Development of a Freeway Congestion Index Using an Instrumented Vehicle

GLEN S. THURGOOD

The purpose of this study, funded by the Utah Department of Transportation, was to produce a freeway congestion index (FCI). The data required for the FCI can be developed with or without the benefit of automated traffic surveillance or data collection systems. A 9.7-km (6-mi) segment of I-15 in the Salt Lake City metropolitan area was used to test the viability of the FCI. The FCI reflects both the extent (length) and duration of congestion on a given freeway segment and can be used to compare congestion levels on different freeway segments or subsystems, and to compare congestion levels on freeway systems of differing sizes. It can also be used to compare changes in the level of congestion as they occur over time (from year to year or between different seasons of the year). Speed was used as the indicator of congestion onset, with acquisition of the needed data for calculation of the FCI being done using an instrumented moving vehicle. It was also found that measurements taken in a single lane can be used to accurately determine the FCI for all lanes of a six-lane freeway.

Current federal legislation (the Intermodal Surface Transportation Efficiency Act) requires that urbanized areas of the United States implement congestion management systems. To implement such systems it is necessary to settle on a definition of congestion and arrive at an acceptable and repeatable means of measuring it. In this study is an outline of one method of measuring freeway congestion that can be employed regardless of whether the freeway has extensive instrumentation for monitoring traffic flow parameters.

Traffic congestion generally can be described as the operating conditions that exist on any roadway at any point in time when the quality of traffic flow (as measured by parameters such as travel time, speed, delay, etc.) deteriorates below a level acceptable to the user. Traffic congestion on urban freeways generally can be categorized into two types: recurring and nonrecurring. Nonrecurring or incident-based congestion is the result of some planned or unplanned event (e.g., a maintenance operation or traffic accident) that temporarily causes a significant reduction in the capacity of any transportation system. It may be as severe as a total closure.

Although any transportation facility may experience congestion at any time due to an incident, recurring congestion is the type that occurs repeatedly and is time-predictable as to its onset, extent, and duration. It is simply the result of demand exceeding the capacity of some point or section of the freeway, which creates a bottleneck. It could even be referred to as the "background level of congestion" or that level of congestion that could be expected to occur regularly on a given day at a specified location. On Utah freeways, the bottlenecks often occur in weaving sections that are too short or otherwise inadequate, in merge areas downstream of on-ramp noses, at the intersection of off-ramps and arterial crossroads causing exiting traffic to back up and obstruct flow on the freeway main lanes, or as a result of some combination of these three problems.

As a result of its time-predictable, repetitive nature, recurring congestion is easier to deal with than nonrecurring congestion. When a freeway is operating near its capacity, traffic flow becomes unstable and even slight surges in traffic demand will cause congestion to occur and travel speeds to diminish. As long as traffic demand exceeds the available capacity, forced flow [level of service (LOS) F] will occur. Freeway traffic congestion manifests itself in severely restricted speeds and the development of long, slowly moving queues in which stop-and-go driving may occur on the freeway, and long queues and delay may develop on the access system.

The urbanized areas along the Wasatch Front in Utah, from Provo on the south to Ogden on the north are no exception to this generality. Although the duration and severity of congestion on Utah freeways may not be as extensive as in other urban areas, it is nonetheless a major concern to the citizenry and public officials.

The primary objective of this study was to develop and test an index that describes both the extent and duration of freeway congestion. The method of measurement was to be cost effective, to be repeatable, and able to be implemented using equipment and skill levels presently available in the Utah Department of Transportation (UDOT). The index needed to be capable of reflecting changes in congestion levels over time and between segments and systems without the benefit of extensive automated data collection.

CONGESTION INDEX

When Does Congestion Begin?

The logical first step in developing a method for measurement of level of congestion on freeways is to reach agreement on some value or condition that describes when congestion begins. This can be very difficult because congestion is as much subjective (qualitative) as it is quantitative. Although congestion is a commonly occurring phenomenon, there is no commonality of definition as to what level of degradation in the quality of traffic flow constitutes congestion. To make quantitative comparisons between congestion levels at different locations, we must settle on a definition of what constitutes congestion and when it begins. The specific definition may vary according to such variables as type of facility, functional classification, and location.

Speed as an Indicator of Congestion

After extensive investigation of the problem of congestion definition and quantification, for this study (which was limited to measurement of recurring congestion on freeways) an onset-of-

Civil & Environmental Engineering Department, Brigham Young University, Provo, Utah 84602.

congestion definition based on the LOS dropping from E to F (breakpoint, E/F) as determined by speed measurement was selected for the following reasons:

1. A significant reduction in speed below that normally expected or desired is an operational parameter to which drivers relate. When a significant speed reduction is encountered during travel, the driver knows that his travel time is going to be increased and he will be delayed in reaching his desired destination if operation at the reduced speed persists significantly in time and in distance.
2. Speed is a traffic parameter that can be measured rather easily, at relatively low cost, using a variety of devices and methods.
3. Speed is the parameter second-most preferred (24 percent) for use by most agencies in measuring congestion. Delay is the most favored (31 percent). The measurement actually used most often, at present, is LOS (90 percent) (*1*).

