Traffic Analysis Toolbox Volume VI:

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U.S. Department of Transportation
Federal Highway Administration

Foreword

Traffic analysis tools are used pervasively by transportation professionals to analyze transportation systems. While traffic analysis tools have the capability to provide meaningful insights into transportation analyses, far too often the definition and interpretation of the output measures of effectiveness vary between the analysis tools.

The purpose of the Definition, Interpretation, and Calculations of Traffic Analysis Tools Measures of Effectiveness document is to provide transportation professionals with an understanding of some of the most commonly used measures of effectiveness (MOEs) generated by traffic simulation and analytical tools, and to provide guidance on the calculation of the MOEs in some of the common analysis tools. It is hoped that this document will assist the transportation community in creating a more consistent process in the interpretation of MOEs from various analysis tools.

The intended audience for this report is the transportation professional or manager who needs an understanding of the MOEs generated by traffic simulation and analysis tools.

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16. Abstract

This report presents the results of an investigation into the appropriate definition, interpretation, and computation of measures of effectiveness (MOEs) for traffic operations and capacity improvements. Information and guidance on which MOEs should be produced, how they should be interpreted, and how they are be defined and calculated in traffic analysis tools are detailed in this report. The document recommends a basic set of MOEs that can help rapidly assess the current problems, and benefits of alternative improvements at the system level, in a form readily understandable by the decision-maker. These basic set of MOEs for decision-making consists of five basic measures: 1) throughput, 2) mean delay, 3) travel time index, 4) Freeway segments at breakdown, and 5) surface street intersections with long queues, turn bay overflows and exit blockages. The report recommends that vehicle trajectories should be used as the common denominator for comparison of results between tools and methods between field data collection and analytical tools (HCM, Microsimulation, etc.). At this microscopic level, the analyst can compare field data to analysis tool outputs, whether the tool is microscopic or macroscopic.

Finally, this report concludes by illustrating the computation and interpretation of the recommended systemwide MOEs for a freeway and an urban arterial street.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
^oC	Celsius	1.8C+32	Fahrenheit	^oF
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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EXECUTIVE SUMMARY

This report presents the results of an investigation into the appropriate definition, interpretation, and computation of measures of effectiveness (MOEs) for traffic operations and capacity improvements.

STUDY OBJECTIVES

The goal of this study was to develop information and guidance on which MOEs should be produced, how they should be interpreted, and how they are be defined and calculated in traffic analysis tools. Specific objectives of the study were to:

1. Gain an understanding of the current use and interpretation, by transportation professionals, of some of the most commonly used MOEs generated by traffic simulation and analytical tools, such as HCM procedures;

2. Identify how field measurements are processed to estimate the MOEs used in conducting traffic analysis studies;

3. Provide guidance on how these MOEs are defined and calculated in the tools;

4. Develop an innovative approach to interpret these MOEs when conducting traffic analysis studies; and

5. Demonstrate the validity of the approach through a case study of representative tools.

STUDY APPROACH

The above objectives were accomplished in the following five tasks:

1. A review of current practice regarding the use and interpretation of commonly used MOEs (Task B);

2. A review of how MOEs are computed from field data (Task D);

3. A review of how MOEs are defined and computed within traffic simulation models and the Highway Capacity Manual (Task C);

4. Development of innovative approach to interpret MOEs produced by traffic studies (Tasks D and E); and

5. Demonstration of innovative approach on a case study (Task F).

THIS REPORT

The intended audience for this technical report is transportation planners, traffic analysts, traffic engineers, and decision-makers. The purpose of the report is to educate transportation professionals on how to correctly interpret their findings and present them

in a manner that clearly supports their recommendation and is easy to comprehend by the decision-makers and the public.

MEASURES OF EFFECTIVENESS (MOES)

The purpose of computing one or more traffic performance measures of effectiveness is to quantify the achievement of a project's traffic operations objectives. This study identified seven basic measures of effectiveness, which are the building blocks of most existing and potential future systems for evaluating the traffic operations performance of highway facilities. They are:

- Travel Time;
- Speed;
- Delay;
- Queue;
- Stops;
- Density; and
- Travel-Time Variance.

Travel time, speed, and delay are closely related measures of the amount of time that the general public must expend in order to complete their trips on the system.

Queues are indicators of operational problem spots within the system where capacity inefficiencies and/or safety problems may exist because of intersection blockages or turn bay overflows.

Stops, delay, and speed are inputs into signal timing optimization algorithms and into fuel consumption and air pollutant emission computations.

Density is used in the Highway Capacity Manual (HCM) to compute level of service for uninterrupted flow facilities (facilities without stop signs or traffic signals).

Travel-time variance currently is a little used performance measure that will soon become an important component of various travel-time reliability indices being proposed for the assessment of the benefits of traffic operations improvements.

In addition there are two commonly used indicators of performance that are used to communicate to decision-makers the quality of the facility performance:

- Highway Capacity Manual (HCM) Level of Service; and
- Volume/Capacity.

Poor letter grade levels of service (e.g., "F") and volume/capacity ratios greater than 1.00 are readily recognizable indicators of poor traffic operations.

Table 1 describes how these MOEs are typically used in practice. More details are provided in Chapter 2 of this report.

FIELD MEASUREMENT OF MOES

Table 2 summarizes the techniques commonly used to measure each MOE in the field. These field measurement methods are often mimicked in simulation models to compute MOEs. More details are provided in Chapter 3 of this report.

SIMULATION OF MOES

There is, of course, a significant difference in how macroscopic, analytic tools compute MOEs and how microscopic simulation tools compute the same nominal MOEs. However, even among microscopic simulation tools, there are a wide variety of methods used to compute MOEs.

For example, some simulation tools compute the vehicle miles traveled only for vehicles that enter the link during the analysis period. Others include the vehicles present on the link at the start of the period, presuming that they traveled the full length of the link. Others include step-wise integrate the distance traveled on a second by second basis. Others include only the vehicles able to exit the link during the analysis period.

Another example is the computation of vehicle hours traveled (VHT). Some simulation tools include the delay incurred by vehicles denied entry to the system. Most others do not. The analyst must remember to add the delay in, when appropriate.

Most tools measure delay against the coded free-flow speed of the link. Some take into account the effect of maximum safe turning speed and reduce the computed delay accordingly. One tool measures delay against each driver's desired travel speed, not the link free-flow speed.

There is a great deal of variation among the tools in the reported queue lengths for a signal, even under low-flow, pretimed signal conditions when only uniform delay occurs. The variations are related to the geographic area included in the search for queuing vehicles and the definition of what constitutes a queuing vehicle.

Simulation model MOEs are usually not directly translatable into Highway Capacity Manual (HCM) level of service measures, because the HCM bases hourly level of service on the performance of the facility during the peak 15-consecutive-minute period within the analysis hour. Also, most all simulation tools report the density of vehicles, while the density used in HCM level of service (LOS) for uninterrupted flow facilities (no signals or stop signs) is the passenger-car equivalent in passenger car units (pcu) of the actual density of vehicles on the facility.

Chapter 4 provides more detail on the variety of methods used to compute the MOEs by the Highway Capacity Manual and various traffic analysis tools.

Table 1. Common Usage of MOES in Practice.

Building Blocks of Performance Measurement Systems

MOE	Typical Usage
Travel Time	• Used in long-range planning studies at regional or corridor level to evaluate traveler benefits of alternative improvements. • Used to evaluate traveler benefits of signal timing improvements for individual facility.
Speed	• Used to evaluate alternatives in long-range planning studies at regional or corridor level. • Used to evaluate benefits of signal timing improvements for individual facility. • Used to estimate fuel consumption and air quality impacts.
Delay	• Used to evaluate alternatives in long-range planning studies at regional or corridor level. • Used to evaluate benefits of signal timing improvements for individual intersection or facility. • Used to compare different degrees of congestion (Level of Service F). • Used to estimate fuel consumption and air quality impacts.
Queue	• Used to identify hot spots, operations problems at points of facility (left turn bays, blockages, safety).
Stops	• Used to evaluate fuel and air pollution savings of signal timing improvements for individual facility.
Density	• An input to the Highway Capacity Manual level of service for uninterrupted flow facilities.
Travel-Time Variance	• Rarely used due to difficulty of computation. Potential use for evaluating benefits of traffic operations improvements that reduce variability but not mean travel time or delay.

Indicators of Performance

MOE	Typical Usage
HCM Level of Service	• Used to determine if facility design (for a given set of signal control parameters) will provide acceptable traffic operations as reported for the peak 15 minutes.
Volume/Capacity	• Used in planning studies to quickly determine if facility has sufficient number of lanes (sizing the facility) regardless of signal timing.

Table 2. Field Measurement of MOES.

Building Blocks of Performance Measurement Systems

MOE	Field Measurement Technique
Travel Time	• Travel time can be measured in the field through a variety of instrumented vehicle or vehicle tracing techniques. Mean travel time is the simple average of the traced vehicle travel times. • Mean travel time can be estimated from point measurements of speed (less accurate than tracing techniques), such as at video or loop detectors. The road segment length represented by the detector is divided by the harmonic mean speed measured at the loop detector to obtain mean travel time.
Speed	• The mean speed for a road segment can be estimated by measuring travel time and dividing the segment length by the mean travel time. • Instantaneous speed measurements along the length of a road segment can be obtained from instrumented vehicles. • The mean speed also can be estimated from point measurements of speed (less accurate than tracing techniques), such as at video or loop detectors. The harmonic mean speed is computed for the speeds measured at the loop detector.
Delay	• Delay over the length of a road segment is measured in the field using travel-time measurement techniques described above. Delay is the difference between the measured travel time and the free-flow travel time. • Delay at an intersection is measured by counting the queued vehicles every 15 seconds (or so). The total delay is the number of queued vehicles times the interval between queue counts (15 seconds). Judgment is required to determine if a slow (but not stopped) vehicle is in a queue. This method misses deceleration/acceleration delay so the total delay is factored up to account for the missed delay. Stopped delay is multiplied by a factor greater than one to obtain control delay (stopped delay plus acceleration and deceleration delay). The average delay is the total delay divided by the number of vehicles arriving on the subject approach during the analysis period.
Queue	• The best way to measure a queue in the field is to count the second by second arrivals at an upstream point and the second by second departures at a downstream point. The difference between the cumulative arrivals and the cumulative departures at time "t" (after shifting the departure pattern for the free-flow travel time between the upstream and downstream points) is the queue at time "t." • The average number of vehicles queuing at an intersection can be measured in the field using the same technique as described above for measuring delay at an intersection. Judgment is required to determine if a slow (but not stopped) vehicle is in a queue.
Stops	• Stops along a road segment can be measured using the same vehicle tracing techniques as described above for travel time. • Stops can be measured at an intersection using the intersection delay method described above. • Both methods require judgment as to when a slow vehicle is considered stop and when a vehicle is moving up in a queue (stops within a queue are not counted).

Table 2. Field Measurement of MOES (continued)

Building Blocks of Performance Measurement Systems (continued)

MOE	Field Measurement Technique
Density	• The average density over time at a given point in space is computed by dividing the measured flow rate per hour by the measured arithmetic mean speed at the point. • The average density over the length of a segment at a given point in time is measured using aerial photography and counting the number of vehicles present on the segment.
Travel-Time Variance	• Travel-time variance is computed from the measured travel times (sum of the squared differences between the observation and the mean value).

Indicators of Performance

MOE	Field Measurement Technique
HCM Level of Service	• The measurement of HCM LOS in the field is described above for speed, delay, and density for freeways, highways, arterials, and intersections. • For 2-lane highways, the percent time spent following is estimated by measuring the percent of vehicles in platoons passing a given point for the peak 15-minute flow period within the analysis hour. A vehicle is defined to be in a platoon if it is following another vehicle by 3 seconds or less. The percent of vehicles in platoon is assumed to be roughly equal to the percent time spent following.
Volume/Capacity	• If the demand exceeds capacity for at least 15 consecutive minutes then the capacity can be measured in the field. Capacity is the queue discharge flow rate observed for at least 15 consecutive minutes. Once the capacity of a facility is known, then the v/c ratio is measured by simply counting the hourly volume and dividing by the estimated hourly capacity.

LIMITATIONS IN HOW MOES ARE CURRENTLY COMPUTED

Our ability to measure the MOEs in the field and the ability of simulation tools to estimate the MOEs are both severely strained by extreme congestion (See Table 3. Common Limitations of MOES in Practice).

Under severe congestion conditions it is very difficult to study a large enough geographic area over a long enough analysis period to ensure that congestion does not extend back beyond the limits of the study area and congestion is not present at the start or the end of the analysis period. Thus most simulation modeling of severe congestion conditions usually has queues that extend beyond the temporal and physical limits of the model.

Failure to include in the MOEs the queues that stretch beyond the geographic and the temporal bounds of the study area will bias the computation of travel time, speed, and delay, making capacity improvements within the study area appear to perform worse than no improvements.

Table 3. Common Limitations of MOES in Practice.

Building Blocks of Performance Measurement Systems

MOE	Limitations
Travel Time	• Treatment of delays and travel time for incomplete trips or trips that cannot start within the analysis period is an issue. • Difficult for a decision-maker to interpret (no value of time is obviously too high or too low without knowing more about the trip characteristics).
Speed	• Treatment of incomplete or unbegun trips is an issue, as for travel time. • Interpretation is facility-specific. Low speed may be quite acceptable on an arterial, but not on a freeway. • Once all vehicles come to a stop, the mean speed conveys no further information on the severity of congestion (speed cannot go below zero). • Speed is a poor indicator of how close the facility is to breakdown (capacity).
Delay	• Treatment of incomplete trips or trips that have not started is an issue. • Definition of free-flow speed, against which delay is measured, is a problem. Some use the posted speed limit for the free-flow speed; others use the mean speed under very low-flow conditions (can be higher or lower than the posted speed limit).
Queue	• Definition of when vehicle joins a queue and when it leaves a queue is a problem. • Interpretation is road segment and facility-specific. Queues are normal for signals, but queues that overflow turn bays or block cross streets are not desirable. • Tallying of queued vehicles unable to enter the road segment is an issue for many tools. Many tools cannot report a queue longer than the storage capacity of the road segment or turn bay. • Tallying of vehicles, which have not been able to enter the road network during the analysis period, is an issue.
Stops	• Definition of what minimum speed is a stop is an issue. (One reviewer recommended that stop speed be defined as zero so that model results can be better compared to two-fluid models of traffic flow.) • Since tallying of stops is normally suspended while a vehicle is moving up within a queue, the definition of a queue is an issue. • Once all vehicles are queued on a road segment, further increases in congestion have no effect on stops.
Density	• Once all vehicles are queued, then further increases in congestion have no effect on density.
Travel-Time Variance	• Rarely used due to difficulty of computation. Prediction tools are close to nonexistent. • Once all vehicles are queued on a road segment, the variation in travel time tends to drop towards zero. Variance will tend to peak when the volume is around capacity.

Table 3. Common Limitations of MOEs in Practice (continued)

Indicators of Performance

MOE	Limitations
HCM Level of Service	• HCM LOS is designed to convey how close the facility is to reaching capacity or unacceptable LOS. Once LOS "F" reached, HCM LOS letter grades give no further information on relative severity of different degrees of congestion. • HCM LOS does not give information on the duration of the condition. • HCM LOS ratings do not exist for several situations: roundabouts, collector/distributor roads, local residential streets.
Volume/Capacity	• Cannot measure in field or simulate volumes passing a given point that are greater than capacity (measured v/c is always less than 1.00). In such situations, must add to the measured flow rate the buildup in the queue.

There also are problems with reporting queues that extend beyond the turn bay and/or beyond the link. Only one simulation tool will track the buildup of queues beyond the subject link, and none of them will track congestion beyond the temporal or geographic limits of the model. With one exception, the reported queue is, by definition, never longer than the storage capacity of the turn bay or the link. Thus, the analyst cannot rely upon the reported queue length to identify queue overflow problems. The analyst must find the upstream links and review the reported queues there.

Chapter 5 of this report provides more details.

INHERENT LIMITATIONS OF CURRENT MOES

Most MOEs are satisfactory measures of traffic performance for uncongested conditions. Travel time, delay, queues, stops, density, and travel-time variance all increase as traffic demand increases relative to capacity and traffic operations worsen.

Among these MOEs, speed is a less satisfactory indicator of how close a facility is to breakdown, because speed is comparatively insensitive to changing traffic flow rates until capacity is reached.

Most all of the MOEs tend to break down under extreme congestion conditions. Speed, density, stops, and travel-time variance are invariant under "parking lot" conditions where no movement is possible (speed equals zero, density equals jam density, and travel-time variance is zero). The only MOEs that continue to function under parking lot conditions are travel time and delay, which continue to increase over the length of the analysis period (See Table 3. Common Limitations of MOES in Practice).

Chapter 5 of this report provides more details.

RECOMMENDED SET OF KEY SYSTEM MOES

Traffic operations analyses can generate a great deal of numerical output. Any one of the numerical outputs can be important to the analyst depending upon the purpose and scope of the analysis and the alternatives being evaluated. The set of key systemwide MOEs recommended below is designed to be the "starting set" but not the end all set of MOEs for any traffic operations analysis.

This basic set is kind of like the first set of exams given to every patient when they first check into the emergency room. It does not matter what the patient's complaint, the health of every emergency room patient is measured by four indicators: temperature, pulse, blood pressure, and blood oxygen. These four basic indicators give the doctors a basic understanding of the general health of the patient, and some indication of general fields to investigate for the source of the problem. But they are not the definitive diagnostic tests. They are not the MRIs, X-Rays, or exploratory surgeries that come later.

Similarly, our basic system MOEs are designed to be that first round of tests every traffic engineer and planner should perform to assess the general health of his or her transportation system. They give an indication of the overall health of the system, and how serious the problems are. But they do not necessarily tell the engineer/planner precisely what is wrong. That is the purpose of additional analyses and additional tests.

This basic set of MOEs is not designed to replace the more detailed intersection and segment MOEs engineers and planners already are accustomed to perform to diagnose and solve traffic operations problems on the transportation system. This basic set is designed to help the engineer/planner and decision-maker rapidly assess the state of the system and identify key avenues of additional analysis to better identify needed improvements.

This basic set of MOEs also is good for rapidly assessing the benefits of alternative improvements at the system level, in a form readily understandable by the decision-maker.

The basic set of MOEs for decision-making consists of five basic measures:

1. Throughput;

2. Mean Delay;

3. Travel Time Index;

4. Freeway Segments at Breakdown; and

5. Surface Street Intersections with long queues, Turn Bay Overflows and Exit Blockages.

Each of these basic MOEs is highlighted in Table 4. Key Measures of Effectiveness for Decision-Making.

Table 4. Key Measures of Effectiveness for Decision-Making.

