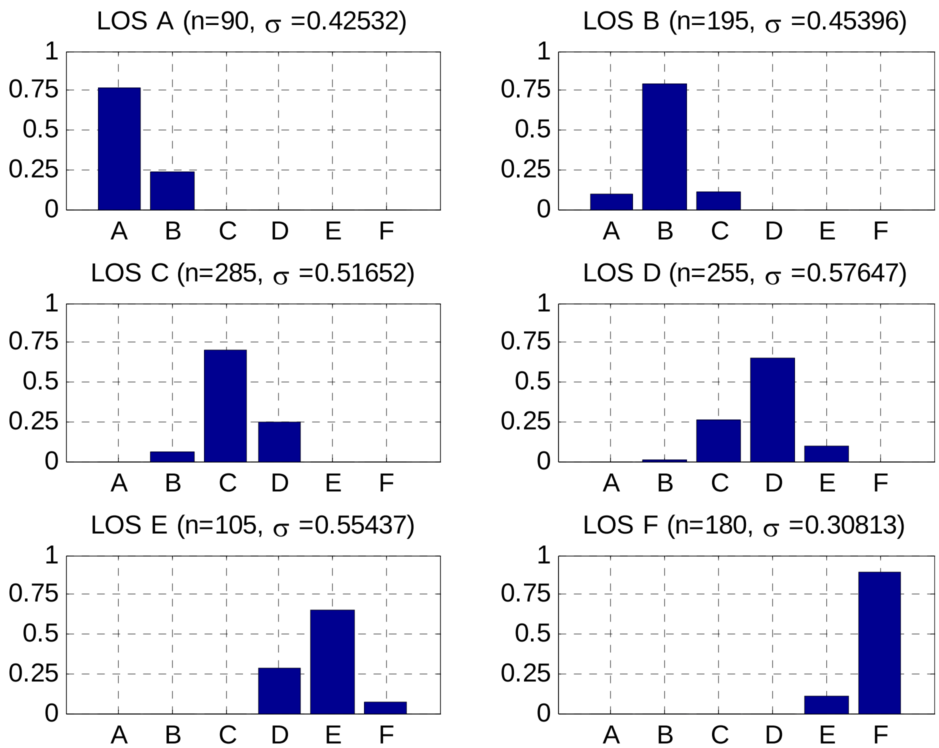


FIGURE 6 Variation within 15-minute traffic flow

CONCLUSIONS

This study investigated the variability of traffic flow quality measured by speed and acceleration noise within and between density-based LOS ranges. These measures were selected as indicators of traffic flow quality, because they directly reflect individual driving experiences. The traffic flow quality measures were compared with each density-based LOS through confidence intervals and ellipses. These comparisons revealed that even under the same LOS condition, drivers may experience significant differences in traffic flow quality, which was most apparent under LOS D range. Additional findings indicated that drivers under different LOS conditions may experience a similar level of traffic flow quality.

The results from this research effort suggest that the macroscopic perspective of the current density-based LOS concept may not be an appropriate representation of the quality of traffic flow faced by individual drivers and that a different roadway performance measure considering the variability should be developed to remedy this drawback. It has also been shown that speed combined with acceleration noise is an excellent candidate measure of traffic flow quality.

The widespread utilization of acceleration noise as an indicator of traffic flow quality will require high-resolution speed profiles, which are currently not available in most regions. However, with today's rapid integration of GPS and communication systems into new vehicles, speed/acceleration profiles will become much more readily available. Temporal and spatial coverage will be available at previously unheard of levels. This situation is likely to remove the barriers and limitations associated with data collection and make non-traditional traffic measures such as acceleration noise feasible. One drawback that will be difficult to address, even with increased integration of in-vehicle instrumentation, is a measure of each driver's perceived traffic conditions. By integrating driver perception surveys or simulation studies into future data collection efforts, research extensions should be able to correlate performance measures such as speed and acceleration noise with a driver's perception of traffic flow.

REFERENCES

1. Highway Capacity Manual. TRB, National Research Council, Washington, D.C., 2000.
2. Pfefer, R. C. Toward Reflecting Public Perception of Quality of Service in Planning, Designing, and Operating Highway Facilities. *Transportation Research Record, No. 1685*, TRB, National Research Council, Washington, D.C., 1999, pp. 81- 89.
3. Hostovsky, C., S. Wakefield, and F. L. Hall. Freeway User's Perceptions of Quality of Service: Comparison of Three Groups. *Transportation Research Record, No. 1883*, TRB, National Research Council, Washington, D.C., 2004, pp. 150-157.
4. Kockelman, K. M. Changes in Flow-Density Relationship Due to Environmental, Vehicle, and Driver Characteristics. *Transportation Research Record, No. 1644*, TRB, National Research Council, Washington, D.C., 1998, pp. 47-56.
5. Carter, M., H. Rakha, and M. Van Aerde. Variability of Traffic-flow Measures across Freeway Lanes. *Canadian Journal of Civil Engineering*, Vol. 26, No. 3, 1999, pp. 270-281.
6. Herman, R. and R. Rothery. Microscopic and Macroscopic Aspects of Single Lane Traffic Flow. *Journal of the Operations Research Society of Japan*, Vol. 5, No. 2, 1962, pp. 74-93.
7. Jones, T. and R. Potts. The Measurement of Acceleration Noise - A Traffic Parameter. *Operations Research*, Vol. 10, No. 6, 1962, pp. 745 - 763.
8. Drew, D. and C. Keese. Freeway Level of Service as Influenced by Volume and Capacity Characteristics. *Highway Research Record, No. 99*, HRB, National Research Council, Washington, D.C., 1965, pp. 1-47.
9. Herman, R., E. Montroll, R. Potts, and R. Rothery. Traffic Dynamics: Analysis of Stability in Car Following. *Operations Research*, Vol. 7, 1959, pp. 86-106.
10. Drew, D., C. Dudek, and C. Keese. Freeway Level of Service as Described by an Energy-Acceleration Noise Model. *Highway Research Record, No. 162*, HRB, National Research Council, Washington, D.C., 1967, pp. 30-85.

11. Babu, Y. and S. Pattnaik. Acceleration Noise and Level of Service of Urban Roads - A Case Study. *Journal of Advanced Transportation*, Vol. 31, No. 3, 1997, pp. 325-342.
12. Ogle, J., R. Guensler, and V. Elango. Commute Atlanta Value Pricing Program: Recruitment Methods and Travel Diary Response Rates. CD-ROM. Presented at 84th Annual Meeting of the Transportation Research Board, Washington, D.C., 2005.
13. Ogle, J., R. Guensler, W. Bachman, M. Koutsak, and J. Wolf. Accuracy of Global Positioning System for Determining Driver Performance Parameters. *Transportation Research Record, No. 1818,* TRB, National Research Council, Washington, D.C., 2002, pp. 12 -24.
14. Croft, F. and E. Clark. Quantitative Measure of Levels of Service. *Transportation Research Record, No. 1005*, TRB, National Research Council, Washington, D.C., 1985, pp. 11 - 20.
15. Barth, M. J., E. Johnston, and R. R. Tadi. Using GPS Technology to Relate Macroscopic and Microscopic Traffic Parameters. *Transportation Research Record, No. 1520,* TRB, National Research Council, Washington, D.C., 1996, pp. 89-96.
16. Conover, W. J. Practical Nonparametric Statistics. New York, John Wiley and Sons, 1980.
17. Johnson, R. and D. Wichern. Applied Multivariate Statistical Analysis. New Jersey, Prentice-Hall, Inc., 1992.