Although speed reduction was the parameter used in this study for defining congestion onset, the freeway congestion index (FCI) as developed in this paper is flexible enough to accept other definitions and parameters.

For many years the characteristic speed-flow (volume) relationship for freeways was generally accepted as being similar to that shown in Figures 3 and 4 of Chapter 3, Basic Freeway Sections, of the *Highway Capacity Manual* (HCM) (*2*). Examination of the curve shows a gradual decline in speed as flow increases, with a progressively increasing rate of change of speed as capacity is approached. Speed at capacity (LOS E/F breakpoint) was generally believed to be around 56 kph (35 mph). In January 1995, the 1994 updates to the HCM, including a revised Chapter 3, were released by the TRB. Included were new speed versus flow curves for basic freeway sections. Examination of these curves shows that there is relatively little deterioration in speed from the free-flow speed as traffic flows increase. As capacity is approached, only about a 16-kph (10-mph) decrease in speed to 80 kph (50 mph) is experienced (for a freeway having a 100-kph (60-mph) free-flow speed) before reaching the LOS E/F breakpoint and dropping into LOS F, in which flow is forced and speeds substantially decrease. The new, higher LOS E/F breakpoint speeds no doubt are a reflection of the more aggressive behavior of present-day drivers.

The new maximum densities at the LOS E/F breakpoint are 36.7 to 47.9 passenger cars per mile per lane, depending on the free-flow speed of the facility. These density values are considerably less than the 67 passenger cars per mile lane density given for the LOS E/F breakpoint in the present (1985) HCM. In summary, the revised procedures of the HCM seem to indicate that on freeways the LOS E/F breakpoint seems to occur at significantly higher speeds and lower densities than previously believed.

For purposes of this research, it was decided, in concert with the study advisory panel, that the onset of congestion on Utah freeways would be based on traffic stream speeds falling below a threshold speed of 64 kph (40 mph). This is higher than the old breakpoint speed of 56 kph (35 mph) but lower than the new values of 80 kph (50 mph). This decision was based on the premise that a traffic stream speed of 64 kph (40 mph) is a strong indicator that flow is falling into the LOS F (forced-flow) realm. The speed profile studies performed as part of this study seem to verify this perception. A threshold speed of 72 kph (45 mph) or even 80 kph (50 mph) would not likely have changed the results significantly because, in most instances, once speeds fell below 80 kph (50 mph), they also fell below 64 kph (40 mph).

Use of density as the parameter of choice to determine the onset of congestion was considered but was rejected because of the difficulty and cost of directly measuring density. Aerial photography is about the only reliable way of directly measuring density; however, this type of data collection is expensive and is time-consuming to reduce. Some density measurement using oblique photography was done as a part of this study, with densities in mixed traffic of approximately 50 to 75 vehicles per mile per lane being measured in periods identified as being the onset of congestion.

Development of a Congestion Index

The primary objective of this study was to develop and test an index for quantifying recurring congestion that reflects both its extent (length) and duration. Cottrell (*3*) presented the idea of a lane-mile duration index (LMDI), which came close to providing an index that met these objectives.

$$\mathrm{LMDI}_f = \sum_{i=1}^{m} \mathrm{LM}_i \times D_i \qquad (1)$$

where

i = a two-way freeway segment of uniform capacity, generally between two adjacent access points;
m = the total number of freeway segments in a given urban freeway system;
LM_i = the total lane-miles in freeway segment i; and
D_i = the duration of LOS F congestion, in hours, on i.

In Cottrell's calculation of the LMDI, traffic volumes (annual average daily traffic) from the Highway Performance Monitoring System data base were used as a basis for determining whether a two-way freeway segment of uniform capacity would be expected to experience LOS F congestion during the day and for how long. If any portion of the segment was congested, it was assumed that the entire two-way segment was congested. The LMDI also makes no provision for comparing segments or systems of significantly differing sizes (i.e., lane-miles).

If Equation 1 is normalized by dividing by the number of lane-miles in a freeway segment, then an index is provided that has the units of lane-mile-hours per lane-mile. This enables a direct comparison of the extent (length) and duration of congestion on different freeway segments having differing lengths (i.e., long versus short segments). It can also be used to reflect the level of congestion on the freeway system in an entire geographical area, such as an urbanized area, and compare it with the system in another urbanized area even though the areas may be considerably different in size (i.e., lane-miles of freeway).