Decision MOE	Use/Description/Interpretation
Throughput (Vehicles/Hour) and Percent Incomplete Trips	• Use – Provides a measure of the relative productivity of the system compared to an alternative. This MOE also is required to compute mean delay. • Definition – The number of vehicles present at the start plus those attempting to enter and successfully entering the system during the analysis period. • Computation – At start of analysis period tally number of vehicles present within system. During analysis period tally number of vehicles attempting to enter the system but never successfully enter. Tally number of vehicles that both enter and exit the system during the analysis period. Tally number of vehicles entering the system during the analysis period that are remaining on system at end of analysis period. • Reporting – Number of vehicles at start that successfully exit system during analysis period (V1). Number of vehicles at start that fail to exit the system during the analysis period (V2). Number of vehicles that entered but did not exit during the analysis period (V3). Number of vehicle generated but never entered the system during the analysis period (V4). Number of vehicles that successfully both entered and exited the system during the analysis period (V5). Report the percent of incomplete trips as the ratio of (V1+V2+V3+V4)/(V1+V2+V3+V4+V5). • Interpretation – The throughput is compared for different alternatives to determine the relative productivity of each alternative. Higher values are desired. If the ratio of incomplete trips exceeds 5 percent then the decision-maker should consider lengthening the analysis period or investigate the MOEs computed for solely the through trips (V5) to see if they might better represent system performance.
Delay/Trip	• Use – Comparison of traveler perceptions of average traffic performance of alternatives. • Definition – The travel time (for all vehicles entering and attempting to enter the system during the analysis period) minus the theoretical travel time at the free-flow speed. This difference is divided by the number of vehicle trips to obtain mean delay per trip. The free-flow speed is defined as the minimum of the maximum safe speed or the analyst coded speed limit. Note that turning vehicles at an intersection would have a lower maximum safe speed than through vehicles. • Computation – Accumulate distance traveled (VMT) and time expended (VHT) each second by vehicles on system (or attempting to enter system) during analysis period. Simultaneously accumulate theoretical VHT that would have been expended if vehicle had been able to travel the same VMT at free-flow speed. At the end of the analysis period the free-flow VHT is subtracted from the accumulated VHT to obtain Delay VHY. The Delay VHT is converted to seconds and then divided by the total number of vehicle trips over which the delay was accumulated (V1+V2+V3+V4+V5). If the number of incomplete trips (V1+V2+V3+V4) is greater than 5 percent of all trips, then either the analysis period should be lengthened, or Delay VHT should be accumulated separately for through trips (V5) and averaged over only the through trips (V5). • Reporting – Delay is reported in vehicle hours traveled (VHT) and mean seconds per trip. If incomplete trips account for over 5 percent of all trips, that should be noted. • Interpretation – Subjective. If trips are long in system, then high mean delays may be acceptable. If trips are short, even low mean delay may be unacceptable.

Table 4. Key Measures of Effectiveness for Decision-Making (continued)

Decision MOE	Use/Description/Interpretation

Travel Time Index	• Use – To determine if facility operation during peak periods is unacceptably worse than for off-peak periods.
	
	• Definition – Ratio of observed vehicle hours traveled (VHT) to theoretical VHT at free-flow speed for same VMT.
	
	• Computation – See notes above on computation of mean delay. The travel time index is the accumulated VHT divided by the theoretical free-flow VHT.
	
	• Reporting – System travel time index plus a few words qualifying the result, such as "Good," "Bad."
	
	• Interpretation –
	  – The TTI minus 1.00 gives the mean delay as a percentage of the mean trip time.
	  – The inverse of the TTI gives the mean speed as a percentage of the free-flow speed for the system.
	  – For an entire metropolitan area (including local streets, arterials, and freeways) a peak-period TTI of 1.4 or better was typical of 90 percent of the metropolitan areas of United States in 2005.
	  – For more focused systems of mixed freeway and arterial facilities (no local streets) a TTI of under 2.5 is roughly indicative of generally uncongested conditions and good signal coordination.
	  – For a system of solely unsignalized facilities (freeways, highways, 2-lane rural roads) a TTI of over 1.4 is indicative of a facility that is overcapacity for the entire length of analysis period.
	  – For a system of exclusively signalized arterials a TTI of over 2.5, is generally indicative of overcapacity conditions and/or poorly coordinated traffic signals.
	  – A qualifier of "Good" for TTIs <= 1.5, "Potentially Acceptable" for TTIs between 1.5 and 2.5, and "Less Desirable" for TTIs > 2.5 would help the decision-makers.

Freeways: Percent Breakdowns	• Use – To identify geographic and temporal extent of unsatisfactory operations for freeways in system.
	
	• Description – Breakdown is defined as a density of vehicles per lane greater than the density at capacity flow rate. The HCM assigns LOS "F" to these densities higher than capacity.
	
	Two percents are computed:
	  – Maximum percent of directional freeway miles at LOS F at any onetime during the analysis period.
	  – Percent of analysis period when any directional freeway segment is at LOS F.

Table 4. Key Measures of Effectiveness for Decision-Making (continued)

Decision MOE	Use/Description/Interpretation
Freeways: Percent Breakdowns (continued)	• Computation – Determine maximum LOS "E" density for each directional freeway segment in system according to the Highway Capacity Manual. Determine PCE values for each vehicle type in system for each directional freeway segment according to the Highway Capacity Manual. For each second in the analysis period tally number of vehicles on directional segment and multiply by appropriate PCE value to obtain equivalent PCUs. At end of model run compute 15-minute running averages of PCUs for each directional segment. Identify start and end times when 15-minute average PCU exceeds HCM LOS E maximum density. Find earliest start time of LOS F and latest end time of LOS F for system. The percent duration of LOS "F" is equal to the latest end time minus the earliest start time of LOS F, divided by the length of the analysis period. The maximum percent LOS "F" is the maximum number of directional segment miles operating at LOS "F" (averaged over 15 minutes) at any one time divided by the total directional miles of freeway in the system. • Interpretation – The geographic and temporal percents LOS "F" are indicators of congested freeway operations. The lower, the better.

Surface Street: Percent of Intersections Exits Blocked	• Use – To identify geographic and temporal extent of unsatisfactory operations for urban streets in system. Intersection exit blockages due to downstream queues extending back to an upstream intersection reduce through capacity and are potential safety concerns.
	
	• Definition – Two percents are computed:
	  – Maximum percent of intersection exits that are blocked at any onetime during the analysis period.
	  – Percent of analysis period when any intersection exit is blocked.
	
	• Computation – For every directional street link and for each second in the analysis period compare the distance of back bumper of last car in any lane of the directional street link to the total estimated distance to the nearest upstream intersection (If the upstream node has only one link feeding the subject downstream link, that node is not an intersection. Abandon the test on the subject link and perform the test instead on the upstream link.). Determine if the back of queue is within 25 feet of storage length of the directional link.
	  – Accumulate number of seconds during analysis period when one or more directional links are full. The percent of the analysis period with one or more full directional links is the number of seconds when one or more directional links are full divided by the number of seconds in the analysis period.
	  – Tally number of directional links meeting this "full" criterion at any one time. The maximum percent full links is the maximum number of full directional links at any one time divided by the total number of directional street links (exclude freeway links which have their own LOS F test) in the system.
	
	• Report – Maximum percent of full directional street links at any one time. Percent of analysis period during which one or more directional street links are "full."
	
	• Interpretation – The geographic and temporal percents of "full" links are indicators of potential capacity and safety problems. The lower, the better. Since a common goal for designs of new turn bays is to provide storage for the 95 percentile demand per cycle, a goal of no more than 5 percent of the analysis period with full street links would be desirable for a new design.

Table 4. Key Measures of Effectiveness for Decision-Making (continued)

Decision MOE	Use/Description/Interpretation

Surface Street: Percent Turn Bay Overflows	• Use – To identify geographic and temporal extent of unsatisfactory operations for urban streets in system. Turn bay overflows reduce through capacity and are potential safety concerns.
	
	• Definition – Two percents are computed:
	  – Maximum percent of full turn bays at any onetime during the analysis period.
	
	  – Percent of analysis period when any turn bay is full.
	
	• Computation – For each second in the analysis period compare the distance of back bumper of last car in turn bay from stop bar to total estimated turn bay storage length. Determine if the back of queue is within 25 feet of storage length of turn bay.
	  – Accumulate number of seconds during analysis period when one or more turn bays are full. The percent of the analysis period with one or more full turn bays is the number of seconds when one or more turn bays are full divided by the number of seconds in the analysis period.
	
	  – Tally number of turn bays meeting this "full" criterion at any one time. The maximum percent full turn bays is the maximum number of full turn bays at any one time divided by the total number of turn bays in the system.
	
	• Report – Maximum percent of full turn bays at any one time. Percent of analysis period during which one or more turn bays are "full."
	
	• Interpretation – The geographic and temporal percents of "full" turn bays are indicators of potential capacity and safety problems. The lower, the better. Since a common goal for designs of new turn bays is to provide storage for the 95 percentile demand per cycle, a goal of no more than 5 percent of the analysis period with full turn bays would be desirable for a new design.

Their use, definition, computation, reporting, and interpretation are presented in this table.

There are, of course, many other MOEs that every good planning or engineering study also will want to consider, such as, user benefits, user costs, fuel consumption, noise, air pollutant emissions, and safety. However, the 5 basic system MOEs listed above will give the decision-maker and the analyst a good idea of how well the system is performing and how one alternative improvement compares to another. Chapter 6 describes them in more detail.

ADDITIONAL KEY SYSTEM MOES FOR FUTURE RESEARCH

The technical review suggested four additional key MOEs that are likely to be valuable to decision-makers but could not be included at this time due to several uncertainties about them requiring more research and additional practical experience in order to better define them. They are:

- Buffer Index;

- Fuel Consumption Ratio;

- NO$_x$ Emissions Ratio; and

- Safety.

The buffer index is one of a dozen different measures of travel-time reliability. Future research needs to address the selection of the appropriate set of reliability measures for decision-making, as well as the extent to which the variability already incorporated into microsimulation models can be expanded to include the much larger variability associated with demand fluctuations and capacity reducing incidents in the real world.

The fuel consumption and NO$_x$ emissions ratios are an attempt to incorporate energy consumption and air pollution considerations in an easily understandable form for decision-making. However, there are several issues of how these indices might be computed, and consequently there are concerns as to their real meaning. Indeed, the United States Environmental Protection Agency may not accept air quality conformity analyses results that are produced by any tool except EPA approved tools.

Safety is one measure of effectiveness that many analysts would like to include in operations analysis considerations, however; the tools to do so are still very limited and in the development stage, where available.

COMPARISON OF MOES BETWEEN HCM AND OTHER ANALYSIS TOOLS

Since each microscopic and macroscopic analysis tool (including the Highway Capacity Manual method) has notably different definitions of what constitutes stopped and queued vehicles and because the tools also vary significantly in the determination of which vehicles to include in the computations (vehicles that both entered and exited during the analysis period, vehicles that did neither, or vehicles that either entered or exited but not both during the analysis period), it is not feasible for an analyst to take the macroscopic output from one tool, apply a conversion factor (or procedure) and compare the results to that of another tool. The analyst simply does not have access to sufficient data at the macroscopic level to be able to compare MOEs across tools.

This conclusion means that looking up Highway Capacity Manual levels of service using MOEs produced by a different analytical method is not appropriate. It is prone to bias and error.

For similar reasons, the analyst should not be switching tools in the middle of a comparison between alternatives. One set of tools should be consistently used to evaluate MOEs across all alternatives. One should not evaluate one alternative with one tool, another alternative with a second tool, and then use the MOEs produced by both tools to select among the alternatives.

Comparison of results between tools and methods is possible only if the analyst looks at the lowest common denominator shared by all field data collection and analytical tools:

vehicle trajectories.[1] At this microscopic level, the analyst can compare field data to analysis tool outputs, whether the tool is microscopic or macroscopic. By computing aggregate, macroscopic MOEs from the vehicle trajectory data the analyst can compare the results of macroscopic and microscopic tools to field data and to each other in a consistent manner. This is the only appropriate method for comparing results between tools, validating the model results against field data, or using the outputs of other tools to compute level of service as defined by the Highway Capacity Manual.

Consequently, it would be highly desirable if all microscopic analysis tools had the option of generating vehicle trajectory data in a universally readable format (for example, a generally accepted database format, such as DBASE), so as to make post-processing and comparison of results across tools possible.

PRACTICAL APPLICATION OF RECOMMENDED MOE SYSTEM

This report concludes with a chapter illustrating the computation and interpretation of the recommended systemwide MOEs for a freeway and an urban arterial street.

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[1] The author is indebted to Dr. Hani Mahmassani for suggesting this concept.

1.0 INTRODUCTION

Traffic analysis tools play a critical role in prioritizing public investment in strategies employed by transportation professionals to relieve congestion. Traffic analysis tools help practitioners to:

- Measure the operational performance of transportation facilities;

- Evaluate various ITS strategies and innovative transportation management concepts;

- Evaluate alternate designs and operational improvements;

- Decrease the time and cost for evaluation and design of transportation facilities and systems; and

- Reduce the risk and disruption to traffic caused by field experimentation.

1.1 PROBLEM STATEMENT

Use of the Highway Capacity Manual (HCM) and traffic simulation tools has become the standard approach for evaluating transportation design alternatives, operational performance, Intelligent Transportation Systems (ITS), and traffic operations strategies. However, the HCM procedures and traffic simulation tools seldom result in identical performance measurements. Moreover, there are no guidelines on interpreting these performance measurements. This leaves decision-makers and transportation professionals with the dilemma of identifying the true performance of the design alternatives and strategies.

1.2 PROJECT OBJECTIVES

The goal of this study was to develop information and guidance on which MOEs should be produced, how they should be interpreted, and how they should be defined and calculated in traffic analysis tools. Specific objectives of the study were to:

1. Gain an understanding of the current use and interpretation, by transportation professionals, of some of the most commonly used MOEs generated by traffic simulation and analytical tools, such as HCM procedures;

2. Identify how field measurements are processed to estimate the MOEs used in conducting traffic analysis studies;

3. Provide guidance on how these MOEs are defined and calculated in the tools;

4. Develop an innovative approach to interpret these MOEs when conducting traffic analysis studies; and

5. Demonstrate the validity of the approach through a case study of representative tools.

1.3 REPORT OVERVIEW

This report presents innovative approaches for interpreting and presenting traffic simulation and analytical tool MOEs. This report considers alternative MOEs in addition to the Level of Service performance measure prescribed by the HCM. It recommends MOEs that decision-makers could use to interpret results from traffic analysis studies conducted by transportation professionals.

The Executive Summary provides more detail on the contents of this report.

1.4 REPORT REVIEW PROCESS

A draft of this report was submitted to the FHWA Contracting Officer Technical representative (COTR) and to a panel of volunteer experts in the application of traffic microsimulation to performance measurement for comment.

The volunteer experts were:

Invitee	Affiliation	Type
Scott Aitken	Quadstone	Vendor
John Albeck	Trafficware	Vendor
Jaume Barcelo	Aimsun	Academic/Vendor
Loren Bloomberg	CH2M-HILL	Private
Ken G. Courage	University of Florida	Academic
Mohammed Hadi	Florida International University	Academic
Steve Hague	California Department of Transportation	Government
David Hale	McTrans	Academic/Vendor
Michael Hunter	Georgia Tech University	Academic
Liang Hsia	Florida Department of Transportation	Government
Hani Mahmassani	University of Maryland	Academic/Vendor
Cathy McGhee	Virginia DOT Transportation Research Council	Academic
Arash Mirzaei	North Central Texas Council of Governments	Government
Kiel Ova	PTV-America	Vendor
John Shaw	Wisconsin Department of Transportation	Government

In addition, the report was submitted to the following project team members for review:

John Halkias	Federal Highway Administration
James Colyar	Federal Highway Administration
Grant Zammit	Federal Highway Administration
John Tolle	Federal Highway Administration
James McCarthy	Federal Highway Administration
Vassili Alexiadis	Cambridge Systematics
Vijay Kovvali	Cambridge Systematics
Alexander Skabardonis	University of California, Berkeley

The efforts, advice, and suggestions of the volunteer technical reviewers, the Federal Highway Administration Project Team, and the Consultant Project Team are greatly appreciated. However, it should be noted that the opinions presented in this report are those of the author and not necessarily those of its reviewers. Remaining errors are the responsibility of the author.

1.5 PROJECT OBJECTIVES ACCOMPLISHED

The goal of this study was to develop information and guidance on which MOEs should be produced, how they should be interpreted, and how they should be defined and calculated in traffic analysis tools. The table below explains how the specific objectives of this study have been accomplished.

Table 5. Accomplishment of Project Objectives.

Objective	How Accomplished
1. Gain an understanding of the current use and interpretation, by transportation professionals, of some of the most commonly used MOEs generated by traffic simulation and analytical tools, such as HCM procedures.	Chapter 2 provides an overview of current practice. It describes MOEs used in practice and in research. It identifies commonly used tools for computing MOEs.
2. Identify how field measurements are processed to estimate the MOEs used in conducting traffic analysis studies.	Chapter 3 describes how MOEs are measured in the field.
3. Provide guidance on how these MOEs are defined and calculated in the tools.	Chapter 4 documents how MOEs are computed by a range of macroscopic and microscopic tools.
4. Develop an innovative approach to interpret these MOEs when conducting traffic analysis studies.	Chapter 5 presents a recommended approach to defining, calculating, and interpreting MOEs, which were reviewed by a panel of technical experts in Chapter 6, and refined accordingly. The final refined set of MOEs and their interpretation are provided.
5. Demonstrate the validity of the approach through a case study of representative tools.	Chapter 7 illustrates the application of the MOEs to two case studies taken from vehicle trajectory data developed under the NGSIM program. This chapter illustrates the computation and interpretation of the MOEs. The final set of recommended MOEs and their interpretation based on the results of technical review and the case studies are also provided.

2.0 CURRENT PRACTICE

This chapter reviews current practice in the use of MOEs in traffic operations analysis and recommends a subset of MOEs and traffic analysis tools for further evaluation.

2.1 MOES IN PRACTICE

This section identifies the measures of effectiveness most commonly used by transportation professionals in evaluating transportation design alternatives, operational performance, and ITS/traffic operations strategies. Three primary sources were consulted:

1. NCHRP Synthesis 311, Performance Measures of Operational Effectiveness for Highway Segments and Systems;

2. Interim report for NCHRP 7-15, Cost-Effective Measures and Planning Procedures for Travel Time, Delay, and Reliability; and

3. Interim report for NCHRP 3-68, Guide to Effective Freeway Performance Measurement.

NCHRP Synthesis 311 [Shaw, 2003] examined the use of performance measures for the monitoring and operational management of highway segments and systems. The study surveyed the current state of practice and assessed the relative strengths and weaknesses of the more than 70 measures identified.

The most successful measures related to conditions directly experienced by the traveler, e.g., travel time, speed, and delay. Measures derived from these, such as travel indices, were less relevant to the operational environment than to policy planners.

For purposes of this project, the most relevant finding is on performance measures that are used by public agencies. Table 6 below shows the results of a survey of state DOTs and MPOs on the performance measures they use. LOS, traffic volume, and VMT were the measures cited most often. Travel time, speed, and incidents also were frequently cited. Most other measures were used by only one or a few of the agencies interviewed. All of the top six most frequently cited measures, except for incidents, can be estimated by current traffic analysis tools.

NCHRP 7-15 [Cambridge Systematics 2005] is intended to develop structured, cost-effective methods and procedures that calculate measures of travel time, delay, and reliability. These methods are to be used by practitioners to measure, predict, and report on transportation system performance from a customer-oriented perspective and make decisions about policies, programs, or projects.

The interim report includes the findings of a review of current research and literature, a review of current agency and industry practice, and the results of several practitioner workshops.

Table 6. Performance Measures Reported in Survey of State DOTs and MPOs.