The FCI has been developed to measure, in a quantitative manner, the severity of recurring congestion on Utah freeways. Its mathematical expression is given by Equation 2.

$$\mathrm{FCI} = \sum_{i=1}^{n} \left(\frac{\mathrm{CLM}_i \times D_i}{\mathrm{LM}_i} \right) \qquad (2)$$

where:

FCI = Freeway Congestion Index (lane-mile-hours per lane-mile), usually computed per day or per average weekday (AWD);

i = a one-way freeway segment, the length of which is determined by the responsible agency as desired;
n = the total number of freeway segments in a given urban freeway system, or a defined subsystem;
CLM_i = total congested lane-miles in freeway segment i operating at LOS F congestion [e.g., < 64 kph (40 mph)];
D_i = duration of LOS F congestion, in hours, on freeway segment i; and
LM_i = total lane miles in freeway segment i;

Although Equations 1 and 2 appear quite similar, there are some significant differences. First, the segment lengths are defined differently. In the LMDI equation, segment length is for a two-way segment, usually limited in length to the distance between two access points. In the FCI, the segment is directional and its length may be defined as the user desires. Second, the LMDI equation assumes congestion based on two-way volumes and a calculated LOS for the entire link. The FCI equation uses field-measured values for duration and length of congestion, and only that portion of the link that is congested is reported in the calculation. The FCI has the advantage of allowing the summation of multiple segment or lane FCI values. This allows several segments to be grouped together so that system or regional comparisons can be made.

Determining Extent and Duration of Congestion

Any suitable method for determining the time of onset of congestion, how long it lasts, and the number of congested lane-miles with reasonable accuracy can be used to provide the needed inputs for determining the FCI. The one described here is operational below a prescribed speed, but a density criteria could be used as well.

The development of congestion during peak traffic periods is a dynamic process, with the length of the congested area changing from minute-to-minute. As traffic demand volumes begin to approach bottleneck capacity, vehicle speeds decrease and a queue begins to form. As demand continues to increase, the queue is propagated upstream and the congested area lengthens. Initially, only one lane may be affected, but congestion soon spreads to adjacent lanes as drivers shift lanes to avoid the congestion and maintain a higher speed. As long as the vehicle arrival rate at the back of the queue exceeds the departure rate from the front of the queue, the length of the congested area will continue to increase. Once the arrival rate falls below the departure rate, the length of the congested area will begin to decrease until congestion has dissipated.

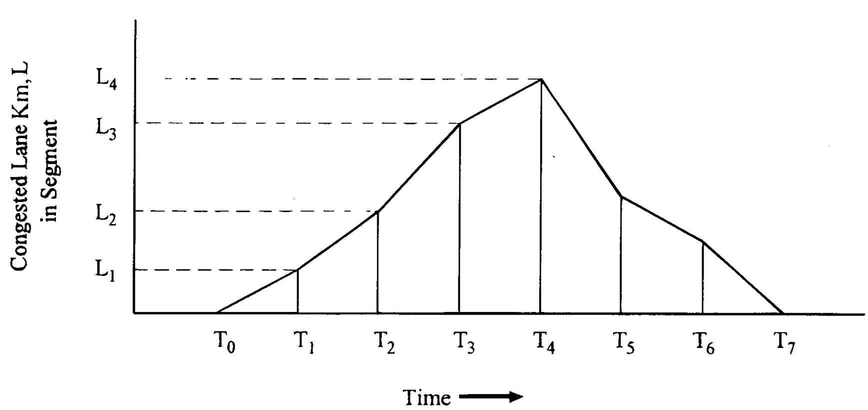
To quantify the extent (length) of the congested area, a sampling process is needed because the extent of congestion will change with time. This process is illustrated in Figure 1. At some time (T_0), congestion, as defined, does not exist but is just beginning to develop. As yet, no major speed reduction has occurred, but congestion is impending. T_0 is determined by the time of the last sample taken during which traffic stream speeds at no point fall below the threshold value of 64 km/hr (40 mph). At some later sampling time (T_1), a slow-moving queue of length (L_1) exists. The length of this queue could also be detected using aerial photography and employing a density criterion for defining the onset of congestion and the length of congested roadway. By periodic sampling (e.g., aerial photography of a given freeway segment at uniform time intervals) a curve such as that in Figure 1 could be developed for a given freeway segment. This can also be done by sampling traffic stream speeds using an instrumented probe vehicle periodically traveling the study segment, as was done in this study, or using some other speed measurement technique. Although the shape of the curve between points of measurement is almost certainly not strictly linear, if the sampling interval ($T_{j+1} - T_j$) is kept short relative to the length of the congested period, a reasonable approximation to the true shape of the curve may be obtained.

The area under this curve represents the product of duration of congestion and length of the congested area ($CLM_i \times D_i$) as required for computation of the FCI. The computational process can, of course, be done stepwise using the relationship

$$CLM_i \times D_i = \sum_{j=1}^{m} \frac{(L_{j+1} - L_j)}{2} \times (T_{j+1} - T_j) \qquad (3)$$

where

j = successive observations of the congested area, 1 to m;
T_0 = the latest observation (time) during which no congestion is detected;



T_0 = the latest sampling time during which no congestion is detected

T_j = the time at which L_j lane miles of congestion is measured

FIGURE 1 Development of congestion on a freeway segment over time.

T_j = the observation time at which L_j lane-miles of congestion is measured;
L_j = number of congested lane-miles measured at time j, and CLM_i and D_i are as previously defined.

This becomes the computation of the area of successive trapezoids in Figure 1. Once this computation has been done for a selected segment (i), then the FCI for that segment is computed by dividing the sum arrived at using Equation 3 by the total number of lane-miles in that segment (LM_i).

For the calculation of the FCI for a larger system, such as the freeway system in a given urban area (or a defined subsystem), the system could be subdivided into logical segments, the product of the number of congested lane-miles and duration for each segment determined as described above, these products summed, and the total divided by the number of lane-miles in the system (or subsystem) to yield an FCI for that system (or subsystem). The FCI would usually be computed for each weekday and averaged for an AWD-FCI. The computed FCI for that system could then be compared with that computed for another system to give a relative value for the level of congestion between the two. Comparison of changes in the level of congestion over time in a particular system could be accomplished by determining and comparing the FCI from year-to-year or season-to-season.

PILOT STUDY

To investigate the applicability of the FCI, a pilot study was performed on a 9.7-km (6-mi) segment of I-15 in the Salt Lake City metropolitan area. Speed, distance, and travel time data were collected during the morning and evening peak periods, in both the northbound (a.m. peak period) and southbound (p.m. peak period) directions, for 1 week during August 1993, supplemented with additional observations during October 1993.

To calculate the FCI, it is necessary to determine the time of onset, duration, and extent (length) of congestion. The onset of congestion was defined as the time when traffic speeds at any point within the study section dropped below some threshold value, in this case 64 kph (40 mph). The duration of congestion was defined as the time from the onset of congestion to the time when traffic speeds within the segment no longer fell below the threshold value. The extent of congestion was defined as the distance between the points where the speed of the traffic stream dropped below, and then went back above, the threshold value. Thus, the measurement method selected would need to track speeds versus distance along the segment, as well as keep track of the times of onset and dissipation of congestion, and times the length of congestion was measured. Several congested subsections could exist within the study segment.

Study Segment Description

The Salt Lake City metropolitan area lies at the crossroads of two Interstate highways, I-80 and I-15. In addition to being the dominant north-south through-traffic carrier, I-15 is the major commuter route serving traffic traveling to and from the central business district (CBD) of Salt Lake City and suburban communities to the north and the south of the city. East-west traffic is carried to I-15 via perpendicular arterial cross streets. This particular segment of I-15, located south of the CBD, is a six-lane facility (three lanes per direction) and is inside the I-215 loop.

In the northbound, a.m. peak direction, recurring congestion occurs beginning at the merge areas of on-ramps from I-215 and from interchanges at 5300 South, 4500 South, and 3300 South. The latter three of these are ramps from arterial cross roads having compressed diamond interchange configurations with two-way service roads, and they exhibit similar congestion characteristics. The former consists of a single-lane loop on-ramp from eastbound I-215 followed by a two-lane on-ramp from westbound I-215 with the two ramp lanes merging into the same outside through-lane of I-15. This particular geometric configuration is a violation of the AASHTO lane-balance criteria and creates a particularly hazardous merge situation during periods of heavy traffic, with slowing and eventual backups occurring in all three through lanes.

During peak periods, mainline slowing occurs at all of these on-ramp merge locations caused, in part, by an insufficient number of gaps in the outside lane to accommodate the number of merging vehicles. This problem is exacerbated by the fact that the signalized intersections at the ramp terminals operate at capacity during the peak periods, requiring the use of long cycle lengths to maximize intersection capacity. This, in turn, results in the release of large queues onto the ramps, which causes a surge of traffic to arrive at the ramp merge area.

In the southbound, p.m. peak direction, the 5300 South, 4500 South, 3300 South, and the I-215 and I-15 interchanges were again included within the study area limits. Mainline slowing at on-ramp merge locations occurs on I-15 at the 3300 South, 4500 South, and 5300 South interchanges. At the I-215 and I-15 interchange, mainline slowing on I-15 occurs because of the merge of single-lane ramps from both eastbound I-215 and westbound I-215.

In addition to exhibiting similar congestion characteristics, these sites were chosen based on the following:

- The causes of congestion observed at each site was representative of the causes seen at other Utah sites.
- This study area was small enough that extensive data could be collected in a cost-effective manner.
- Methods used in collecting data were repeatable.
- Potential remedies to recurring congestion could be studied in conjunction with data collection efforts.
- This site represented an area where recurring congestion causes noticeable effects and has a high impact on commuter traffic. It is one of the more congested segments on the freeway system in Utah.

Northbound data collection began at the westbound I-215 diverge from northbound I-15 and ended at the eastbound I-80 diverge from northbound I-15. The southbound segment began at the westbound I-80 merge with southbound I-15 and ended at the 7200 South off-ramp diverge from southbound I-15.

Data Collection Methodology

There are no advanced traffic surveillance or traffic management technologies presently in place on Utah freeways. The only permanent remote data collection devices in this segment are permanent counting stations for volumes and speeds midway between each of the diamond interchanges. Volume data were collected at these locations during the study period. Traffic densities, as supplemental data, were also obtained during the study through the use of oblique aerial photography. Three probe vehicles were instrumented to allow them to collect speed, position, and related data.

Vehicle Instrumentation

Instrumentation consisted of a distance measuring instrument (DMI), a laptop computer, and the Moving Vehicle Run Analysis Package (MVRAP) developed by the University of Florida (*4*). The DMI was connected to the transmission of the probe vehicles and to the laptop computer. The transmission gives off a certain number of pulses for each unit of distance traveled by the vehicle and these pulses are converted into speeds and distances. This system keeps track of time, distance traveled, and speed. A speed profile (a continuous plot of speed versus distance) can be obtained for any traveled roadway segment. In addition, the time the vehicle passes the beginning and ending points of the study segment and, thus, the elapsed time to traverse the segment are recorded by the software.