Performance Measure	Typical Definition	N*
Level of Service (LOS)	A (best) to F (worst) based on measures of effectiveness	11
Traffic Volume	Annual average daily traffic, peak-hour traffic, or peak-period	11
Vehicle Miles Traveled	Volume times length	10
Travel Time	Distance divided by speed	8
Speed	Distance divided by travel time	7
Incidents	Traffic interruption caused by a crash or other unscheduled event	6
Duration of Congestion	Period of congestion	5
Percent of System Congested	Percent of miles congested (usually defined based on LOS E or F)	5
Vehicle Occupancy	Persons per vehicle	5
Percent of Travel Congested	Percent of vehicle miles or person miles traveled	4
Delay Caused by Incidents	Increase in travel time caused by an incident	3
Density	Vehicles per lane per period	3
Rail Crossing Incidents	Traffic crashes that occur at highway–rail grade crossings	3
Recurring Delay	Travel time increases from congestion; this measure does not	3
Travel Costs	Value of driver's time during a trip and any expenses incurred	3
Weather-Related Traffic Incidents	Traffic interruption caused by inclement weather	3
Response Times to Incidents	Period required for an incident to be identified, verified, and for an appropriate action to alleviate the interruption to traffic to arrive at the scene	2
Commercial Vehicle Safety Violations	Number of violations issued by law enforcement based on vehicle weight, size, or safety	1
Evacuation Clearance Time	Reaction and travel time for evacuees to leave an area at risk	1
Response Time to Weather-Related Incidents	Period required for an incident to be identified, verified, and for an appropriate action to alleviate the interruption to traffic to arrive at the scene	1
Security for Highway and Transit	Number of violations issued by law enforcement for acts of violence against travelers	1
Toll Revenue	Dollars generated from tolls	1
Travel-Time Reliability	Several definitions are used that include: 1) variability of travel times; 2) percent of travelers who arrive at their destination within an acceptable time; and 3) range of travel times	1

Source: Shaw, 2003.

*N = Number of responses from agencies.

The key findings on performance measures include the following:

- Several state DOTs use congestion and reliability measures.

- MPOs and smaller agencies still measure capacity and level of service.

- Most agencies surveyed acknowledge the growing importance of congestion and reliability performance measures.

- Some practitioners believe that the general public and high-level transportation officials are less interested in reliability measures than in total delay and congestion measures. The consensus opinion was that reliability has not yet gained the attention of the vast majority of the general public and decision-makers at the current time.

- Many organizations use economic measures such as benefit/cost ratios in their planning processes.

NCHRP 3-68 will develop a guidebook that codifies best practices in freeway performance measurement. The Interim Report [Cambridge Systematics, 2004] covers the results of interviews with more progressive agencies on their use of performance measures. The interviews covered the motivation for performance measures, the performance measures used, and use of the reported performance measures.

With regard to the types of performance measures used by agencies, the main findings were as follows:[2]

- Both outcome and output measures are used by agencies. It is clear that agencies who have undertaken freeway performance measurement have accessed the literature on performance measurement because they use the outcome/output terminology.

- For outcome measures, derivatives of speed and delay are commonly used by both operating and planning agencies. The Travel Time Index is a popular metric. Level of service as a metric is still in use in both planning and operations agencies, though it is not as widespread as it might have been 10 years ago. Reliability metrics have not yet found their way into widespread use. (Seattle and Minneapolis are exceptions.) These metrics are usually formulated for short segments or at key locations. An exception is Seattle where a series of defined "freeway trips" have been defined – these can involve travel over multiple freeway routes for extended lengths.

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[2] Quoted directly from the NCHRP 3-68 Interim Report by Cambridge Systematics.

- Some of the more interesting metrics used by agencies include:

  – The number of very slow trips (half of free flow speed) that occurs each year by time of day and major trip (Seattle);

  – Percentage of reduction in incident congestion delay; and

  – Percent of freeway lane-miles below congested volumes (based on volume per lane).

- Output measures are used primarily by operating agencies, and then primarily for incident management activities and the operation of field equipment (e.g., sensors, cameras).

Many areas are beginning to define more sophisticated measures for measuring congestion/mobility performance but have not yet implemented them. Overall, there appears to be a trend away from the general categories of performance (LOS) and toward continuous measures that are based on delay and travel time. Further, consideration of travel-time reliability is growing in acceptance, though its implementation is still problematic, primarily due to data requirements.

Florida Mobility Performance Measures Program

The Florida Department of Transportation (FDOT) has identified four dimensions for measuring the effectiveness of programs in meeting the objectives of FDOT. They are:

1. Quantity of Travel – The number of vehicles or people using a facility or service;

2. Quality of Travel – The degree of congestion;

3. Accessibility – The ease with which people can gain access to the transportation system; and

4. Utilization – The percentage of capacity utilized.

The first table below shows the measures of effectiveness for highway performance. The second table below shows the MOEs selected for transit systems. The performance measures are reported for two time periods: Peak Hour and Daily.

Data on existing performance is obtained from FDOT's Roadway Characteristics Inventory (RCI) and Traffic Characteristics Inventory (TCI). Average vehicle occupancy data is obtained from the 1990 National Personal Transportation Survey (NPTS). Transit system data is collected from local transit authorities. A land use database (GIS) was used to measure accessibility. Special studies were performed to obtain reliability data. Travel demand modeling and the Highway Capacity Manual methods are used to forecast the MOEs.

Table 7. FDOT Mobility Performance Measures for Highways.

Dimension	Mobility Performance Measure	Definition
Quantity of Travel	Person miles traveled	AADT * Length * Vehicle Occupancy
	Truck miles traveled	AADT * Length * Percent Trucks
	Vehicle miles traveled	AADT * Length
	Person trips	Total person trips
Quality of Travel	Average speed	Average speed weighted by person miles traveled
	Delay	Average delay
	Average travel time	Distance/mean speed
	Average trip time	Door-to-door trip travel time
	Reliability	Percent of travel times that are acceptable
	Maneuverability	Vehicles per hour per lane
Accessibility	Connectivity to intermodal facilities	Percent within 5 miles (1 mile for metro area)
	Dwelling unit proximity	Percent within 5 miles (1 mile for metro area)
	Employment proximity	Percent within 5 miles (1 mile for metro area)
	Industrial/warehouse proximity	Percent within 5 miles
	Percent miles bicycle accommodations	Percent miles with bike lane/shoulder
	Percent miles pedestrian accommodations	Percent miles with sidewalk
Utilization	Percent system congested	Percent miles at LOS E or F
	Percent travel congested	Percent daily VMT at LOS E or F
	Vehicles per lane-mile	AADT * Length/lane miles
	Duration of congestion	Percent miles at LOS E or F

Source: FDOT Mobility Performance Measures Brochure (2000) [FDOT 2000].
http://www.dot.state.fl.us/planning/statistics/mobilitymeasures/mmbrochure.pdf.

Notes: AADT = average annual daily traffic.

Table 8. FDOT Mobility Performance Measures for Transit Systems.

Dimension	Mobility Performance Measure	Definition
Quantity of Travel	Ridership	Total passenger trips
Quality of Travel	Auto/Transit Travel-Time Ratio	Door-to-door trip time
	Reliability	On-time performance
Accessibility	Coverage	Percent person minutes served
	Frequency	Buses per hour
	Span	Hours of service per day
Utilization	Load Factor	Percent seats occupied

Source: FDOT Mobility Performance Measures Brochure (2000) [FDOT 2000].
http://www.dot.state.fl.us/planning/statistics/mobilitymeasures/mmbrochure.pdf.

2.2 INTERPRETATION OF MOES BY AGENCIES

Interpretation of MOEs consists of distinguishing between acceptable and unacceptable traffic operations.

Local and state public agencies primarily use the HCM LOS grades to determine if operations are acceptable or unacceptable. A certain letter grade is set as the agency standard. Then project designs and project impacts are compared against that letter grade standard. A project design is considered unacceptable if the letter grade level of service is below the agency standard. An impact is determined to be significant if the project changes the letter grade from an acceptable letter to an unacceptable letter.

The meaning of density on a freeway or highway is interpreted based upon its equivalent HCM LOS grade. Similarly the meaning of speed on an arterial street and delay at an intersection is determined based upon their equivalent HCM LOS grades.

Volume/capacity ratios are used by some agencies to determine acceptability of operations. A v/c less than one is acceptable. A v/c greater than one is unacceptable.

There is however no guidance or standard practice on the interpretation of the other MOEs that do not have HCM LOS equivalents, such as travel time, reliability, vehicle hours traveled, vehicle miles traveled, mean system speed, etc.

Agencies typically use non-HCM performance measures for comparing alternatives. In an alternatives analysis, less of an undesirable feature (such as vehicle hours traveled or variability of travel time) is considered better, but there is no threshold of acceptability. Interpretation of these non-HCM measures is currently difficult, in the absence of information on national averages or national practice that would help an agency characterize a particular value of a non-HCM MOE as acceptable.

2.3 SELECTION OF MOES FOR FURTHER EVALUATION

Volume 1 of the Traffic Analysis Toolbox [FHWA 2004a] lists numerous performance measures that are generated by most analysis tools. The list is a mix of input performance measures, basic performance measures, and derived performance measures. Some of the measures in this list, such as v/c ratio, are necessary for computing the basic travel time, speed, and delay performance measures. Travel time and speed are interchangeable. IF one is known the other can be computed. Other performance measures, such as delay or fuel consumption can be derived from the basic travel time/speed performance measure. LOS, in particular, is a derived performance measure. LOS is not strictly a performance measure, but a method of reporting one or more selected numerical performance measures in a system of easily understandable letter grades.

Basic Performance Measures

Basic performance measures are those measures, which cannot be derived from other performance measures. The major task of the analytical tool is to compute these basic performance measures. Once these measures have been computed, it is possible (at least in theory) to load the output into a spreadsheet and compute the other measures.

Capacity, although often considered to be an input, is a basic facility characteristic crucial to the calculation of many of the other performance measures. For simulation models, capacity is a calibratable output. For analytic models it is often a direct input or a computed input based on the geometric characteristics of the facility.

Speed, and its inverse, travel time, are the basic performance measures from which most all other performance measures can be computed.

Number of stops is another basic performance measure that cannot be derived directly from the other performance measures. It is crucial for predicting fuel consumption, noise, and air pollutant emission performance measures.

Travel-time reliability is another basic performance measure that cannot be directly derived from the other performance measures. The profession currently is exploring how "reliability" might be used in decision-making, so it has not seen much use so far. Many popular analytical tools do not produce measures of reliability.

Derived Performance Measures

Derived performance measures are those that could, at least in theory, be computed from the basic performance measures and other inputs. It is often not practical though for the user to go through model output to extract the data needed to make the computations. Thus it is a practical advantage to the user if the analytical tool computes these derived measures automatically.

Volume or throughput can be computed from demand and capacity, although upstream capacity constraints need to be considered in determining downstream volumes. Volume then becomes an input to several performance measure computations.

Delay is the difference between ideal travel time and the actual travel time.

Density can be computed from volume and speed from the "flow equals density times speed" equation.

The number of vehicles in queue can be derived from the volume arriving on red (for signals) and/or the difference between the volume and the capacity. The queue length is the number of vehicles in queue divided by the density (for freeways) or the average spacing between stopped vehicles (for signals).

Travel Distance and accumulated Travel Time (VMT/PMT and VHT/PHT) can be derived from the volume and the travel time. Distance traveled is the sum of link volumes and link distances or the volume divided by speed times the number of hours.

The volume capacity ratio (V/C) is computed from volume and capacity, which are inputs to the other performance measures.

The duration of congestion is the difference between the demand and the capacity, divided by the capacity.

Mode split is computed from the ridership, AVO, and auto volume performance measures.

Crashes are beyond the ability of commonly used traffic analysis tools to predict.

Noise, fuel consumption, and pollutant emissions are measures that can be calculated from the other measures of volume, speed, delay, stops.

Methods of Summarizing Performance Results

The methods for summarizing performance take quantitative physical performance results (e.g., stops, delays, etc.) and convert them into qualitative or quantitative results, either letter grades or monetary values. The innovative approaches considered in this research will look at different methods for summarizing facility and system performance.

Level of service (LOS) is computed based on delay or density depending on the facility type. A look-up table is used to convert quantitative numerical results into qualitative letter grades.

Benefit/Cost is computed from the other performance measures. The other measures are converted into monetary equivalents and summed to obtain benefits and costs.

Whatever method is used to summarize performance results, it should be capable comparing alternatives that differ along the following dimensions:

- Type. Increasingly, managers are faced with deciding between different types of alternatives: e.g., operations improvements versus capacity improvements, maintenance of existing facilities versus constructing new facilities.

- Physical scale, e.g., a large single interchange reconstruction on a freeway versus signalization improvements to all interchanges along a freeway.

- Time scale, i.e., alternatives with different lifetimes.

Recommended MOEs for Focus of Tool Evaluation

It is recommended that the following eight measures of effectiveness shown in the table below become the focus of analytical tool evaluations for this study. They were selected because they constitute the basic building blocks of most all performance measures currently used by public agencies to monitor agency performance. Thus, if one can predict HCM LOS, volume/capacity ratio, travel time, speed, delay, queues, stops, and travel-time variance, one can estimate most any performance measure currently used by public agencies in the transportation sector. Economic costs, air quality, noise, and energy use can be estimated from these basic eight MOEs.

Table 9. Recommended Focus MOEs.

• HCM Level of Service	• Delay
• Volume/Capacity	• Queue
• Travel Time	• Stops
• Speed	• Density
	• Travel-Time Variance

2.4. COMMONLY USED TRAFFIC ANALYSIS TOOLS

This section provides an inventory of commonly used traffic simulation and analytical tools that are used to evaluate transportation design alternatives, operational performance, ITS, and traffic operation strategies.

Following the typology laid out by Volume 1 of the Traffic Analysis Toolbox, the tools fall into the following categories:

1. Sketch Planning Tools;

2. Travel Demand Models;

3. Deterministic Analytical Tools;

4. Traffic Signal Optimization Tools;

5. Macroscopic Simulation Models;

6. Mesoscopic Simulation Models; and

7. Microscopic Simulation Models.

Since the focus of this research effort is on tools for design and operation analysis, we will focus on the traffic signal optimization tools and simulation models (macro, meso, and micro). Within these four categories Volume 1 of the Toolbox identifies dozens of software.

The determination of "commonly used" was based upon the extent to which the tools are referenced in the published technical literature for papers accepted for presentation at the 2004 and 2005 Annual Meeting of the Transportation Research Board. The selection of analysis tools to be used in this research was then made from among the most popular tools with the intent of obtaining a representative sample of the range of commonly used analysis tools, while keeping the total number of tools evaluated to a tractable number.

Table 10. Initial List of Commonly Used Tools.

Category of Analysis Tool	Representative Software
Deterministic Analytical Tools	
Signalized Intersections	Synchro6
Urban Streets	FDOT ARTPLAN
Rural Two-Lane Roads	HCS
Rural Multi-Lane Highways	HCS
Freeways	HCS
Traffic Optimization Tools	
Signalized Intersections	Synchro6
Freeway Ramp Metering	FREQ
Macroscopic Simulation Tools	
Urban Streets	Transyt-7F
Rural Highways	None
Freeways	TRAF-CORFLO
Mesoscopic Simulation Tools	Dynasmart-P
Microscopic Simulation Tools	CORSIM
	SimTraffic
	Vissim
	Paramics
	Aimsum

2.5 SELECTION OF TRAFFIC ANALYSIS TOOLS FOR FURTHER EVALUATION

It is beyond the budget and timeframe available for this research to investigate all tools and MOEs they produce, so the initial list of commonly used tools was narrowed down to the following recommended subset of analysis tools for evaluation during the remainder of the project.

Table 11. Recommended Tools for Evaluation.

Tool Category	Representative Tool to be Evaluated
Deterministic Analytical Tools	Synchro6 and HCS
Traffic Optimization Tools	Synchro6
Macroscopic Simulation Tools	Synchro6
Mesoscopic Simulation Tools	Dynasmart-P
Microscopic Simulation Tools	CORSIM, SimTraffic, Vissim, Paramics, Aimsum

The above list is not intended as an exhaustive list or a list of even the most commonly used tools for evaluation of traffic operations in the United States. Indeed, many popular tools are absent from this list. It would be beyond the resources available to this project to investigate all of the popular tools in the United States. This list is intended to be a representative cross-section of typical tools illustrative of the range and breadth of tools employed in the United States for traffic operations analysis at the macroscopic, mesoscopic, and microscopic levels.

3.0 FIELD MEASUREMENT OF MOES

This chapter identifies how field measurements are processed to estimate the eight MOEs selected for further investigation in the previous chapter.

3.1 MEASURING HCM LOS IN THE FIELD

The Highway Capacity Manual to date has used single field measurable performance measures for level of service. For freeways it is density in terms of equivalent passenger cars. For two-lane rural highways it is percent time delay. For arterial streets it is mean speed of through traffic. For an intersection it is mean delay. The measurement of these performance measures in the field is described below in the following sections.

3.2 MEASURING V/C

Volume/capacity (v/c) ratio cannot be measured in the field unless there is a time period when the facility is observably at capacity.[3] Then the v/c for any other period can be estimated by taking the ratio of the counted demand to the observed capacity.

3.3 MEASURING TRAVEL TIME AND SPEED

The FHWA publication #FHWA-PL-98-035, Travel Time Data Collection Handbook, dated March 1998, prepared by the Texas Transportation Institute provides a complete overview of techniques for gathering travel-time data (see http://www.fhwa.dot.gov/ohim/start.pdf).

There are numerous speed and travel-time measuring techniques, but they can all be grouped into three large categories according to their method of sampling the travel-time universe.

1. Spot speed measurement techniques measure vehicle speeds only for a given point of geography or a given point of time.

2. Vehicle tracing techniques measure vehicle travel times only for a select portion of all trips.

3. Trip maker tracking techniques are similar to vehicle tracing techniques but measure traveler trip times rather than vehicle trip times.

The mechanics of employing many of these techniques are described in the Institute of Transportation Engineers publication, *Manual of Transportation Engineering Studies*, Edited by H. Douglas Robertson, 2000. The Transportation Research Board Publication, *Highway*

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[3] There is a queue of vehicles waiting to be served by the facility that persists for at least 15 continuous minutes.

Capacity Manual, 2000 also provides some limited guidance on travel time, speed, and delay data collection in the appendices to Chapters 15 and 16 of the manual.

Spot Speed Measurement Techniques

Spot speed measurement techniques use roadside sensors to measure the instantaneous speeds of vehicles either at specific spots of the roadway or at specific times of the day. These techniques are very cost-effective at gathering large amounts of speed data for specific segments of the transportation system but cannot provide door-to-door travel times.

Roadside sensors include in-the-road loop detectors, roadside radar, microwave sensors, video sensors, and infrared sensors. They are "location-based sampling" methods which suffer from the biases inherent in measuring speeds at a point and assuming the speed is applicable to other points on the roadway. Technological variations include: single loop detectors, double loop detectors, portable machine double hose counters, radar, lidar, microwave, and infrared sensors, and video camera sensors. Recent technological advances; such as vehicle signature and platoon signature matching, may allow measurements of elapsed time between stations.

Single loop detector occupancies are converted to speeds based upon an estimated average vehicle length during the survey period. This average length varies according to the mix of autos and heavy vehicles present on the facility by time of day and direction.

Radar guns register only the fastest vehicle speed in the platoon, so there may be some upward bias. Also, the "angle of incidence" (the angle between the road centerline and the hypothetical straight line between the radar gun and the vehicle) of roadside radar and lidar measurements affect the precision of the speed results, but usually the effect is considered negligible.

The minimum sample size is determined based upon the desired confidence interval for the mean speed. Larger variances in measured speeds require larger sample sizes to achieve a desired confidence interval for the mean speed.

Vehicle Tracing Techniques

Vehicle tracing techniques involve tracking either test vehicles or randomly selected vehicles through to determine the travel times between preselected checkpoints. Vehicle tracing techniques are an example of "trip-based" method of sampling travel times. They are good techniques for measuring trip segment travel times (a geographic portion of the traveler's total trip). However, they generally are not easily adaptable to measurement of door-to-door travel times, because of the expense and difficulty of obtaining a reasonable sample of door-to-door locations.