The software records speed information from the DMI at 60-m (200-ft) increments along the test segment and notes the locations of link ends. When plotted, speeds along the segment are printed as points, each at approximately 60-m (200-ft) intervals. Using this plot, in conjunction with run start and end times, it is possible to determine the parameters needed to calculate the FCI.

Data Collection Preparation

The first data collection run, also known as the calibration run, required the vehicle driver to mark the starting and ending point of the segment, as well as each link end location (e.g., merge points, etc.) within the segment, by pushing the computer space bar as the point was passed. Each of these points of interest had been previously marked for easy identification. From this, the MVRAP software was able to set all the distances between the starting and ending point, as well as all link end points. The calibration run must be very precise in locating starting, ending, and link end points, because all subsequent runs are referenced to the calibration run. During subsequent runs, the driver needed only to identify the starting and ending point for the entire pilot segment by pushing the computer space bar as the reference point was passed.

For each run it was important for the vehicle to follow the same path, and for the driver to push the space bar at the same starting and ending point location as for the calibration run. The software is tolerant of small errors and will allow slight adjustments in subsequent run lengths to be made. However, the software will discard all data collected for runs that show a discrepancy of greater than 2 percent of the calibration run length, or 60 feet for link lengths or 120 feet for the total segment length, whichever is less. Driver experience and care become important.

Data Collection Procedure

Proper orientation of the probe drivers before beginning data collection is critical to a successful effort. After orientation, all three vehicles, one following directly behind the other, proceeded onto I-15 and into their preassigned lane (outside, middle, or inside) so that each passed the starting point at approximately the same time.

Speed and distance data for each lane were obtained, enabling the production of speed profiles and computation of the FCI for the entire segment. Comparisons of the outside and inside lanes with the middle lane and with the average of all three lanes could be made to determine lane differences. The hope was that a good correlation could be established between the extent and duration of congestion in one lane and the total for all lanes. Data could then be collected in one lane only and still yield a reasonable FCI for the entire section, thus lowering data collection and reduction time and costs.

Each vehicle then traveled as an "average car" in its respective lane until it passed the segment ending point. They then exited the freeway at the next interchange, reversed direction, and returned to the starting point to begin another run. At the completion of each run, all three cars would once again meet before proceeding with the next data collection run. During the study, no recurring congestion occurred in the off-peak direction, otherwise data would have been collected in this direction as well. The length of the study section was chosen, in part, so that a trip by the probe vehicles could be made through the section every 20 to 30 min.

This method was selected for the pilot project because it could be done within existing budgets using equipment available within UDOT and could be repeated using existing UDOT personnel. It is applicable to any freeway not having advanced technologies in place for monitoring traffic flow conditions.

Data were collected in each of the three lanes during the morning and evening peak period, Monday–Friday, August 16–20, 1993. Data collection began before the usual time of onset of congestion and continued until congestion had dissipated. A minor amount of congestion was sometimes encountered during the first data collection run, in which case the time marking the onset of congestion was estimated based on observations in the adjacent lanes or on the experience of other days.

Because this study was focused on quantifying recurring rather than incident-based congestion, it was essential to record all incidents that were observed by the probe drivers. In addition, traffic reports by local radio stations were monitored for news of such incidents. One member of the study team was able to observe traffic conditions while flying with an aerial traffic reporter, noting any incidents that occurred. In addition, each driver made note of any observed incidents. This became very helpful when interpreting results.