Vehicle tracing techniques consist of: Test Vehicle, Non-Instrumented Vehicle Tracking, and Passive Probes.

1. Test Vehicle (Floating Car) Technique – The test vehicle technique is the most common travel-time collection technique employed to date. This technique consists of hiring a driver and vehicle to drive a vehicle along a preselected route and measuring the elapsed time and distance traversed. The driver is instructed to "pass as many vehicles as pass him or her" so that the vehicle is in effect driving at the median speed of traffic. Labor saving variations equip the test vehicles with distance measuring instrument (DMI) or global positioning satellite (GPS) to automate measurement and recording and to eliminate the need for a second person in the vehicle.

2. Non-Instrumented Vehicle Tracking Technique – This technique uses any one of several technologies for identifying randomly selected vehicles at various checkpoints within the study area and measuring the time between appearances at each checkpoint. Vehicle tracking is different than using test vehicles, because the drivers have not been hired to do the study. The drivers may take different paths and they may make stops in between checkpoints, throwing off the travel-time computations. Technological variations include: License Plate matching, License Plate matching with matching software, and Loop detectors with vehicle signature matching.

3. Passive Probe Technique – This technique requires some sort of special tracking instrumentation on the vehicles as well as the roadside. The vehicle driver is not hired to drive a particular route and goes about his or her normal business. Either readers are mounted on the road to record the time and identity of all transponder-equipped vehicles passing by, or readers are mounted in the vehicle to record the times and movements of the vehicle past each transponder location. The drivers may take different paths and they may make stops in between checkpoints, throwing off the travel-time computations. Technological variations include: Automatic vehicle location (AVL), Automatic vehicle identification (AVI), Emergency vehicle tracking, Cellular phone geolocation, and Global positioning satellite (GPS).

4. Transit Vehicle Tracking Techniques – The previous vehicle tracing techniques are applicable to all vehicles, including transit vehicles. The discussion under this category focuses on the special issues involved in working with public transit agencies to monitor public transit vehicles. Most public transit operators already publish route schedules and monitor on-time performance. A few operators are able to use automated techniques for tracking vehicle movements, but most currently rely upon manual checkpoint and ride check techniques. The data is stored in varying formats in varying software formats, making electronic transmittal of data difficult.

5. Truck Tracking Techniques – Trucks also can be tracked using all of the previously described vehicle tracking techniques. Tracking trucks though requires the active cooperation of the vehicle fleet owner who must consent to the placement of any special devices in the vehicle, or must transcribe manual logs and share the information with interested public agencies. Public agencies wishing to track commercial vehicles must demonstrate to the vehicle fleet owner that the owner will receive some direct benefit in return for the expense of transcribing and sharing the vehicle tracking information. In most cases, travel-time information is mixed in with

sensitive proprietary information on customers, and must be manually sorted out by the operator before it can be transmitted to a public agency.

Tripmaker Tracing Techniques

Trip maker tracing techniques survey travelers either after they have completed their trip or recruit volunteers in advance to record and report their travel times as part of their daily activities.

1. Retrospective Surveys – Retrospective surveys quiz the traveler about their trip travel times and experiences after the fact. The traveler is not prepped in advance, so questions must be limited to what can be reasonably remembered from the previous day's or that morning's commute. Variations explored here include: household telephone surveys, surveys of employees at their work sites, and web site/e-mail surveys.

2. Prospective Surveys – Prospective surveys involve at least two contacts with each individual: one contact to recruit the individual, and a second to collect the information. A third contact may be required to deliver a trip diary form or a GPS unit to the individual to aid in recording information. Travelers can be asked in advance to note a great deal of detail about their trips, including travel times for specific segments of the trip. Technological variations include: global positioning satellite receivers/recorders, e-mail reporting, and cell phone call-in.

HCM Method for Measuring Arterial Speed

Appendix B of Chapter 15 of the Highway Capacity Manual describes the following method for measuring the mean speed of through traffic on an arterial street.

> *"a. Use the appropriate equipment to obtain [cumulative travel time and stopped delay time]. The equipment may be computerized or simply a pair of stopwatches.*
>
> *b. Travel times between the centers of signalized intersections should be recorded, along with the location, cause, and duration of each stop.*
>
> *c. Test-car runs should begin at different time points in the signal cycle to avoid all trips starting first in the platoon.*
>
> *d. Some mid-block speedometer readings also should be recorded to check on unimpeded travel speeds and how they relate to FFS.*
>
> *e. Data should be summarized for each segment and each time period, the average travel time, the average stopped time for the signal, and other stops and events (four-way stops, parking disruptions, etc.).*
>
> *f. The number of test-car runs will depend on the variance in the data. Six to 12 runs may be adequate for each traffic-volume condition."*

3.4 MEASURING DELAY

The Highway Capacity Manual defines delay as "The additional travel time experienced by a driver, passenger, or pedestrian." Delay is thus the difference between an "ideal" travel time and the actual travel time. Since the definition of delay depends on a hypothetical "ideal travel time," delay is not always directly measurable in the field.

If the ideal travel time is defined as the off-peak travel time, then the measured delay is the difference between the actual measured travel time during the peak period, and the actual measured travel time during the off-peak period.

If the ideal travel time is defined as travel at the posted speed limit, then the delay cannot be directly measured in the field. It is estimated by subtracting the hypothetical travel time at the posted speed limit from the measured mean travel time in the field.

HCM Method for Measuring Free-Flow Speed

Appendix B of Chapter 15 of the Year 2000 Highway Capacity Manual explains how to measure the free-flow speed for an arterial street.

"This can be determined by making runs with a test car equipped with a calibrated speedometer during periods of low volume. An observer should read the speedometer at mid-block locations when the vehicle is not impeded by other vehicles and record speed readings for each segment. These observations can be supplemented by spot speed studies at typical mid-block locations during low-volume conditions."

HCM Method for Measuring Intersection Control Delay

The Year 2000 Highway Capacity Manual (see Appendix A, page 16-90 of the HCM) describes the following field procedure for measuring and computing intersection control delay for a signalized intersection.

1. The survey should begin at the start of the red phase of the lane group.

2. At regular intervals of between 10 and 20 seconds (but not an interval length that is evenly divisible into the cycle length) count the number of queued vehicles.

3. A vehicle is considered as queued when it approaches within one car length of a stopped vehicle and is itself about to stop.

4. All vehicles that join a queue are then included in the vehicle-in-queue counts until the rear axel of the vehicle crosses the stop line.

5. Simultaneously count the total number of arriving vehicles (whether they stop or not).

6. At the end of the survey period, continue counting vehicles in queue for all vehicles that arrived during the survey period until all of them have exited the intersection. This step requires mentally noting the last stopping vehicle that arrived during the survey period in each lane of the lane group and continuing the vehicle-in-queue

counts until the last stopping vehicle or vehicles, plus all vehicles in front of the last stopping vehicles, exit the intersection. Stopping vehicles that arrive after the end of the survey period are not included in the final vehicle-in-queue counts.

The time in-queue per vehicle is equal to 90 percent of the interval between queue counts multiplied by the sum of the vehicles in queue each interval divided by the total arriving vehicles. The 90 percent factor is intended to correct for the tendency of this method to over count delay.

$$TQ = 90\% * I * \frac{\sum Q(i)}{V} \qquad\qquad \text{Equation 1}$$

$$D = TQ + CF * \frac{VS}{V} \qquad\qquad \text{Equation 2}$$

Where:

D   = Average control delay per vehicle (secs).
TQ   = Time in-queue per vehicle (secs).
I   = The interval (length of time) between queue counts (secs).
Q(i) = The number of vehicles in queue at time point "i."
V   = Total arriving volume of vehicles (whether or not queuing).
CF   = Correction Factor to convert stopped delay to control delay.
VS   = Number of arriving vehicles stopping.

The correction factor is determined from the following look-up table taken from Exhibit A16-2 of the HCM.

Table 12. Acceleration-Deceleration Delay Correction Factor, CF(s).

Free-Flow Speed	<= 7 Vehicles	8-19 Vehicles	20-30 Vehicles
<=37 mph	+5	+2	-1
>37-45 mph	+7	+4	+2
> 45 mph	+9	+7	+5

Source: Exhibit A16-2, Highway Capacity Manual, Transportation Research Board, 2000.

3.5 MEASURING QUEUES

According to the ITE *Manual of Transportation Engineering Studies*, the macroscopic approach to measuring queues is to count the arrival and departure volumes for facility aggregated to five-minute intervals. The count should start before any queues are present and it should not end until the queues have all cleared. The difference between the

cumulative five-minute arrivals and the five-minute departures is the number of vehicles in queue. The arrival data must be counted just upstream of the end of the longest expected queue.

For a microscopic analysis, the license plate, arrival time, and departure time of each vehicle is recorded. The number of vehicles in queue at any point in time is the difference between the cumulative number of arrivals up to that point minus the cumulative departures up to that point in time.

The Year 2000 *Highway Capacity Manual* (HCM) defines a Queue as: "A line of vehicles, bicycles, or persons waiting to be served by the system in which the flow rate from the front of the queue determines the average speed within the queue. Slowly moving vehicles or people joining the rear of the queue are usually considered part of the queue. The internal queue dynamics can involve starts and stops. A faster-moving line of vehicles is often referred to as a moving queue or a platoon."

The HCM defines the Back of Queue as: "The distance between the stop line of a signalized intersection and the farthest reach of an upstream queue, expressed as a number of vehicles. The vehicles previously stopped at the front of the queue are counted even if they begin moving."

The HCM method described above for measuring control delay at a signal also can be used to measure queues.

3.6 MEASURING STOPS

The number of stops is can be obtained from a floating car survey, where the number of stops during each run is recorded. The number of stops obtained in this manner is representative only of vehicles driving the same path as the floating cars (usually just through traffic on the arterial).

Similarly, the HCM control delay measurement method described above can be used to identify the number of vehicles stopping on the approach to a traffic signal.

3.7 MEASURING DENSITY

The Year 2000 Highway Capacity Manual does not describe a method for directly measuring density in the field.

Aerial photography has been used to measure densities on freeways in several cities for the purposes of congestion monitoring (see Santa Clara VTA Annual Congestion Monitoring Reports for an example). A single photo is shot every half hour during the peak period and the number of vehicles counted between interchanges to obtain an average density representative of that half-hour period for each segment of the freeway facility. Vehicle density is NOT converted to passenger car equivalents.

Alternatively, density can be computed from loop detector measurements of speed and flow using the fundamental relation $d=v/s$ (shown in HCM, equation 23-4, page 23-12),

where "v" is the flow rate in vehicles per hour, "d" is the density in vehicles per mile, and "s" is the speed in mph.

The volume is counted manually, with temporary machine counters, or with permanent loop detectors for the desired analysis period. If an axle counter is used then an adjustment may be made to the count based on a separate truck axle count (See ITE Manual of Transportation Engineering Studies).

The spot speed is measured using any one of a variety of devices (see Measuring Speed, above). A sample size is selected to reduce the confidence interval for the true mean speed to the desired size.

3.8 MEASURING VARIANCE OF TRAVEL TIME

The variance of travel time is not usually measured because of the expense involved. An agency may take the inverse of speed (travel time per mile) measured at loop detectors and compute the variance of the travel time per mile at the detectors.

4.0 CALCULATION OF MOES BY TRAFFIC ANALYTICAL TOOLS

This chapter presents the results of a comprehensive investigation into how commonly used traffic analytical tools define and calculate commonly used MOEs. First the computation methodologies are explained based upon published user guides for each tool and informal correspondence with the software developers. Then the tools are tested on a simple test bed under both free-flow and congested traffic demand conditions. Variations in the reported MOEs are noted.

4.1 DESCRIPTION OF MOE COMPUTATION METHODOLOGIES

This section describes the methodologies used by the operations analysis tools to compute the MOEs that were selected for further investigation in Chapter 2.

4.1.1 HCS

The section describes how the MOEs are computed by the HCS software, Version 5.2, developed by the University of Florida, in 2005.

Computation of HCM Level of Service

The HCS software is intended to be a faithful implementation of the Highway Capacity Manual. As such, excepting for programming errors, which are corrected as soon as they are found, the HCS software computes the HCM LOS exactly according to the HCM methods. HCS implements the following HCM methods: Signalized Intersections, Unsignalized Intersections, Urban Streets, Freeway Basic, Freeway Weave, Freeway Ramps, Freeway Facilities, two-lane Rural Roads, Multi-lane Rural Highways, and Transit.

Computation of Volume Capacity Ratio

The HCS software computes capacity per the HCM method.[4] The HCM defines capacity as; "The maximum sustainable flow rate at which vehicles or persons reasonably can be expected to traverse a point or uniform segment of a lane or roadway during a specified time period under given roadway, geometric, traffic, environmental, and control conditions…" The HCM capacity for each facility type is computed according to the equations below.

The following equation is used to compute the capacity of all uninterrupted flow facilities (freeways, multi-lane highways, and two-lane rural roads):

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[4] Highway Capacity Manual, Transportation Research Board, Washington D.C., 2000.

Cap = Base Cap * N * f_{hv} * PHF* f_p* f_g **Equation 3**

Where:

Cap   = Capacity in terms of vehicles per hour.
Base Cap = Base capacity in terms of passenger cars per hour per lane (varies by facility type).
N   = Number of through lanes.
f_{hv} = Heavy vehicle adjustment factor (varies by facility type, vehicle mix, and grade).
PHF   = Peak-hour factor (the ratio of the peak 15-minute flow rate to the average hourly flow rate).
f_p = Driver population adjustment factor (used for freeway and multilane only).
f_g = Adjustment factor for grades (used for two-lane highways only).

For freeway and highway weaving sections the capacity is a function of weaving type, number of lanes, free-flows speed, length and weaving ratio. Due to the discontinuous nature of the procedure for weaving sections, no closed form equation for capacity is available.

The following equation is used to compute the lane group capacity for an approach to a signalized intersection:

$s = (g/C) \, s_o \, N \, f_w \, f_{HV} \, f_g \, f_p \, f_{bb} \, f_a \, f_{LU} \, f_{LT} \, f_{RT} \, fL_{pb} \, f_{Rpb}$ **Equation 4**

Where:

cap   = Capacity for subject lane group, expressed as a total for all lanes in lane group (veh/h).
g/C   = Effective green time per cycle ratio for lane group.
s_o = Base saturation flow rate per lane (pc/h/ln).
N   = Number of lanes in lane group.
f_w = Adjustment factor for lane width.
f_{HV} = Adjustment factor for heavy vehicles in traffic stream.
f_g = Adjustment factor for approach grade.
f_p = Adjustment factor for existence of a parking lane and parking activity adjacent to lane group.
f_{bb} = Adjustment factor for blocking effect of local buses that stop within intersection area.
f_a = Adjustment factor for area type.
f_{LU} = Adjustment factor for lane utilization.
f_{LT} = Adjustment factor for left turns in lane group.
f_{RT} = Adjustment factor for right turns in lane group.
fL_{pb} = Pedestrian adjustment factor for left-turn movements.
f_{Rpb} = Pedestrian-bicycle adjustment factor for right-turn movements.

The following equation is used to compute the lane group capacity for the approach to a roundabout and for a stop sign controlled approach to an intersection:

$$c_{p,x} = v_{c,x} \frac{\exp\left(-v_{c,x} t_{c,x} / 3600\right)}{1 - \exp\left(-v_{c,x} t_{f,x} / 3600\right)}$$ **Equation 5**

Where:

$c_{p,x}$ = Potential capacity of minor movement x (veh/h).
$v_{c,x}$ = Conflicting flow rate for movement x (veh/h).
$t_{c,x}$ = Critical gap (s).
$t_{f,x}$ = Follow-up time for minor movement x (s).

For a roundabout x=1, since there is only one movement on the approach.

The capacity of an all-way stop is a function of the demands on the other approaches and is determined through an iterative procedure.

Capacities and volume/capacity ratios are reported by HCS as follows:

Facility Type	Lane or Movement V/C and Capacity	Overall V/C and Capacity
Signals	Yes – v/c by lane group	Yes – v/c only
Two-Way Stops	Yes – v/c by lane group	No
All-Way Stops	Yes – Capacity by lane group	No
Roundabouts	Yes – Upper/lower bounds v/c of approaches	No
Arterial	Yes – Intersection v/c and through capacity	No
Freeway Basic	No	No
Freeway Weave	No	Yes – Capacity only
Freeway Ramp	Yes – Capacity of ramp and two lanes of freeway	No
Freeway System	Yes – Capacity and v/c by freeway segment	No
Two-Lane Highway	Yes – Two-way and one-way v/c	No facility capacity
Multi-Lane Highway	Not applicable	No facility capacity
Transit	No capacity by bus	No capacity by route

Computation of Speed and Travel Time

HCS computes mean speeds for urban streets, freeway facilities, multilane highways, and two-lane highways. The HCM formulae used by HCS are explained below.

Freeway Facilities

HCS computes the mean speeds for individual freeway segments and time periods using the following procedure from HCM.

If no queuing is present on the segment during any of the time periods then HCS uses the heuristic formula contained in the HCM for basic freeway sections to predict speed given the equivalent passenger volume and the free-flow speed.

If queuing is present on one or more segments during the analysis period then the speed = flow/density equation is used to compute speed:

$$U(i, p) = \frac{SF(i, p)}{K(i, p)} = L(i) * \frac{SF(i, p)}{NV(i, p)}$$

Equation 6

Where:

U(i,p)   = The average speed on segment "i" during period "p" (mph).
SF(i,p) = The segment flow rate (vph).
K(i,p)   = The average segment density (veh/mi).
L(i)   = The length of segment (miles).
NV(i,p) = The number vehicles.

The segment performance measures are then summed to total and average system performance using the following formulae:

$$SMS = \frac{\sum_{p}\sum_{i} SF(i, p) * L(i)}{\sum_{p}\sum_{i} SF(i, p) * \dfrac{L(i)}{U(i, p)}}$$

Equation 7

Where:

K   = Mean facility density across all segments (i) and time periods (p) (veh/mi).
L   = Length of segment (miles).
U   = Mean speed on segment (mph).

Multilane Highways

For volumes less than capacity a heuristic formula contained in the HCM for multilane highways is used to predict speed given the equivalent passenger volume and the free-flow speed. No procedure is provided for volumes greater than capacity.

Two-Lane Highways

For volumes less than capacity HCS uses the following HCM formula for estimating speed for two-lane highways:

ATS = FFS – $0.00776v_p$ – f_{np}

Equation 8

Where:

ATS   = Average travel speed for both directions of travel combined (mi/h).
FFS   = Free-flow speed (mi/h).
f_{np} = Adjustment for percentage of no-passing zones.
v_p = Passenger-car equivalent flow rate for peak 15-min period (pc/h).

No procedure is provided for volumes greater than capacity.

Urban Streets

HCS uses the following HCM formulae to estimate mean speed (in one direction) for urban streets.

$$SMS = \frac{3600 * \sum L_i}{RT * \sum_i L_i + \sum_j d_j}$$

Equation 9

Where:

SMS = Space mean speed over the length of the facility (mph or kph).
L_i = Length of segment "i" (mph or kph).
RT = Running time per mile (sec/mile or sec/km).
d_j = Delay at signal "j" for through traffic in the subject direction.