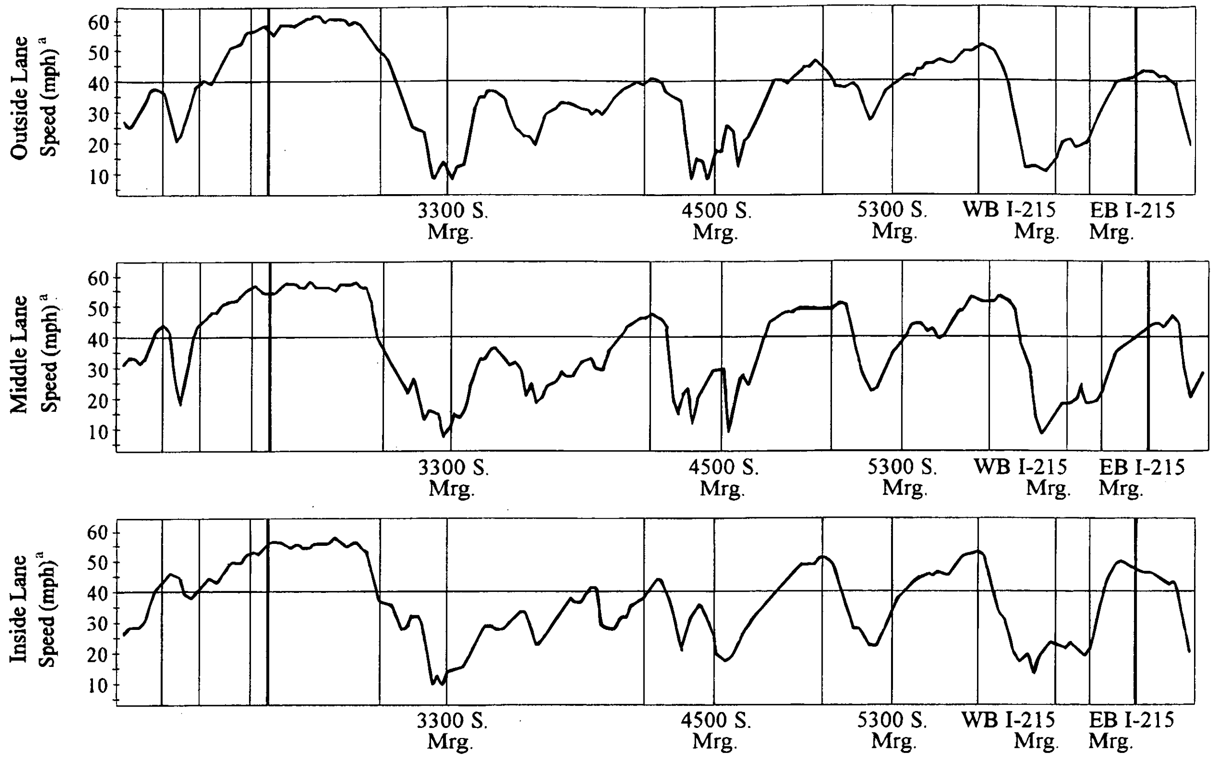
Data Reduction

Speed Profiles

All data collected by the three vehicles were combined into one file, and a speed profile was printed for each run in each lane during the week. A summary was made noting the run start and end times, the travel time between each link, the number of stops within the section, and the average running speed within each link, as well as overall segment average running speed.

After the plots were printed, all of the plotted speed points were manually connected. Each point represented the average running speed of the vehicle over a 60-m (200-ft) travel increment. Each speed profile plot occupied several sheets of paper and therefore were printed using a dot-matrix, continuous-feed printer.

Using the plot and the run information data sheet, the following information was obtained for each run:



[a]1 Km/h=0.6 mph

FIGURE 2 Speed profile well into the congested period, outbound (southbound) direction.

- The overall length of the study segment.
- The length of each congested section [i.e., traffic speed less than 64.4 km/hr (40 mph)] within the segment.
- The time between the end of one run and the end of the following run.

A typical speed profile run during the congested part of the outbound (p.m. peak) direction is shown in Figure 2.

Length of Each Congested Section Within the Study Segment

Link lengths for each link in the section are shown on the left side of the run information data sheet, as is the total or overall length of the segment. To calculate the FCI, the total number of lane-kilometers (lane-miles) within the pilot section is required. In this case, this value is three times the length of the segment because there are three lanes throughout the segment.

Each link length was used to establish a horizontal scale on the speed profiles. Once the speed points on the plot were connected, a line was drawn horizontally across the plot at 64.4 km/hr (40 mph). A congested section was defined by the point at which the vehicle speed line dropped below 64.4 km/hr (40 mph) to the point that it went back above the same line.

The total congested length for each lane was determined for each run by scaling it off the plot. When a plot was missing because of a run length problem, congested lane-kilometers (lane-miles) were estimated based on the values obtained in the other lanes if available. For an operational tool, the MVRAP software could be modified to yield the distance traveled below any selected speed and eliminate the need for this manual calculation. In fact, the software could be modified to yield the FCI itself.

Time Between Runs

The software records the travel time, in seconds, for each link and the total travel time for the entire segment for each run. The start time for the run is also recorded. The run end time (T_j) was obtained by adding the total travel time to the run start time. The difference between the ending time of one run and the ending time of the next, obtained in a similar manner, gave the duration for that run.

SUMMARY OF FINDINGS

Pilot Study FCIs

Using the procedures outlined above, Equation 3 was used to determine the product of congested lane-kilometers (lane-miles) and duration. The time taken by the probe vehicle to make a complete run from the end of the test section and return to the same point is the sampling period duration. The duration of each sampling period ranged from 19 to 44 min depending on the severity and extent of congestion, with most intervals being between 20 and 30 min. If a shorter sampling period is desired, it can be accomplished by sending multiple instrumented probes through the study segment at specified time intervals.

Equation 2 was then used to calculate an FCI for each of the three lanes, by direction, for each day of the week that sampling was done. The lane FCIs were then combined to yield an average FCI for each direction for each day of the week and an AWD-FCI. These values are summarized in Table 1 and are graphically portrayed in Figure 3.

The patterns on Tuesday, Wednesday, and Thursday were similar, with outbound (southbound) FCIs ranging from a low of 0.901 on Tuesday to 1.217 on Thursday evening. The patterns on Monday and Friday were significantly different (higher), with the highest outbound FCI being 1.892 on Friday. For the AWD (Monday–Friday) the outbound AWD-FCI was 1.298 lane-kilometer-hours per lane-kilometer. To lend some perspective, it should be noted that the FCI can range from 0 (no congestion) to a maximum of 24 lane-mile-hours per lane-mile for a 24-hr period. A value of 24 means that all lanes were operating below the threshold speed of 64 kph (40 mph) for all hours of the day.

In the a.m. (inbound) peak direction, the calculated FCIs were substantially lower, ranging from 0.303 to 0.598, as shown in Table 1. An AWD-FCI could not be accurately calculated for the inbound direction because data collection for Friday was terminated as the result of a traffic accident in the northbound lanes, which substantially increased the level of congestion. This deficiency should have been compensated for by collecting data the next Friday, but it was not done.

It should be noted that the inbound FCIs were substantially lower than those for the outbound direction, a reflection of the fact that the evening peak traffic flows persisted substantially longer than the morning peaks. The day-of-week inbound pattern at first seemed to be different from the outbound pattern, with the inbound (a.m.) FCIs appearing to be somewhat more constant. The highest inbound FCI was found on Tuesday, which is not what one would normally

TABLE 1 Freeway Congestion Index (FCI)

Southbound I-15 -- P.M. Peak Period

Date of Data Collection	Inside Lane CLM * D	Middle Lane CLM * D	Outside Lane CLM * D	Average	Standard Deviation	SLM	FCI
Mon. 8/16/93	7.937	8.810	9.837	8.861	0.951	6.066	1.461
Tues. 8/17/93	4.808	5.683	5.899	5.463	0.578	6.066	0.901
Wed. 8/18/93	5.980	5.967	6.641	6.196	0.385	6.066	1.021
Thur. 8/19/93	6.706	7.610	7.826	7.381	0.594	6.066	1.217
Fri. 8/20/93	11.370	11.369	11.695	11.478	0.188	6.066	1.892
Average Weekday FCI							1.298
Tues. 10/26/93		2.772				6.066	0.457
Thur. 10/28/93		1.642				6.066	0.271
Adjusted Average Weekday FCI							0.466

Northbound I-15 -- A.M. Peak Period

Date of Data Collection	Inside Lane CLM * D	Middle Lane CLM * D	Outside Lane CLM * D	Average	Standard Deviation	SLM	UFCI
Mon. 8/16/93	2.517	---	---	---	---	5.686	0.499 *
Tues. 8/17/93	2.911	3.512	3.779	3.401	0.445	5.686	0.598 **
Wed. 8/18/93	1.253	1.971	2.199	1.808	0.494	5.686	0.318
Thur. 8/19/93	1.650	1.910	1.601	1.720	0.166	5.686	0.303
Fri. 8/20/93	---	---	---	---	---	5.686	---
Average Weekday FCI (4-day week)							0.429
Tues. 10/26/93		4.505				5.686	0.792
Thur. 10/28/93		3.043				5.686	0.535
Adjusted Average Weekday FCI (4-day week)							0.632

CLM = Congested lane miles in segment i.
D = Duration of congestion in hours.
SLM = Total lane miles in segment i.
Adjusted Average = Adjusted to an equivalent 5-day sample
* Adjusted to the average of all lanes based on inside lane measurements only.
** Transients (see Table 1) were effecting congestion levels.

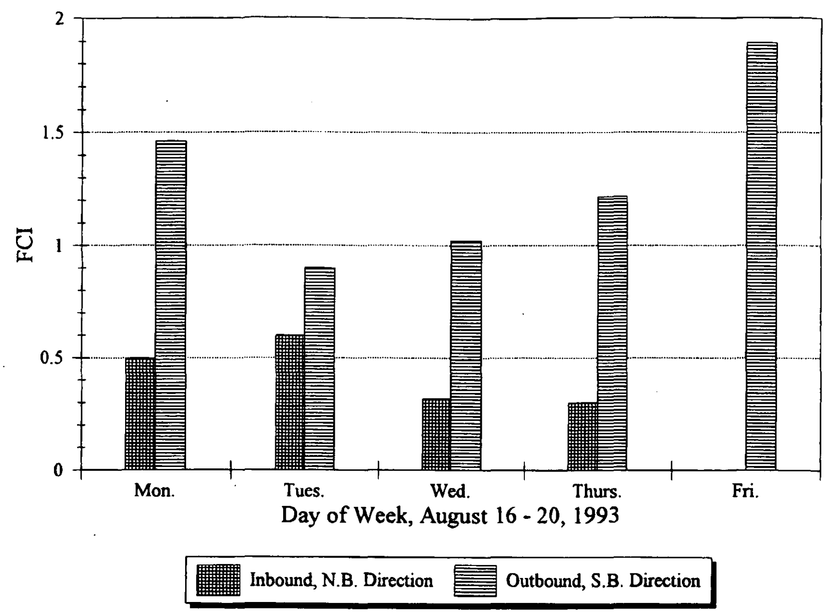


FIGURE 3 Inbound and outbound August FCI values by day of week.

expect. This anomaly is probably explained by the fact that during this particular observation period two transients were observed pushing a shopping cart along the shoulder of the freeway. The probe drivers thought that this may have been causing an increase in the level of congestion that particular morning. The elevated FCI (0.598) was confirmation of that. Taking this situation into consideration, it is probable that the inbound and outbound patterns were similar but with the inbound FCIs being substantially smaller, which was expected.