The delay for through traffic at each signal is computed according to the following formulae.

$$d = d_1(PF) + d_2 + d_3$$

Equation 10

$$d_1 = \frac{C * [1 - (g/C)]^2}{2 * [1 - (g/C) * \min(1, X)]}$$

Equation 11

$$d_2 = 900 * T * \left\{ (X - 1) + \sqrt{(X - 1)^2 + \frac{8 * k * I * X}{cap * T}} \right\}$$

Equation 12

Where:

d = Control delay (sec/veh).
d_1 = Uniform delay (sec/veh).
d_2 = Incremental delay (sec/veh).
d_3 = Initial queue delay (sec/veh).
PF = Progression adjustment factor.
C = Cycle length (secs).
g = Effective green time for the lane group (secs).
X = Volume/capacity ratio for the subject lane group.
k = Actuated control factor.
I = Upstream filtering factor.
v = Volume per hour (veh/hr).
cap = Capacity (sat * g/c) for the through lane group (veh/hr).
T = Duration of analysis period (hr).

Computation of Delay

HCS computes delay only for intersections. The analyst must use the output speeds for freeway facilities, multilane highways, two-lane highways, and urban streets to manually compute facility delay.

Freeway Facilities

The HCM does not provide a procedure for estimating delay for freeway facilities, so the HCS does not output this MOE. However the analyst can manually compute facility delay by dividing the predicted speed into the length of the facility to get travel time. Subtracting the predicted travel time from the free-flow travel time gives facility delay.

Multilane Highways

The HCM does not provide a procedure for estimating delay for multilane highways, so the HCS does not output this MOE. It can be estimated manually by the analyst from the HCS outputs as described above for freeway facilities.

Two-Lane Highways

The HCM does not provide a procedure for estimating delay for two-lane highways, so the HCS does not output this MOE. It can be estimated manually by the analyst from the HCS outputs as described above for freeway facilities.

Urban Streets

Urban street speed is computed by HCS but not delay. Mean and total facility delay can be estimated manually by the analyst using the HCS outputs as described above for freeway facilities.

The HCS does directly compute delay for each individual signalized intersection as described above under speed estimation for urban streets.

Unsignalized intersection delay is computed by HCS using an intersection approach delay formula similar to the one described above for signalized intersections.

Computation of Queue

Freeway Facilities

HCS computes queue lengths for freeway facilities based on an assumed linear relationship between flow and density. The density at capacity is determined based upon the capacity flow rate and the mean speed at capacity. The capacity and the speed at capacity are taken from the basic freeway section speed-flow curves in the HCM. They vary according to the free-flow speed for the freeway.

Once the density at capacity is known, then the flow rate is assumed to decrease linearly until it reaches zero at an assumed jam density of 190 passenger cars per lane-mile.

The queue density is computed as follows:

$$KQ(i,t,p) = KJ - \frac{(KJ - KC) * SF(i,t-1,p)}{SC(i,p)}$$

Equation 13

Where:

KQ(i,t,p)   = The density of queue on segment "i," at time step "t" for period "p" (veh/mi).
KJ   = The jam density (veh/lane/mi).
KC   = The density at capacity (veh/lane/mi).
SF(1,t-1,p) = The segment flow (veh/hr).
SC(i,p)   = The segment capacity (veh/hr).

The number of vehicles in the queue divided by the queue density and then divided by the number of lanes gives the length of the queue.

Multilane Highways

The HCM does not provide a procedure for estimating queues for multilane highways, so the HCS does not output this MOE.

Two-Lane Highways

The HCM does not provide a procedure for estimating queues for two-lane highways, so the HCS does not output this MOE.

Urban Streets

The HCM does not compute queuing directly for urban streets, so HCS does not do so either. The HCM and HCS do compute queues for intersections.

The mean queue for a lane group approaching a signalized intersection is computed according to the following formulae.

$$Q = Q_1 + Q_2$$

Equation 14

$$Q_1 = PF * \frac{v * C * [1 - (g/C)]}{3600 * [1 - (g/C) * \min(1, X)]}$$

Equation 15

$$Q_2 = 0.25 * cap * T * \left\{ (X - 1) + \sqrt{(X - 1)^2 + Z} \right\}$$

Equation 16

Where:

Q   = Control delay (sec/veh).
Q_1 = Uniform delay (sec/veh).
Q_2 = Incremental delay (sec/veh).
PF = Progression adjustment factor.

C = Cycle length (secs).

g = Effective green time for the lane group (secs).

X = Volume/capacity ratio for the subject lane group.

Z = Composite factor (see page 16-153 of HCM for details).

v = Volume per hour (veh/hr).

cap = Capacity (sat * g/c) for the through lane group (veh/hr).

T = Duration of analysis period (hr).

The HCM also provides for calculating various percentile probability queues as a function of the mean queue.

Computation of Stops

The HCM does not provide any procedures for computing number of stops. Thus HCS does not provide this MOE.

Computation of Density

Freeway Facilities

If no queuing is present the equivalent passenger car flow rate per lane is divided by the mean speed to obtain the density in units of equivalent passenger cars per lane-mile. If queuing is present then the following equation is used:

$$K(i, p) = \frac{NV(i, p)}{L(i)}$$

Equation 17

Where:

K(i,p) = The average segment density (veh/mi).

L(i) = The length of segment (miles).

NV(i,p) = The number vehicles.

The segment performance measures are then summed to total and average system performance using the following formula:

$$K = \frac{\sum_{p} \sum_{i} K(i, p) * L(i)}{\sum_{p} \sum_{i} L(i) * NV(i, p)}$$

Equation 18

Where:

K = Mean facility density across all segments (i) and time periods (p) (veh/mi).

L = Length of segment (miles).

U = Mean speed on segment (mph).

NV = Number of vehicles on segment.

Multilane Highways

HCS computes the mean passenger car density by dividing the mean speed into the passenger car equivalent flow rate.

Two-Lane Highways

The HCM does not provide a procedure for estimating delay for two-lane highways, so the HCS does not output this MOE. However the analyst could divide the mean speed into the flow rate to obtain density if desired.

Urban Streets

The HCM does not provide a procedure for computing density on urban streets and therefore HCS does not output this MOE for urban streets.

Computation of Travel-Time Variance

The HCM does not provide any procedures for any facilities for computing travel-time variance. Thus HCS does not provide this MOE.

4.1.2 Synchro 6

This section describes the formulae used by Synchro 6 (Build 614), released 2005 by Trafficware of Sugarland, Texas.[5] Synchro is designed to evaluate the performance of urban streets, signalized intersections, and unsignalized intersections (two-way stop, all-way stop, and single-lane roundabouts). Synchro does not provide performance data for freeways, multilane highways, or two-lane rural roads.

Computation of HCM Level of Service

Synchro computes the signalized intersection, unsignalized intersection, and arterial LOS according to the HCM. For signalized intersections, Synchro provides the user with two additional intersection levels of service (LOS). One is called the Intersection LOS; the other is called the ICU LOS.

The Intersection LOS is based upon a "percentile" control delay computation but uses the same numerical delay thresholds as the HCM. The percentile control delay is different than the HCM control delay for the intersection. The computation is explained below under the delay MOE.

The ICU LOS is based upon the critical flow ratio (ICU) for the intersection. The critical flow ratio is the sum of green +clearance times required to serve the critical movements at the intersection divided by a reference cycle length. The ICU LOS is designed to be insensitive to the actual signal timing for the intersection.

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[5] Source: Synchro6 Help.

$$ICU = \frac{\sum_i Max\left[(\min grn, CL*(v/s)_i\right] + L_i}{CL}$$

Equation 19

Where:

ICU = Intersection capacity utilization ratio.
Mingrn = Minimum green time for critical movement "i" (secs).
CL = Reference cycle length (secs). Set to 120 seconds.
L = Loss time for critical movement "i" (secs).

The ICU is converted into a letter LOS grade according to the following table.

Table 13. ICU LOS Thresholds.

LOS	Maximum ICU
A	55%
B	64%
C	73%
D	82%
E	91%
F	100%
G	109%
H	over 109%

Computation of Volume Capacity Ratio

Synchro provides volume/capacity ratios calculated using HCM saturation flow rates for signalized intersections, and unsignalized intersections (including two-way stop, all-way stop, and roundabouts).

Synchro provides volume/capacity ratios at intersections for each lane group. Capacity is computed using the HCM saturation flow computation method.

For the intersection as a whole, Synchro reports the maximum lane group v/c ratio for the intersection. A special HCM report provides the critical v/c (x) that is computed according to the HCM.

Computation of Speed and Travel Time

Synchro computes the arterial travel time according to the HCM method.

Computation of Delay

Synchro computes control delay according to the HCM method for signalized intersections, two-way stops, and all-way stops. Control delay is not computed for roundabouts in accordance with the HCM.

For signalized intersections Synchro also provides an alternative computation of delay based upon an assumed distribution of traffic volumes for the intersection. This is called the Percentile Delay to distinguish it from the HCM control delay.

The percentile delay computation uses only the first and third delay terms of the HCM. The incremental delay and the progression factor for the uniform delay in the HCM method are dropped. The incremental delay term of the HCM is modified for X>1 to use the saturation flow rate. The fourth term, queue delay, is added to cover delays due queue blockages resulting in unused green time.

$$d = d_1 + d_3 + d_4 \qquad\qquad\qquad \textbf{Equation 20}$$

$$d_1 = \frac{C * [1 - (g/C)]^2}{2 * [1 - (g/C) * X]} \quad \text{if X} <= 1.00 \qquad\qquad \textbf{Equation 21}$$

$$d_1 = \frac{s * C * [1 - (g/C)]^2}{2 * 3600} \quad \text{if X} > 1.00 \qquad\qquad \textbf{Equation 22}$$

Where:

D = Delay (sec/veh).
d_1 = Uniform delay (sec/veh).
d_3 = Initial queue delay (sec/veh).
d_4 = Queue interaction term (sec/veh).
C = Cycle length (secs).
S = Saturation flow rate (veh/hr-green).
G = Effective green time for the lane group (secs).
X = Volume/capacity ratio for the subject lane group.

Synchro introduces the random component of delay (that, in the HCM, was contained in the incremental delay term) by computing the uniform delay term using a series of 5 volume scenarios. Uniform delay (d_1) is computed for the 90th percentile volume, the 70th percentile volume, the 50th percentile volume, the 30th percentile volume, and the 10th percentile volume. The 5 delay estimates are averaged to obtain the average delay.

If the traffic signal is traffic actuated, then the green times also are computed for each percentile volume when computing the percentile delay.

The percentile volumes are computed assuming a Poisson arrival pattern with mean equal to the input traffic volume for the lane group divided by the number of cycles per hour.

$$v(p) = v + \left[z(p) * \sqrt{(v * C / 3600)}\right] * \frac{3600}{C}$$

Equation 23

Where:

$v(p)$ = Percentile volume for percentile "p" (veh/hr).
V = Lane group volume (veh/hr).
$z(p)$ = Number of standard deviations for percentile "p" for Poisson Distribution.
    = -1.28 for 10%.
    = -0.52 for 30%.
    = 0 for 50%.
    = +0.52 for 70%.
    = +1.28 for 90%.
C = Cycle length (secs).

The initial queue delay (d_3) is the same as the HCM term.

The queue interaction term (d_4) takes into the account blockages and demand starvation resulting from queues that extend longer than the available distance between intersections.

If Min[CapDist, VolDist) > Distance,   **Equation 24**

Then queue interaction is likely to occur.

Where:

Distance = Available distance between intersections to store queues (ft).
CapDist = Distance required to store a flow at capacity.
    = AVL * [2+g*s/(n*3,600)].
VolDist = Distance required to store the 90% volume.
    = AVL*[2+v90*C/n*3,600)].
AVL = Average Vehicle Length (ft).
G = Green time per cycle (secs).
S = Saturation flow rate (veh/hr-green).
N = Number of lanes.
v90 = 90th percentile volume.
C = Cycle length (secs).

If the queue interaction is likely to occur then Synchro calculates the likely reduction in capacity flow rates at the downstream intersection for the 50 percentile and 90 percentile volumes. The queue interaction delay is then computed using the HCM incremental delay formula (d2) and the reduced capacities.

The storage blocking portion of the queue interaction calculation was recently disabled (as of Build 610) due to problems with its representation of short left turn pocket blockages.

Computation of Queue

For unsignalized intersections Synchro computes queue lengths according to the HCM method.

For signalized intersections Synchro computes queues for the 50 percentile and 95 percentile volumes. The 50 percentile queue is computed as follows.

If the volume is less than capacity then the following formula is used.

$$Q(p) = \frac{v(p)}{3600} * (R-6) * \left[1 + \frac{1}{\{s/v(p)\}-1}\right] * \frac{AVQ}{N*F_u} \qquad \text{Equation 25}$$

If the volume is equal to or greater than capacity then the following formula is used.

$$Q(p) = \left[v(p) + (v(p) - s*g/C)\right] * \frac{C*AVQ}{3600*N} \qquad \text{Equation 26}$$

Where:

Q(p) = Queue length for percentile "p" volume (ft).
v(p) = Percentile "p" volume for lane group (veh/hr).
R   = Red time (secs).
S   = Saturation flow rate (veh/hr-green).
AVQ = Average front-to-front spacing of vehicles in queue (ft).
N   = Number of lanes in lane group.
Fu   = Lane utilization factor.
C   = Cycle length (secs).
PHF = Peak-hour factor.

A special value of the 95 percentile volume is used to compute the 95 percentile queue.

$$v(95) = v(50) * Min[PHF, 0.90] * \left[1 + \frac{1.64 * \sqrt{3600}}{\sqrt{v(50)*C}}\right] \qquad \text{Equation 27}$$

If the upstream signal has the same cycle length as the subject intersection, then the 95 percentile volume on the subject approach is compared to the maximum volume that can be delivered by the upstream signal and reduced accordingly for the "metering" effect of the upstream signal.

Computation of Stops

Synchro computes the number of stops for a signalized intersection approach as equal to the number of vehicles queued multiplied by a stopping rate percentage obtained from Transyt 7-F (see table below).

Table 14. Conversion of Delay to Stops.

Delay (Secs)	Percent Stopping
0	0%
1	20%
2	58%
3	67%
4	77%
5	84%
6	91%
7	94%
8	97%
9	99%
10 secs or greater	100%

Computation of Density

Synchro does not compute density.

Computation of Travel-Time Variance

Synchro does not compute travel-time variance.

4.1.3 Dynasmart-P

This section discusses Dynasmart-P Version 1.0, August 2004.[6]

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[6] Hani S. Mahmassani, Hayssam Sbayti, and Xuesong Zhou, *Dynasmart-P Version 1.0 User's Guide*, Federal Highway Administration, Office of Operations Research and Development, McLean, Virginia, August 2004.

Overview of MOEs

Dynasmart-P outputs overall vehicle statistics for the network, including trip times, travel times, stop times, entry queues, and travel distances. Also, the following link-specific statistics are provided averaged over all simulation intervals.

1. Number of generated vehicles;

2. Number of vehicles;

3. Vehicle queue length (number of vehicles in queue);

4. Link speed (average mph);

5. Link density (average pc/lane-mile);

6. Mean Speed of moving vehicles; and

7. Mean PC Density of moving vehicles.

Dynasmart also can output individual vehicle trajectories enabling the user to use ACCESS or to write a program to compute their own custom measures of effectiveness.

Computation of HCM Level of Service

Dynasmart-P does not output HCM level of service.

Computation of Volume Capacity Ratio

Dynasmart-P does not output link volume/capacity ratios. However, the analyst can compute the v/c ratios by dividing the output link volumes by the input link capacities.

Computation of Speed and Travel Time

Dynasmart-P outputs system total trip distance (VMT), trip time (VHT), network entry delay (entry queue time), stop time, and average speed. Dynasmart-P also outputs link-specific mean speeds and mean speeds outside of queues.

The total trip distance is the sum of the vehicle volume on each link multiplied by the link length. Note that Dynasmart requires that all links be longer than the distance that can be traveled in one simulation interval (six seconds) at the free-flow speed. The software will increase the coded link length as necessary to meet this requirement. Thus some minor distortions of the distance traveled may occur for shorter links that fail to meet this requirement.

The total trip time is the sum of the vehicle volume on each link divided by the mean link speed plus the entry delay time for vehicles denied entry to the network.

The system average speed is the system distance traveled divided by the system trip time (inclusive of delays to vehicles denied entry to the network).

The link-specific mean speed is the simple arithmetic average of the spot speeds of all vehicles on the link at the end of each six-second simulation interval. The user can average the spot speeds over multiple simulation intervals to obtain an hourly average for each link. The variance of the mean speeds can be computed manually by reporting the mean speed for each simulation interval and porting the file into a spreadsheet.

The mean speed of vehicles on a link is estimated by Dynasmart-P using a modified Greenshields equation. A two-regime equation is used for freeways (shown below). A single regime equation is used for arterials.

$$v_i = v_0 + Min\left[(FFS - v_0), (v_f - v_0)\left(1 - \frac{k_i}{k_{jam}}\right)\right]$$ **Equation 28**

Where:

Vi   = Mean speed (mph).
V0   = Minimum mean speed (mph).
FFS   = Free-flow speed (mph).
Vf   = Hypothetical speed at y-intercept of Greenshields equation.
Ki   = Mean density (pc/lane-mile).
Kjam = Theoretical jam density (pc/lane-mile).

The single regime equation uses the same equation above with the hypothetical y-intercept speed (vf) set equal to the actual free-flow speed (FFS).

Computation of Delay

Dynasmart-P does not output delay statistics, however; the analyst can compute the delay for individual links using the link data output by Dynasmart-P. The individual link delays can be summed to system totals in a spreadsheet.

Computation of Queue

The method used by Dynasmart-P to identify queued vehicles on the network is not described in the Users Guide.[7]

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[7] This is not documented in User Guide. Response from the developer regarding their definition of queues not received in time for publication.

Computation of Stops

Dynasmart-P tallies stop time for vehicles at a complete stop (zero speed).

Computation of Density

Dynasmart-P reports the average equivalent passenger car density by link (pc/mile/lane) averaged over as many six-second simulation intervals as desired by the analyst. A separate density also can be reported for the queue-free portion of each link.

Trucks are converted to passenger car equivalents using the PCE values for each link input by the analyst.

The extra storage space available on links with left and/or right turn bays is not included in the denominator of the density computation. However vehicles in these bays are included in the numerator.

The impacts of partial lane closures on the available storage space due to work zones and incidents are not included in the density computation.

Note that the density computation may be distorted slightly for short links with lengths less than FFS*528/60 (where FFS is the free-flow speed). Dynasmart-P will increase the lengths of the short links to equal the minimum length.

Computation of Travel-Time Variance

Dynasmart-P does not output variance statistics. Vehicle trajectories are output by Dynasmart-P which would enable an analyst working with database or similar high-capacity data processing software to compute variances.

However, the finest level of disaggregation available in Dynasmart is the link and six-second-long simulation intervals. Acceleration or deceleration within the link are not treated. Variation of vehicle speeds around the link mean speed is not included in the model. Thus the variances computed from the vehicle trajectories would not be expected to be as large as would be observed in the field.

4.1.4 SIMTRAFFIC

This section describes the formulae used by SimTraffic 6 (Build 614), released 2005 by Trafficware of Sugarland, Texas.[8] SimTraffic is based on CORSIM. As such, it is designed to evaluate the performance of freeways, urban streets, signalized intersections, and unsignalized intersections (two-way stop, all-way stop, and single-lane roundabouts). SimTraffic does not model passing in opposing flow lanes, and thus is not designed to evaluate two-lane rural roads.

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[8] Source: SimTraffic 6 Help.

Computation of HCM Level of Service

SimTraffic does not output levels of service.

Computation of Volume Capacity Ratio

SimTraffic does not compute capacity or volume/capacity ratios.

Computation of Speed and Travel Time

SimTraffic outputs travel time and average speed by turn movement, for arterials, and for the entire network.

The Travel Time (VHT) is the total time each vehicle was present on the link. The travel time includes time spent by vehicles Denied Entry (waiting to enter the network), but does not include the spent by vehicles on the upstream link waiting to enter the subject link.

$$VHT = \sum_i t(i) + \sum_i w(i)$$
Equation 29

Where:

VHT = Total vehicle hours traveled on link or spent in zone waiting to access link (hr).
t(i) = Time spent by vehicle "i" on link (hr).
w(i) = Time spent by vehicle "i" in zone waiting to enter link (hr).

The Average Speed is calculated by dividing Total Distance (VMT) by Total Time spent on the network. The time used in the calculation of Average Speed does not include time spent by denied entry vehicles while they are waiting to enter the network. Average speed may therefore be higher than Total Distance (VMT) divided by Total Time (VHT) for the link.

$$AveSpd = \frac{VMT}{VHT - VHT(w)}$$
Equation 30

Where:

AveSpd = Average link speed (mph).
VMT = Total vehicle miles traveled on link (mi).
VHT = Total vehicle hours traveled on link or spent in zone waiting to access link.
VHT(w) = Total vehicle hours spent by vehicles in zone waiting to access link.

The Total Distance (VMT) is the total distance traveled by all vehicles on the link. Vehicles waiting to enter the link do not travel any distance on the link, so they have no impact on the VMT computation.

$$VMT = \sum_i d(i)$$
Equation 31

Where:

VMT = Total vehicle miles traveled on link (mi).
d(i) = Distance traveled by vehicle "i" on link (mi).

The Arterial Report is a special report that reports delay, travel time (VHT), distance (VMT), and speed for a select subset of vehicles on a select subset of links. It uses origin destination data to only count vehicles on the current link that came from the arterial on the next upstream link. This is not the same as taking the travel time of only those vehicles that travel the entire length of the arterial.

Computation of Delay

SimTraffic outputs total delay, delay/vehicle, and stopped delay by turn movement, for arterials, and for the entire network.

Total Delay is defined as the travel time (VHT) minus the time it would take the vehicle if traveling at the maximum permitted speed (the speed limit or the maximum safe turning speed, whichever is lesser). The delay accrued by vehicles denied entry to the network during each 1/10 second time slice is added to this total.

$$TD = \sum_t \sum_i 0.1 * \frac{spd\max(l,r) - spd(i,t)}{spd\max(l,r)} + \sum_i 0.1 * NDE(t)$$ **Equation 32**

Where:

TD   = Total vehicle-delay (hr).
spdmax   = Maximum speed on link "l" for turn "r."
         = Link speed limit except when approaching turn, during turn, and accelerating out of turn.
spd   = Actual vehicle speed for vehicle "i" at time slice "t." Each time slice = 1/10 of second.
NDE   = Number of vehicles denied entry during time slice "t."

Delay per Vehicle is the total delay divided by the Number of Vehicles.

The Number of Vehicles is defined as the number of vehicles that exited the link during time slice "t": plus one-half of those vehicles remaining on the link at the end of time slice "t" minus one-half of those vehicles that were present anywhere on the link at the start of time slice "t." The assumption is that vehicles that were present at the start of the time slice and vehicles that were present at the end of the time slice contributed delay for half the time as for vehicles both entering and exiting the link during the time slice.

$$NV = N(x) - 0.5N(s) + 0.5N(e)$$ **Equation 33**

Where:

NV   = Number of vehicles.

N(x) = Number of vehicles exiting the link during time period.

N(s) = Number of vehicles present on link at start of time period.

N(e) = Number of vehicles present on link at end of time period.

Spd = Actual vehicle speed for vehicle "i" at time slice "t." Each time slice = 1/10 of second.

NDE = Number of vehicles denied entry during time slice "t."

Note that this formula results in zero vehicles if the link is totally jammed with vehicles during the time period with nobody entering or exiting during the time period.

The Stopped Delay is the sum over all time slices of the number of vehicles traveling at less than 10 ft/s (3 m/s) times the length of the time slices (1/10 of one second). The sum of the number of denied entry vehicles each time slice times the length of the time slices is added to the stopped delay.

Stop Delay/Vehicles is equal to the Stopped Delay divided by the Number of Vehicles.

Computation of Queue

SimTraffic outputs Maximum queue (ft), Average queue (ft), and 95 Percentile queue (feet) by lane by turn movement. SimTraffic also outputs the Upstream Block Time, Storage Block Time, and the queuing penalty.

The maximum queue may be less than the 95 percentile queue because the Maximum queue is observed during the simulation run and the 95 percentile queue is statistically estimated from the mean queue and the standard deviation.

A vehicle is considered queued when it is traveling at less than 10 ft/s (3 m/s) and either at a stop bar or following another queued vehicle. Thus, single vehicle queues are not possible except at intersection stop bars.

All queues in SimTraffic originate at the intersection. Queues cannot originate mid-link.

For queue length computations SimTraffic uses a front-of-vehicle to front-of-vehicle length of 19.5 feet (6 meters).

The Maximum Queue (feet) is the maximum observed distance from the stop bar to the back of queue over the analysis period. Note that Maximum Queue is limited by the length of the link.

Maximum queues are recorded every two minutes during the simulation.

The Average Queue is the average of the observed maximum queues for each of those two-minute periods.

The standard deviation of the maximum queue is computed for all of the two-minute maximum queues recorded during the simulation.

The 95 Percentile queue is computed as 1.65 standard deviations above the average queue.

Thus the 95 Percentile Queue can be greater than the Maximum Queue. Also, the computed 95 Percentile Queue is NOT limited by the length of the link.

SimTraffic will exclude from the queuing statistics most vehicles that stop for a lane change (depending on the circumstances).

The Upstream Block Time is the percent of time that the upstream end of the lane in a link is blocked.

The Queuing Penalty is the traffic volume in the lane times the percent of time during the simulation period that the lane is blocked. For a storage bay the turning volume in the adjacent through lane may be added to the Queuing Penalty volume if the through lane back up is preventing vehicles from accessing the turn bay.

The Storage Bay Block Time is the sum of the percent of time that the storage bay is full and the percent of time that queues in the adjacent through lane exceed the length of the turn bay.

Links may have bend nodes in them. The queue for the intersection at the end of the link includes the queue for the portion of the link upstream of the bend node. A separate column in the report reports the queue upstream of the bend node.

Computation of Stops

SimTraffic outputs total stops and stops per vehicle by turn movement.

The Total Stops is the count of vehicle stops. A stop is added to the tally every time a vehicle's speed drops below 10 ft/s (3 m/s). A stopped vehicle speed must reach 15 ft/s (4.5 m/s) again before it can generate any additional stops. That way vehicles moving up in a queue do not generate multiple stops.

Stops/Vehicles is calculated by dividing the number of Stops by the Number of Vehicles (See the delay description for the formula used to compute number of vehicles).

Computation of Density

SimTraffic does not report vehicle density.

Computation of Travel Time Variance

SimTraffic does not report variance of travel time, but it does provide for the execution and reporting of multiple runs. The standard deviation of the maximum 2-minute queues observed are computed (and used in the 95 percent queue calculation) but the value of the standard deviation is not reported.

4.1.5 CORSIM

This section presents the CORSIM 5.1 software based on the information contained in the CORSIM 5.1 Users Guide by ITT Industries, February 2003.

For freeways CORSIM 5.1 outputs: Vehicles in, Vehicles out, lane changes, VMT, VHT, VHT/veh, Move Time/veh, Delay/veh, Volume, Density, and Speed on a link by link basis.

For arterials streets CORSIM outputs queue time, stop time, percent storage, phase failure, average queue by lane, maximum queue by lane, and lane changes on a link-by-link basis. VMT, vehicle-trips, speed, percent stops, move time, delay time, and total time (VHT) are reported on a turn movement basis.

Computation of HCM Level of Service

CORSIM does not output HCM Level of Service. A CORSIM postprocessor within another software tool, Transyt-7F can be used to derive HCM level of service.

Computation of Volume Capacity Ratio

CORSIM does not compute capacity and therefore does not output v/c ratio. The analyst would have to run CORSIM with increasingly higher flows until capacity is reached and count the sustained average discharge rate at the bottleneck to obtain capacity. Once the capacity is obtained, then the v/c ratio can be computed for the actual volume.

Computation of Speed and Travel Time

CORSIM outputs Total Time, Move Time, Delay Time for each link. It outputs total time per vehicle. It also outputs various speed statistics by link: Total Time Rate (minutes/mile), Delay Time Rate (minutes/mile) and Average Speed.

Total Time (VHT) is the total time on the link for all vehicles. It therefore does not include denied entry vehicle delay.

$$VHT(i) = \sum_t N(i,t) * TS / 60 \qquad \text{**Equation 34**}$$

$$TTPV(i) = \frac{60 * VHT(i)}{N(e,i)} \qquad \text{**Equation 35**}$$

Where:

VHT = Total vehicle-hours traveled on link "i" (veh-min).
TTPV = Total time per vehicle (sec/veh).
TS = Duration of time slice, 1.0 seconds in CORSIM.
N(i,t) = Number of vehicles present on link "i" at time slice "t."
N(e,i) = Number of vehicle exiting the link during simulation period.

The Total Time per Vehicle is computed by dividing the total time by the number of vehicles exiting the link during the simulation period. Note that vehicles that fail to exit the link during the simulation period will generate total travel time but will not be counted in the number of vehicles exiting the link, thus tending to increase the computed total time per vehicle.

The Average Speed is the ratio of VMT over VHT. VMT is computed by multiplying the number of vehicles exiting the link during the simulation period by the length of the link. Note that it excludes the delay to vehicles denied entry to the network.

$$SMS(i) = \frac{60 * VMT(i)}{VHT(i)}$$ **Equation 36**

$$VMT(i) = N(e,i) * L(i)$$ **Equation 37**

Where:

SMS = Mean speed of vehicles on link "i" (mph).
VHT = Total vehicle-hours traveled on link "i" (veh-min).
VMT = Total vehicle-miles traveled on link "i" (veh-mi).
L = Length of link "i" (mi).
N(e,i) = Number of vehicles exiting link "i."

Note that this equation has the effect of shifting to the next simulation period all of the VMT generated by any vehicles that fail to leave the link during the current simulation period.

The Total Time Rate (min/mi) is the inverse of the mean speed.

Computation of Delay

CORSIM divides Total Travel Time into two additive components: Move Time and Delay Time. Move Time is the theoretical time it would take to traverse a link at the free-flow speed (even if the vehicle driver doesn't really want to go at that speed, some may want to go slower, some may want to go faster). The Total Travel Time is the amount of time it actually takes to traverse a link. The Delay Time is then the difference between the observed Total Travel Time and the theoretical Move Time at the free-flow speed. CORSIM also outputs the Delay Time Rate in terms of minutes of delay per mile traveled.

Move Time is the travel time if all travel was done at the link free-flow speed. It is computed in CORSIM by multiplying the Total Time measured by the ratio of the free-flow speed to the average speed for the link.

$$MT(i) = VHT(i) * \frac{SMS(i)}{FFS(i)}$$ **Equation 38**

Where:

MT   = Move Time at free-flow speed on link "i" (veh-min).
VHT = Total vehicle-hours traveled on link "i" (veh-min).
SMS = Mean speed of vehicles on link "i" (mph).
FFS   = Free-flow speed on link "i"(mph).

Delay Time is the difference between the total travel time and the Move Time. It does NOT include delay time for vehicles denied entry to the network.

$$DT(i) = VHT(i) - MT(i)$$ **Equation 39**

Where:

DT   = Delay time on link "i" (veh-min).
VHT = Total vehicle-hours traveled on link "i" (veh-min).
MT   = Move Time at free-flow speed on link "i" (veh-min).

The Delay Time per Vehicle is the Delay Time divided by the number of vehicles exiting the link during the simulation period.

$$DTV(i) = 60 * \frac{DT(i)}{N(e,i)}$$ **Equation 40**

Where:

DTV = Delay time per vehicle on link "i" (secs).
DT   = Delay time on link "i" (veh-min).
N(e,i)= Number of vehicles exiting link "i" during simulation period.

Note that vehicles denied entry to the link are not included in the delay. Note also that vehicles failing to exit the link during the simulation period generate delay that is included in the numerator but the number of these vehicles is not included in the denominator.

The Delay Time Rate (min/mi) is the delay time divided by the VMT.

$$DTR(i) = \frac{DT(i)}{VMT(i)}$$ **Equation 41**

Where:

DTR = Delay time rate on link "i" (min/mi).
DT   = Delay time on link "i" (veh-min).
VMT = Total vehicle-miles traveled on link "i" (veh-mi).

Note that the Delay Time Rate includes all vehicles on the link that generate delay during the current time period in the numerator but may or may not exclude any vehicles failing to exit the link by the end of the current time period from the denominator.[9] Vehicles denied entry to the network or the link are NOT included in the delay.

For non-freeway links CORSIM also identifies two overlapping (and therefore not additive) components of Delay Time. They are the Queue Time and the Stop Time. A vehicle is in a queue all of the time if it is moving below 3 feet per second (with an acceleration rate of less than 2 fpss), and half of the time if it is moving between 3 and 9 feet per second. The vehicle is "stopped" if its speed is less than 3 feet per second.

The Queue Time and the Stop Time are not additive since they overlap. Stop time is a subset of Queue Time.

The mean queue time and the mean stop time are computed by dividing the total queue time or stop time by the sum of the total number of vehicles exiting the link plus the number of vehicles remaining on the link at the end of the simulation period.[10]

Version 5 of TSIS/CORSIM now computes "control delay" for signalized links. Control delay is defined in CORSIM as the difference between the actual travel time through the intersection and the theoretical travel time if the vehicle had been able to continue at its original "operating" speed. Operating speed is defined as the speed of the vehicle prior to the start of deceleration for the signal. Operating speed is lower than the free-flow speed for the link, since it takes into account mid-block congestion effects, unrelated to any signals. The influence area of the signal is defined to start when the vehicle begins to decelerate on a link with a downstream signal and end when the vehicle ceases to accelerate on a link with an upstream signal.[11]

Note that Control Delay will therefore exclude delays that occur on links upstream of the link with the traffic signal.

Computation of Queue

CORSIM reports density but does not report queues for freeway or ramp links.

For all other links CORSIM defines a vehicle as being in a queue when it is moving at less than 3 fps and is accelerating/decelerating by less than 2 fpss. If a vehicle is moving at a

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[9] The Users Guide does not explicitly state how measures of effectiveness for vehicles failing to exit the link during the simulation period are accumulated, if at all.

[10] Source for this statement is footnote to CUMULATIVE NETSIM STATISTICS table in CORSIM output.

[11] There is some dispute among CORSIM experts as to whether this is indeed an accurate description of how CORSIM actually computes control delay. This description is taken from the users guide, but has not been independently verified by this author.

speed of between 3 fps and 9 fps it is considered to be in a queue 50 percent of the time (every other second). The "maximum queue" is the largest number of vehicles observed to be queued in a lane during the simulation period. The "mean queue" is the mean number of queued vehicles over the simulation time period with "zero" queues included in the average.

The percent of link storage use is the mean number of vehicles in queue times the mean distance between vehicles divided by the link length times the number of lanes.

$$\% Storage(i) = \frac{AveQ(i)*6*AVL}{NL(i)*L(i)}$$
                                                                                    Equation 42

Where:

%Storage = Percent of available link storage used.
AveQ   = Mean queue length on link "i."
AVL   = Average vehicle length (ft).
NL   = Number of Lanes, including turn bays.
L   = Length of link.

Phase Failure is the number of cycles during the simulation period that the queue fails to clear a traffic signal. Phase Failure is NOT computed for freeway or ramp links.

Note that the reported queue cannot exceed the length of the link. The percent storage CANNOT exceed 100 percent.

Computation of Stops

CORSIM does NOT compute stops for freeway and ramp links. For all other links a vehicle is recorded as "stopped" if its speed is less than three feet per second.

Computation of Density

CORSIM does not provide density for non-freeway links.

For freeway links density is the average content of the link during the period divided by the length of the link times the number of lanes.

The average content of the link is the cumulative sum of the vehicle-seconds travel time accumulated on the link divided by the cumulative number of seconds in the simulation period.[12]

$$Density(i,T) = \frac{\frac{1}{T}\sum_t N(t)*TS}{L(i)*NL(i)}$$

Equation 43

Where:

Density = Mean density of link "i" over time period "T" (veh/lane-mi).
T = Length of time period (secs).
N = Number of vehicles on link at time "t."
TS = Length of time step (= 1.0 secs in CORSIM).
NL = Number of Lanes, including turn bays.
L = Length of link.

Computation of Travel-Time Variance

CORSIM does not compute the variance in travel time. The model can be run several times with different random number seeds to obtain a variance. A TSIS output processor can be used to make the computations from the runs. However, the computed variance would not include the impacts of variation in demand or capacity reducing incidents on the facility.

4.1.6 Vissim

This section describes how Vissim computes its measures of effectiveness based upon its Users Guide[13] and additional information from the vendor.

MOEs can be collected by Vissim at detector locations or for selected series of links. MOEs also can be gathered for paths.

The link evaluations can produce:

- Density (veh/km);
- Speed;

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[12]It is not clear whether the accumulated VHT at the end of the period is used rather than a running total of vehicle-seconds on the link to compute density. We have chosen to show the formula assuming that CORSIM uses the sum of the running total of vehicle-seconds.

[13]Vissim 4.1 User Manual, PTV, Planung Transport Verkehr AG, Karlsruhe, Germany, March 2005.

- Volume; and

- Lost Time (Delay).

Node Analysis can produce:

- Volume;

- Average Delay;

- Standing Time;

- Number of Stops; and

- Queue Length.

The Network Performance Evaluation will produce the following systemwide MOEs:

- Number of Vehicles Left in Network;

- Number of Vehicles Exiting Network;

- Total Path Distance (VMT);

- Total Travel Time (VHT);

- Average Speed (mph);

- Total Delay (hrs);

- Stopped Delay (hrs);

- Average Stopped Delay;

- Number of Stops; and

- Average Number of Stops.

Computation of HCM Level of Service

Vissim does not directly output HCM Level of Service.

Computation of Volume Capacity Ratio

Vissim does not directly output volume/capacity ratios.

Computation of Speed and Travel Time

The computation of speed (in the link segment evaluation) follows the general space-time definition of average speed:

$$\bar{v} = \frac{\sum_i xx(i)}{\sum_i tt(i)}$$

Equation 44

Where:

$\bar{v}$ = Average speed in the link segment during the analysis period.

xx(i)   = Total distance traveled by vehicle i in the link segment during the analysis period.

tt(i)   = Total time spent by vehicle i in the link segment during the analysis period.

Average speed in the network performance evaluation is defined the same way (total miles traveled divided by total hours spent).

Vissim outputs travel-time results between selected points on the network. The average is computed from the actual travel times of all vehicles that have passed the destination point after they have passed the start point. Vehicles that have not reached the destination point and denied entry vehicles are not included in the travel-time results.

Computation of Delay

Vissim defines delay as the difference between the actual vehicle travel time and its desired travel time. Note that this is a microscopic definition of delay that is specific to each vehicle. This is different than the other software packages that compare actual travel times to an average link free-flow travel time.

The average total delay per vehicle is computed only for the vehicles completing the travel-time measurement section. The delay is computed for each vehicle by subtracting the ideal travel time from the actual travel time. The ideal travel time is computed assuming no other vehicles on the network and no delays at signal controls or stop signs. Reduced speeds for turns are taken into account in the ideal travel time.