The question could be asked whether traffic during this particular week represents a typical August week. To answer this question, traffic volume data for the week of the study were compared with data from August 1992 and were found to be very similar. Thus, it was concluded that traffic flows were normal during the data collection period for the pilot study.

Seasonal Variations

Because seasonal variations in traffic flows are a normal occurrence, it would be reasonable to expect seasonal variations in congestion levels, just as there are daily variations. This situation can be handled by making sampling runs for a week during months representative of the four seasons of the year, much as is done with seasonal sampling of traffic volumes.

To give an idea of the seasonal variations, data collection runs were made on Tuesday and Thursday, October 26 and 28, 1993. The directional FCIs for these 2 days are also shown in Table 1. Interestingly, although the outbound peak FCIs of 0.457 and 0.271 for Tuesday and Thursday, respectively, were much lower than for the same days in August, the inbound peak FCIs were 32 and 77 percent higher than the corresponding August values. The only explanation we have is that this was the week of deer hunting season in Utah, an activity in which a lot of people participate, and this may have altered normal traffic behavior.

Determining the FCI Using Data From a Single Lane

It would be much less expensive to determine the FCI if the required data could be obtained using a probe vehicle in only one lane instead of all lanes of the freeway. This possibility was investigated by using linear regression analysis to compare the FCI for each of the three lanes with the FCI for all lanes combined. Regression equations were developed for each of the three lanes as compared with the average FCI for all lanes combined. The coefficients of determination (*r2*) were all very high, with the lowest being 0.968 and the highest being above 0.990, indicating a very good correlation between an FCI value based on data collection in a single lane and the FCI value based on data from all three lanes.

For an overall, bidirectional FCI based on measurement of congestion in the middle lane, the equation is

$$FCI_{all} = -0.006 + 0.990 \times (FCI_m) \quad (4)$$

where FCI_{all} = the FCI for all lanes, and FCI_m = the FCI based on measurement of congestion extent and duration in the middle lane.

For this equation, r_2 was 0.997 at the 95 percent confidence level. Similar equations were developed for the FCI based on measurement of congestion in any lane.

Implementation in a Freeway Traffic Management System

The FCI could readily be determined using automated traffic data collection. Speed measurement could be done using fixed detectors placed in the freeway lanes. A detector spacing of 0.53 to 0.8 km (1/3 to 1/2 mile) as recommended (*5*) for economical incident detection is suggested. Detector placement should be designed so that speed reductions can be detected in merge areas and other locations where recurring congestion usually begins. Speeds could be sampled at uniform intervals of time to determine the onset of congestion and the extent (length) of the congested area. Software would need to be developed to permit the automated calculation of the FCI.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are made based on the results of this research.

1. An FCI was developed and tested that can be used to quantify both the extent (length) and duration of freeway congestion, based on a definition of the threshold of congestion as being freeway traffic stream speeds below 64.4 km/hr (40 mph).
2. The FCI can be used employing a freeway congestion definition based on a parameter other than speed, such as density, as long as the extent of congestion [number of congested lane-kilometers (lane-miles)] and duration (length of time the congestion persists) can be measured at reasonably short time intervals (e.g., 20 to 30 min).
3. Speed profiles created using an instrumented "average" probe vehicle traveling in a single lane can be used to quantify both extent and duration of congestion for use in calculating an FCI. Although the level of congestion generally decreases somewhat going from the outside lane to the inside lane, regression equations have been developed that accurately provide an FCI for all lanes based on measurement of congestion in only one lane.
4. The FCI should be usable in a congestion management system to compare changes in the congestion level on a freeway segment, subsystem, or system over time, including before-and-after comparisons of the effects of congestion management programs. It can also be used to compare levels of congestion on different segments, subsystems, or systems, including comparisons between freeway systems in different urban areas.

REFERENCES

1. Lomax, T., H. Pratt, H. S. Levinson, P. N. Bay, G. B. Douglas, and G. Shunk. *Quantifying Congestion.* Texas Transportation Institute, Interim Report 7-13. College Station, Tex., 1992.
2. *Special Report 209: Highway Capacity Manual.* TRB, National Research Council, Washington, D.C., 1985.
3. Cottrell, W. D. Measurement of the Extent and Duration of Freeway Congestion in Urbanized Areas. In *Compendium of Technical Papers, 61st Annual Meeting*, Institute of Transportation Engineers, Washington, D.C., 1991, pp. 427–432.
4. *Moving Vehicle Run Analysis Package, A System for Evaluating Urban Congestion with Moving Vehicles.* University of Florida Transportation Research Center, distributed by McTRANS, Gainesville, Fla.
5. Marsden, B. G., and H. B. Wall, III. *Intelligent Data for Vehicle Detection*, SAE Technical Report Series 931924. Society of Automotive Engineers, Warrendale, Pa., 1993.

Publication of this paper sponsored by Committee on Freeway Operations.