Computation of Queue

Vissim allows the user to define a queue according to the maximum vehicle speed for the beginning of the queue (default is 5 km/hr), the minimum vehicle speed at its end (default is 10 km/hr), and the maximum spacing between vehicles (default is 20 meters).

Vissim allows the user to identify a queue counter location. The distance to the farthest upstream point of any queue at this location is tallied. If the queue backs up onto multiple links, the longest distance is recorded. If the front of the queue begins to discharge Vissim keeps tracking to the back of the queue until no queued vehicles remain between the queue counter location and the current back of queue.

$$AVEQ = \frac{\sum_i Q(i)}{I}$$
                                                                                             Equation 45

Where:

AVEQ   = Average Back Of Queue over analysis period (meters).

Q(i)   = Observed Back of Queue length (meters) at end of time step (i).

I   = Total number of time steps in analysis period.

Incidentally, if the queue extends from one queue counter location back to another, the queue length is truncated to that distance.

Vissim also will report the number of stops within the queue (which are defined as situations when the vehicle enters the queue, i.e., when its speed falls below the speed for the beginning of the queue).

Computation of Stops

Stops in the delay and node evaluation are defined as situations when the vehicle's speed falls to zero.

Computation of Density

The computation of density (in the link segment evaluation) follows the general space-time definition of traffic density:

$$k = \frac{\sum_i tt(i)}{T \cdot X}$$
Equation 46

Where:

k   = Average density in the link segment during the analysis period.
tt(i) = Total time spent by vehicle i in the link segment during the analysis period.
T   = Duration of the analysis period.
X   = Length of the link segment.

Computation of Travel-Time Variance

Vissim does not directly output travel-time variance information, however; the software provides a raw data file with all single travel times of the individual vehicles. These can be used to determine the variance.

4.1.7 Paramics

This section discusses the MOEs produced by Quadstone Paramics Version 5.0 (2004).[14]

Paramics produces systemwide and link-specific MOEs.

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[14] *Quadstone Paramics V5.0 Modeler Reference Manual*, Quadstone Limited, Edinburgh, Scotland, August 2004.

Systemwide MOEs (Economic Info) that are reported for every minute of the simulation include:

- Number of Vehicles currently on network;
- Mean speed of vehicles currently on network at specific point in time;
- Cumulative number of vehicles simulated on network;
- Accumulated Total Travel Time (VHT) since start of simulation;
- Accumulated Total Distance Traveled (VMT) since start of simulation;
- Mean Speed of all vehicles on network since start of simulation;
- Total number of stops made by public transit vehicles;
- Total time stopped for public transit;
- Passengers Boarding; and
- Passengers Alighting.

Paramics also outputs performance measures by trip (from origin to destination) and for public transit vehicles.

The Analyzer software of Paramics in addition outputs these link-specific MOEs:

- Turn counts/flows/proportions;
- Link counts/flows;
- Link density;
- Percentage time delay;
- Link delay;
- Link speed;
- Link stop times;
- Link LOS;
- Queues Max/Average;
- Blocking;
- OD Data;
- Journey times;
- User-defined performance criteria; and
- LOS, MOEs, intersection LOS.

Computation of HCM Level of Service

The Paramics Analyzer does output direct level of service grades for individual links. These LOS grades are based upon the threshold numbers given in the HCM.[15]

Vehicle densities are converted to passenger car units using PCEs provided by the analyst. The PCU densities are then used to look up the HCM LOS grade using analyst editable look-up tables.

The Paramics Analyzer can compute Percent Time Delay for use in estimating LOS for two-lane rural roads. However, since Paramics does not simulate passing maneuvers using opposing lanes, it would be most reliable for 2-lane roads with 100 percent no-passing zones.

The Node LOS is the flow weighted average of the link approach LOSs. The flow weights are the number of vehicles exiting each link approach to the node during the analysis period. Note that PCUs are vehicles multiplied by their appropriate PCE. The PCEs are fixed equivalencies input by the analyst by vehicle-type.

Computation of Volume Capacity Ratio

Paramics does not directly output volume/capacity ratios.

Computation of Speed and Travel Time

Paramics outputs system-level VMT, VHT, and mean speed accumulated by one-minute periods throughout the simulation period. These results exclude delays incurred by vehicles denied entry to the network during any part of the simulation period.

Link speed is equal to the link length divided by the actual travel time = VMT/VHT. The delays incurred by vehicles denied entry to the link during any part of the simulation period are excluded from this computation.

Link VMT and VHT are not directly output by Paramics. The link level outputs of flow and speed can be combined with the link length inputs to obtain VMT and VHT by link.

Mean link travel times are not directly output by Paramics but can be computed from the link level outputs of flow, speed, and link lengths.

Computation of Delay

Paramics computes delay as the difference between the cumulative travel time of all vehicles present on a link at some point within each one-minute time period, and the

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[15] *Quadstone Paramics V5.0, Analyser Reference Manual*, Quadstone Limited, Version No. 1.0, July 21, 2004.

theoretical travel time for those vehicles if they had traveled at the user coded free-flow speed for the link. Paramics does not break down the delay into different components.

Link delay is the difference between the actual travel time and the ideal travel time.

$$d(l,i) = \sum_v T(v,l,i) - \frac{L(l)}{Min(FFS(l),MXS(v))}$$
Equation 47

Where:

d(l)   = Total Delay for link (l) (veh-hrs) during interval (i).
T(v,l,i) = Actual travel time for vehicle (v) exiting link (l) during interval (i)(hrs).
FFS (l) = Free-flow speed for link (l) (mph).
MXS(v) = Maximum speed for vehicle (v) (mph).
L(l)   = Length of link (l) (miles).

Average link stop time is the mean time spent stopped for vehicles exiting the link during the analysis period.

Computation of Queue

Paramics allows a user to select their own definition of a queue according to the maximum vehicle speed and a maximum distance between vehicles. The defaults are 2 meters per second (for speed), and 10 meters between vehicles. The minimum number of vehicles before Paramics records them as a queue also can be set by the analyst (page 14 Analyzer Manual). The queue is reported on a second by second basis in terms of number of vehicles and in terms of the starting distance and ending distance within the link.

Paramics Analyzer reports the mean and maximum queue observed over the simulation time period (or a user specified time period). The queue must meet the minimum number of vehicles thresholds selected by the analyst to be identified as a queue and reported.

$$AVEQ = \frac{\sum_i Q(i)}{I}$$
Equation 48

Where:

AVEQ = Average Queue over analysis period.
Q(i)   = Observed Queue at end of time step (i).
I   = Total number of time steps in analysis period.

At the end of each time step the vehicles in queue are converted to a queue length by multiplying each by its appropriate PCE and summing the lengths of the vehicles. The spacing in between vehicles is NOT included in the queue length (see page 21, Analyzer Users Manual).

Note that this mean queue will be different than that for signals, since this mean queue includes time steps when the signal is green as well as red, while the signal mean queue is limited to time steps when the signal is red.

Note that the maximum queue cannot be longer than the length of the link. The Average Queue will be impacted by this limitation on the maximum queue.[16]

Computation of Stops

Paramics does not report the number of stops on the link by non-public transit vehicles.

Computation of Density

Paramics computes the mean density in terms of passenger car units per lane-mile over an analysis period as the sum of the average density during the simulation period and the density of vehicles remaining at the end of the period.

$$k = k(i) + k(r)$$ **Equation 49**

$$k(i) = \frac{\sum_v NV(v,i) * PCE(v)}{NL * L(a)}$$ **Equation 50**

$$L(a) = FFS * I$$ **Equation 51**

Where:

k   = Reported link density for analysis period (pcu/lane-mile).
k(i)   = Computed link density over analysis period (i).
k(r)   = Computed density of vehicles remaining on link at end of analysis period.
NV(v,i) = Cumulative number of vehicles of type (v) exiting the link during period (i).
PCE(v) = Passenger car equivalence of vehicle type (v).
NL   = Number of lanes on link.
L(a)   = Available distance on link (mile-hours).
FFS   = Free-flow speed on link (mph).
I   = Duration of analysis period (hrs).

The density for the remaining vehicles is computed using the same formula as for computing the link density during the analysis period, substituting the PCUs remaining for the PCUs accumulated during the analysis period in the formula.

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[16]The SIAS version of Paramics does have a queue tracker that will track a queue back over several links.

The analyst can exclude the "remainder" vehicles from the density calculation, if desired.

Computation of Travel-Time Variance

Paramics does not directly output travel-time variance information, however; the software can be executed multiple times to determine the variance of the mean travel time for each run. An analyzer program provided with Paramics can be used to compute the variance.

4.1.8 Aimsun

This discussion is based upon an excerpt of the Aimsun Users Guide currently under preparation that was advanced to Dowling Associates on January 13, 2006 by the developers of Aimsun (Dr. Jaume Barcelo and Pablo Barcelo). The equations shown below are quoted from the draft Aimsun Users Guide.

Aimsun outputs flow, speed, density, travel time and delay measures of effectiveness for several different levels of aggregation: whole system, individual links (called sections in Aimsun), series of links, and turning movement. The MOEs can be output by trip origin and destination (OD). Public transport performance outputs also are provided.

Regardless of level of aggregation the following outputs can be generated:

- Mean Flow;
- Density;
- Mean Speed;
- Harmonic Mean Speed;
- Total Travel Distance (VMT);
- Total Travel Time (VHT);
- Mean Travel Time;
- Mean Delay Time;
- Stop Time;
- Number of Stops;
- Fuel Consumed; and
- Pollutants Emitted.

For individual links or series of links the above MOEs are provided plus the following additional outputs:

- Mean Queue Length (veh/lane); and
- Maximum Queue Length (veh/lane).

For OD trip information the general MOEs (listed above for all levels of aggregation) are produced plus the following additional outputs:

- Lost Vehicles – "Total number of vehicles that have been lost while trying to do the trip from origin to destination, and which have therefore not reached the correct destination."

The analyst also can customize the calculation of additional MOEs. Detectors also can be placed on the network to gather point MOEs.

Computation of HCM Level of Service

Aimsun does not directly output HCM level of service.

Computation of Volume Capacity Ratio

Aimsun does not directly output volume/capacity ratios.

Computation of Speed and Travel Time

For system-level MOEs Aimsun accumulates the following statistics for each vehicle in the network.

The total system vehicle travel time (VHT) is computed as follows. Note that only vehicles able to exit the system during the simulation period generate system travel time. Vehicles remaining in the system are excluded from the total system travel-time computation.

$$TotalTravTime_{sys} = \sum_{i=1}^{N_{sys}} TEX_i - TEN_i \qquad \text{Equation 52}$$

Where:

TEN_i = Entrance time of vehicle (i) in the system (seconds).
TEX_i = Exit time of vehicle (i) from the system (seconds).
N_{sys} = Number of vehicles that exit the system during period I.

The total travel distance (VMT) is computed as follows. Note that only vehicles able to exit the system during the simulation period generate system travel distance. Vehicles remaining in the system are excluded from the total system travel distance computation.

$$TotalTrav_{sys} = \sum_{i=1}^{N_{sys}} D_i / 1000$$

Equation 53

Where:

D_i = Total Distance traveled by vehicle (i) in the system (meters).[17]

N_{sys} = Number of vehicles that exit the system during period I.

Two averages are computed for mean system speed. One is the arithmetic average. The other is the harmonic mean.

$$S_{sys} = \frac{\sum_{i=1}^{N_{sys}} S_i}{N_{sys}} * 3.6$$ **Equation 54**

$$HS_{sys} = \frac{N_{sys}}{\sum_{i=1}^{N_{sys}} 1/S_i} * 3.6$$ **Equation 55**

Where:

S_{sys} = Arithmetic Average Speed per vehicle (Km/h).

HS_{sys} = Harmonic mean Speed per vehicle (Km/h).

N_{sys} = Number of vehicles that exit the system during period I.

S_i = Spot speed of vehicle (i) (Km/h).

For individual links the total distance and time traveled are computed as follows. Note that vehicles failing to exit the link during the simulation period are not counted.

$$VMT(l) = \sum_{i=1}^{NX(l)} D(i,l)/1000$$ **Equation 56**

$$VHT(l) = \sum_{i=1}^{NX(l)} TEX(i,l) - TEN(i,l)$$ **Equation 57**

Where:

VMT(l)   = Total distance traveled by all the vehicles (i) exiting the link (l) (Km).

VHT(l)   = Total travel time experienced by all exiting vehicles (i) on link (l) (seconds).

Di   = Distance traveled by exiting vehicle (i) while on link (l).

NX(l)   = Number of vehicles exiting link (l) during simulation period.

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[17] Although only metric are shown here, Aimsun accumulates all measures in the native unit system in which the network is coded, U.S. Customary or Metric units.

The arithmetic average vehicle speed for the link is computed as follows.

$$S(l) = \frac{\sum_{i=1}^{NX(l)} \frac{LS(l) + LT(l)}{TEX(i,l) - TEN(i,l)}}{NX(l)} * 3.6$$

Equation 58

S(l) = Arithmetic Average Speed per exiting vehicle of a link (Km/h).
TEN(i,l) = Entrance time of vehicle (i) to link (l) (seconds).
TEX(i,l) = Exit time of vehicle (i) from link (l) (seconds).
LS(l) = Length of link (m).
LT(l) = Length of turn (m).
NX(l) = Number of vehicles exiting link (l) during simulation period.

A harmonic mean vehicle speed for vehicles exiting the link also is computed.

Computation of Delay

For individual links the delay is computed as follows.

$$DT_{sec} = \frac{\sum_{i=1}^{NX(l)} DT_i}{N \sec}$$

Equation 59

$$DT_i = TT_i - \left[\frac{L_s}{Min(SMax_i, S_s * \theta_i)} + \frac{L_t}{Min(SMax_i, S_t * \theta_i)} \right]$$

Equation 60

Where

DT_{sec} = Average Delay Time per vehicle of a section.
DT_i = Average section delay time of vehicle (i) (seconds).
TT(i) = The difference between the link exit time and the link entrance time for vehicle (i).
S_s = Speed limit of link (m/s).
S_t = Speed limit of turning (m/s).
θ_i = Ratio of Speed Limit accepted by vehicle i.
$SMax_i$ = Maximum desired Speed of vehicle i (m/s).
L_s = Distance of link (meters).
L_t = Distance of turning (meters).
NX(l) = Number of vehicles exiting link (l) during simulation period.

Stop time also is computed. The Users Guide does not identify whether or not slow vehicles are counted as stopped or not.

Computation of Queue

For individual links the average and maximum queue lengths in terms of vehicles are computed as follows. A similar formula is used for measuring queues for individual turning movements.

$$AQL_{\text{sec}} = \frac{\sum\limits_{l \in \text{sec}} \left(\sum\limits_{t_i \in T_l} \left[QL_{l,t_{(i-1)}} * (t_{l,i} - t_{l,(i-1)}) \right] \middle/ I \right)}{NBLanes_{\text{sec}}}$$

Equation 61

$$MaxQL_{\text{sec}} = \frac{\sum\limits_{l \in \text{sec}} MaxQL_l}{NBLanes_{\text{sec}}}$$

Equation 62

AQL   = Average Queue Length (vehicles).
$QL_{l,t}$ = Queue Length in the lane l at time t (veh).
$MaxQL_l$ = Maximum Queue Length in the lane l (veh).
I   = Interval of statistics (seconds).
T_l = $(0, t_{l,1},..., t_{l,m}, I)$: Instants when the queue length in lane l changes.
$NBLanes_{\text{sec}}$ = Number of lanes of link (section).

A vehicle is considered "queued" and therefore "stopped" when its speed below the user-specific queue threshold speed. A vehicle is not considered as having left the queue until its speed exceeds the user specified "queue leaving speed."

Computation of Stops

For individual links the average number of stops is computed as follows.

$$NS(l) = \frac{\sum\limits_{i=1}^{NX(l)} TNS(i)}{NX(l)}$$

Equation 63

NS(l)   = Average Number of Stops per exiting vehicle on link (l).
TNS(l)   = Total Number of stops accumulated on link by exiting vehicle (i).
NX(l)   = Number of vehicles exiting link (l) during simulation period.

A vehicle is considered "stopped" when its speed falls below the user-specific queue threshold speed. A vehicle is not considered as having left the queue, (and therefore cannot generate additional stops) until its speed exceeds the user specified "queue leaving speed."

Computation of Density

The following equation is used to compute mean density of vehicles on a link.

$$k(\sec t) = \frac{\sum\limits_{l \in \sec} \left(\sum\limits_{t_i \in T_l} \left[NVeh_{l,t_{(i-1)}} * (t_{l,i} - t_{l,(i-1)}) \right] \Big/ I \right)}{\sum\limits_{l \in \sec} L_l} * 1000$$

Equation 64

Where:

K(sect) = Density for section (link) (veh/lane-m).
L_l = Length of lane l (m).
$NVeh_{l,t}$ = Number of vehicles in the lane l at time t.
I = Interval of statistics (seconds).
T_l = (0, $t_{l,1}$,..., $t_{l,m}$, I): Instants when the number of vehicles in lane l changes.

Computation of Travel Time Variance

Aimsun does not directly output travel time variance information, however; the software can be executed multiple times to determine the variance of the mean travel time for each run.

4.1.9 S-Paramics

This section discusses the MOEs produced by S-Paramics Version 2005.1. This section has been provided to the author by the vendor. The author respects the expertise of the people who have provided this description, and the section has been incorporated for that reason. However, the author has not independently verified the accuracy of this description.

Paramics produces systemwide, link-specific, path defined, OD and point-specific MOEs.

Systemwide MOEs (Economic Info) that are reported for every minute of the simulation include:

- Number of Vehicles currently on the network;

- Mean Speed of vehicles currently on network at specific point in time;

- Mean Time Traveled reported as mean delay;

- Accumulated Total Distance Traveled (VMT) since start of simulation;

- Total number of vehicles passed through the network;

- Mean Speed of all vehicles on network since start of simulation; and

- Bus statistics, including bus stopped time and number of passengers on or off.

For individual links the following MOE outputs are provided:

- Number of vehicles traveling the link in the period;

- Flow count normalized to vehicles per hour;

- Accumulated time on the link in the period;

- Link length;

- Number of vehicles at present on the link;

- Mean speed on the link;

- Turn counts and flows;

- Link counts and flows;

- Density;

- Emissions; and

- Queue transitions and queued time.

For user-defined paths the following queue MOE outputs are available:

- Minimum, average and maximum vehicles and PCUs queued along the path in a user-defined interval;

- Minimum, average and maximum length of the queue in meters;

- Path length;

- Minimum, average and maximum journey time; and

- Link by link profile of journey time.

The following point data is available, for which histogram distributions are produced:

- Flow;

- Speed;

- Headway; and

- Acceleration.

Lane use and lane changes also may be measured on a per link basis.

Computation of HCM Level of Service

S-Paramics does not directly output level of service.

Computation of Volume Capacity Ratio

S-Paramics does not directly output volume/capacity ratios.

Computation of Speed and Travel Time

Paramics outputs network level total distance VMH, mean travel time (defined as 'mean delay' in S-Paramics) and mean speed, all accumulated by one-minute periods throughout the simulation period. Total travel time, VHT, is calculated by multiplying the mean travel time by the total number of completed trips.

These results exclude vehicles denied entry to the network during any part of the simulation period. However, these vehicles are accounted for separately as off network queue time, collected at one-minute periods throughout the simulation period.

Link VMT and VHT are not directly output by Paramics. The link level outputs of flow and speed can be combined with the link length to obtain VMT and VHT by link. The delays incurred by vehicles denied entry to the link during any part of the simulation period are excluded from this computation.

Computation of Delay

S-Paramics does not directly output delay.

Computation of Queue

Paramics allows a user to select their own definition of a queue according to the maximum vehicle speed and a maximum distance between vehicles. The defaults are 2 meters per second (for speed), and 10 meters between vehicles. The minimum number of vehicles before Paramics records them as a queue also can be set by the analyst. Additionally, the analyst selects the appropriate method to handle multiple queues occurring on the same link and lane.

S-Paramics reports the mean and maximum queue observed over the simulation time period. The queue must meet the minimum number of vehicles thresholds selected by the analyst to be identified as a queue.

Once a vehicle has entered a queue by going below a specified head way and/or speed it remains in the queued state until the headway and/or speed rise above another set of values. Hysteresis is built into the system.

The average queue is computed by the following equation. The end of the queue is defined as the position of the tail of the last vehicle in the queue this may be output by lane or over the link. The average queue may be computed for every time spent in the reporting period or just by those when there was a queue. Including the times when no queue was present will bias the result to a lower value.

$$AVEQ = \frac{\sum_i Q(i)}{I}$$ **Equation 65**

Where:

AVEQ   = Average Queue over analysis period.
Q(i)   = Observed Queue at end of time step (i).
I   = Total number of time steps in analysis period.

At the end of each time step the vehicles in queue are converted to a queue length by multiplying each by its appropriate PCE and summing the lengths of the vehicles. Note that this mean queue will be different than that for signals, since this mean queue includes time steps when the signal is green as well as red, while the signal mean queue is limited to time steps when the signal is red.

It also should be noted that the queue is reported based on user-defined paths, which may span many links, hence the maximum and average queue is not limited by the length of links.

S-Paramics reports the number of times a vehicle enters a queued state on each link and the time spent in this state.

Computation of Stops

S-Paramics reports the number of transitions into a queued state and the time spent in that state per link.

Computation of Density

Paramics computes the mean density in terms of passenger car units per lane-mile over an analysis period as the sum of the average density during the simulation period and the density of vehicles remaining at the end of the period.

$$k = k(i) + k(r)$$ **Equation 66**

$$k(i) = \frac{\sum_v NV(v,i)*PCE(v)}{NL*L(a)}$$ **Equation 67**

$$L(a) = FFS * I$$ **Equation 68**

Where:

k   = Reported link density for analysis period (pcu/lane-mile).
k(i)   = Computed link density over analysis period (i).
k(r)   = Computed density of vehicles remaining on link at end of analysis period.

NV(v,i) = Cumulative number of vehicles of type (v) exiting the link during period (i).

PCE(v) = Passenger car equivalence of vehicle type (v).

NL = Number of lanes on link.

L(a) = Available distance on link (mile-hours).

FFS = Free-flow speed on link (mph).

I = Duration of analysis period (hrs).

The density for the remaining vehicles is computed using the same formula as for computing the link density during the analysis period, substituting the PCUs remaining for the PCUs accumulated during the analysis period in the formula.

The analyst can exclude the "remainder" vehicles from the density calculation if desired.

Computation of Travel Time Variance

S-Paramics reports travel times between OD pairs and also travel times along specified paths in the model. As each individual vehicle is logged, variance can be reported within each run and across a number of runs.

4.2 TEST BED RESULTS

The following tools were tested on a test network to observe how the computations of MOEs varies between the tools: HCS, Synchro, SimTraffic, CORSIM, Vissim, Q-Paramics, S-Paramics, and Aimsun.

The Vissim results produced by Dowling Associates were proofed and corrected by PTV personnel.[18]

Q-Paramics is the Quadstone version of Paramics. S-Paramics is the SIAS version of Paramics. The Q-Paramics results were produced by Dowling Associates. The S-Paramics results were provided by SIAS consultancy. Dowling Associates has not proofed or verified these results, but respects the expertise of the people that produced these results, and has included these results on that basis.

The Aimsun results were provided by Dr. Jaume Barcelo, since Dowling Associates lacks licenses and experienced personnel for operating Aimsun. Dowling Associates has not proofed or verified these results, but respects the expertise of the people that produced these results, and has included these results on that basis.

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[18]Initial results indicated a problem with the Synchro to Vissim conversion software provided by Vissim. There was also a problem with how Dowling had selected the node data collection box in Vissim. PTV made the necessary corrections and returned both input and output files to Dowling Associates.

Dynasmart-P was not tested because Dowling Associates lacks licenses and experienced personnel on this tool.

Test Network

The test network consists of a freeway and an arterial street. They are not connected. They operate independently.

The freeway is a single (right-bound) direction of freeway, 2.75 miles long, 3-lanes wide, with a single-lane on-ramp and a single-lane off-ramp (see figure below).
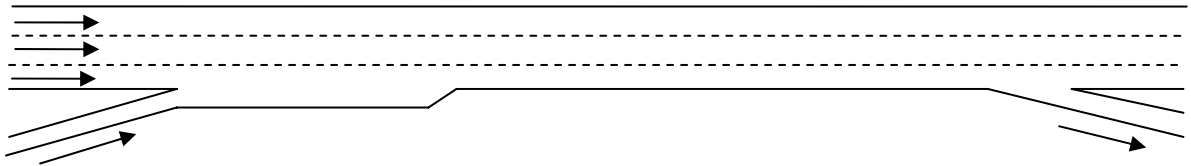

Figure 1. Test Freeway Facility.

The arterial street is bidirectional, one-mile-long, with a single lane in each direction, and two signalized intersections (see figure below).
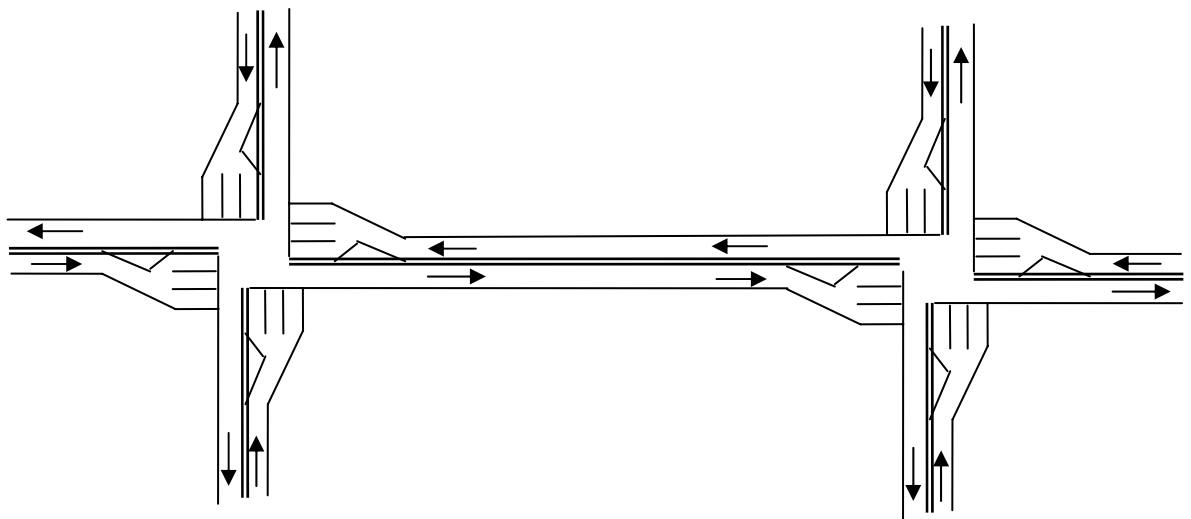

Figure 2. Test Arterial Street.

At each intersection the approach widens to a single exclusive left turn lane, a single exclusive through lane, and a single exclusive right turn. Both signals are 100-second cycle fixed time with exclusive left turn phases. Each left and through signal phase gets the same amount of green time (see figure below). Right turns on red are prohibited.

TIMING WINDOW	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lanes and Sharing (#RL)												
Traffic Volume (vph)	100	100	100	100	100	100	100	100	100	100	100	100
Turn Type	Prot	—	Prot	Prot	—	Prot	Prot	—	Prot	Prot	—	Prot
Protected Phases	7	4	4	3	8	8	5	2	2	1	6	6
Permitted Phases												
Detector Phases	7	4	4	3	8	8	5	2	2	1	6	6
Minimum Initial (s)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Minimum Split (s)	8.0	21.0	21.0	8.0	21.0	21.0	8.0	21.0	21.0	8.0	21.0	21.0
Total Split (s)	24.0	26.0	26.0	24.0	26.0	26.0	24.0	26.0	26.0	24.0	26.0	26.0
Yellow Time (s)	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
All-Red Time (s)	0.0	2.0	2.0	0.0	2.0	2.0	0.0	2.0	2.0	0.0	2.0	2.0
Lead/Lag	Lead	Lag	Lag	Lead	Lag	Lag	Lead	Lag	Lag	Lead	Lag	Lag
Allow Lead/Lag Optimize?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Recall Mode	Max	Max	Max	Max	Max	Max	Max	Max	Max	Max	Max	Max
Actuated Effct. Green (s)	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0
Actuated g/C Ratio	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21

Source: Screenshot of Synchro Input Screen.

Figure 3. Signal Timing for Example Signal on Test Arterial.

For the purpose of comparing HCM results to simulation results, the peak-hour factors within HCS and Synchro have been set at 1.00 for all movements. The percent heavy vehicles was set at 0 percent.

While some of these assumptions would be unusually simplistic for U.S. practice, they have been selected to dampen as much as possible the differences in how the various simulation models reflect vehicle behavior and signal operation. The attempt with this simple test network is to obtain very simplistic vehicle behavior so that observed differences in the MOEs produced by the tools are mostly the result of differences in how the MOEs are computed and to a lesser extent the result of how vehicle behavior and signal operation are modeled within each tool.

Comparison of MOEs Produced Under Free-Flow Conditions

The MOEs computed by the various tools were first tested under free-flow conditions. The freeway mainline volume was 900 vph entering the study section. Each freeway on-ramp and off-ramp carried a volume of 100 vph. Each turning movement of each leg of each signalized intersection on the test arterial was assumed to serve a demand of 100 vph. Thus each intersection carries a total 1,200 vph, summed over all 4 approaches.

Table 15. Basic Freeway Section Results – Free-Flow.

Freeway Section	HCS	Synchro	SimTraffic	CORSIM	Vissim	Q-Paramics	Aimsun	S-Paramics
Vehicles Enter	900	N/A	893	?	?	911	904	901
Vehicles Exit	900	N/A	896	907	886	921	886	900
SMS (mph)	60.0	N/A	52.0	59.4	59.1	62.4	62.4	65.3
Density (v/ln-mi)	5.0	N/A	5.7	5.1	5.0	5.0	4.7	4.6
HCM LOS	A	N/A	A	A	A	A	A	A

- All models were coded with a 60 mph free-flow speed and a demand of 900 vehicles per hour. According to HCM, the 3-lane freeway segment is at 14 percent of capacity at this level of demand.

- All simulation tool results are the average of five runs with varying random number seeds.

- Simulation tools not calibrated. All parameters at default. Note that Aimsun, Q-Paramics, and S-Paramics were produced by their respective vendors and not the authors of this report. Note that Vissim results are based on corrections to author's initial coding by the vendor.

- Shaded cells are not directly output by the tool. Entries in these cells were computed manually by the analyst based on other outputs provided by the tool. Question mark means the data was not readily available in the standard output for a specific link.

- Synchro does not output freeway performance results.

Table 16. Freeway Facility Results – Free-Flow.

Freeway Section	HCS	Synchro	SimTraffic	CORSIM	Vissim	Q-Paramics	Aimsun	S-Paramics
Vehicles Enter	1,000	N/A	999	?	?	1,022	1,007	1,029
Vehicles Exit	1,000	N/A	996	999	987	1,018	956	985
VMT (v-mi)	2,587	N/A	2,583	2,597	2,599	2,805	2,833	2,700
VHT (v-h)	43.3	N/A	49.0	43.8	44.3	45.1	45.7	40.7
SMS (mph)	59.7	N/A	52.7	59.3	58.6	62.2	61.9	64.6

- All models were coded with a 60 mph free-flow speed and a demand of 1,000 vehicles per hour (combination of mainline in and on-ramp volumes).

- All simulation tool results are the average of five runs with varying random number seeds.

- Simulation tools not calibrated. All parameters at default. Note that Aimsun, Q-Paramics, and S-Paramics were produced by their respective vendors and not the authors of this report. Note that Vissim results are based on corrections to author's initial coding by the vendor.

- Shaded cells are not directly output by the tool. Entries in these cells were computed manually by the analyst based on other outputs provided by the tool.

- Synchro does not output freeway performance results.

Table 17. Signalized Intersection Results – Free-Flow.

Intersect MOEs	HCS	Synchro	SimTraffic	CORSIM	Vissim	Q-Paramics	Aimsun	S-Paramics
Vehicles Enter	1,200	1,200	1,200	?	?	?	1,222	1,198
Vehicles Exit	1,200	1,200	1,208	1,199	1,225	1,197	1,198	1,201
Delay/Vehicle(s)	34.9	37.5	38.1	31.8	29.0	26.4	30.6	30.1
EBT Q 50% (ft)	63	54	61	25	17	29	22	90
HCM LOS	C	D	D	C	C	C	C	C

- All models were coded with a demand of 1,200 vehicles per hour for the intersection (100 vph for each of the 12 turn movements. According to HCM, the signal is at 28 percent of capacity).

- All simulation tool results are the average of five runs with varying random number seeds.

- Simulation tools not calibrated. All parameters at default. Note that Aimsun, Q-Paramics, and S-Paramics were produced by their respective vendors and not the authors of this report. Note that Vissim results are based on corrections to author's initial coding by the vendor.

- Shaded cells are not directly output by the tool. Entries in these cells were computed manually by the analyst based on other outputs provided by the tool.

Table 18. Arterial Street Results – Free-Flow.

EB Arterial	HCS	Synchro	SimTraffic	CORSIM	Vissim	Q-Paramics	Aimsun	S-Paramics
Art Speed mph	23.3	21.7	20.0	21.0	19.0	30.6	26.9	26.0
Art LOS	C	C	C	C	C	A	B	B

- For eastbound direction of one-mile-long section of arterial between first and second signals.

- All simulation tool results are the average of five runs with varying random number seeds.

- Simulation tools not calibrated. All parameters at default. Note that Aimsun, Q-Paramics, and S-Paramics were produced by their respective vendors and not the authors of this report. Note that Vissim results are based on corrections to author's initial coding by the vendor.

- Shaded cells are not directly output by the tool. Entries in these cells were computed manually by the analyst based on other outputs provided by the tool.

With the exception of SimTraffic and Paramics, the tools are in pretty close agreement on freeway operation MOEs under free-flow conditions. The default parameters for SimTraffic result in low estimated free-flow speeds for the freeway. The default parameters for Paramics result in high estimated free-flow speeds for the freeway.

The MOEs produced by the tools for arterials under free-flow conditions are in relatively close agreement in some respects and far apart in other respects. The mean signal queues predicted by the various tools range from under one vehicle to slightly under 3 vehicles. The predicted maximum queue length ranges from 145 feet to 188 feet (between 6 and 7.5 vehicle lengths). The predicted mean arterial speed (eastbound direction only) ranges from 19 mph to 31 mph (level of service A to C).

MOEs When Free-Flow Speed Is Calibrated

Based on the free-flow tests, it appeared that CORSIM and Vissim did not require calibration to match the coded free-flow speeds for the freeway.

Both Paramics and SimTraffic free-flow test results indicated that some calibration of the default parameters in each model would be required to match the target free-flow speed input by the analyst.

Unlike the other tools, Paramics treats the coded free-flow speed as a speed limit that can be exceeded. Since Paramics computes delay as the difference between the output speed and the input free-flow speed, it is not possible to calibrate the free-flow speed output by Paramics without also affecting the computed delay for the facility. If the analyst codes a lower free-flow speed to trick Paramics into outputting a lower free-flow speed, the lower input value becomes the new basis for computing delay, not the output speed. Technical support for Paramics suggested that it would be undesirable to adjust the driver aggressiveness to force a lower free-flow speed, because it would impact other behavior as well. Consequently no tests were made with a free-flow speed calibrated Paramics model.

The SimTraffic tool was calibrated to better match the coded free-flow speeds for all links by proportionally increasing the "speed factors" (the percentage of the coded free-flow speed that each driver type is assumed to target) for each of the 10 driver types in the

model. The simulation was rerun with the tool calibrated to better reproduce the coded 60 mph free-flow speed for the freeway and 30 mph for the arterial street. The results are shown below.

Table 19. Basic Freeway Section Results – Calibrated Free-Flow.

Freeway Section	HCS	SimTraffic	
		Uncalibrated	Calibrated
Vehicles Enter	900	893	893
Vehicles Exit	900	896	896
VMT (v-mi)	930	927.6	927
VHT (v-h)	15.5	18	15.7
SMS (mph)	60.0	52	59.0
Tot Delay(v-h)	0.0	2	1.3
Delay/Veh (s)	0.0	8.2	5.3
Density (v/ln-mi)	5		
V/c	0.14		
HCM LOS	A		

Table 20. Freeway Facility Results – Calibrated Free-Flow.

Freeway Facility	HCS	SimTraffic	
		Uncalibrated	Calibrated
Vehicles Enter	1,000	999	998
Vehicles Exit	1,000	996	995
VMT (v-mi)	2,587	2,583	2,601
VHT (v-h)	43.3	49	43
SMS (mph)	59.7	52.7	59.9
VHT Delay (h)	0.2	4.3	2.7
Delay/Veh (s)	0	16.7	9.7

Table 21. Signalized Intersection Results – Calibrated Free-Flow.

Intersect MOEs	HCS	SimTraffic	
		Uncalibrated	Calibrated
Intersection V/C	0.31		
Delay/Vehicle (s)	34.9	38.1	38.4
HCM LOS	C	D	D
Total Delay v-h	11.6	12.8	12.8
Stop Delay (h)	8.9	10.4	10.6
StopDel.Veh(s)	26.8	31.0	31.8
EBT Q 50% (ft)	70	61	58
EBT Q Mean (veh)	2.8		
EBT Q 95% (ft)	152.5	128	111
EBT Q Max (ft)	156.3	188	127
EBT Q Max (veh)	6.3		
Total Stops	900	936	948
Stops/Veh	0.75	0.78	0.79
Vehicles Enter	1,200	1,200	1,202
Vehicles Exit	1,200	1,208	1,206

Table 22. Arterial Street Results – Calibrated Free-Flow.

EB Arterial	HCS	SimTraffic	
		Uncalibrated	Calibrated
Art Speed mph	23.3	20	22.7
Art LOS	C	C	C

The calibration improved the match between the mean freeway and arterial speeds predicted by HCS and SimTraffic. However, the SimTraffic predicted signal delays, stops, and queues generally diverged even further from the HCS results.

Comparison of MOEs for At Capacity Conditions

The tools were rerun this time with volumes determined by the HCS software to be the capacity for the freeway merge and the signalized intersections (6,900 vph for the freeway merge, 4,468 vph for the signalized intersections).

The simulation tools were run again in their uncalibrated state. The results are shown below for HCS, Synchro, SimTraffic, CORSIM, Vissim, and Aimsun.

SimTraffic appears to have a much lower default freeway capacity than the other tools. This is evidenced by the significantly higher freeway facility delay predicted by SimTraffic. CORSIM and Vissim appear to be in closer agreement with the HCS results than SimTraffic. Calibration of the SimTraffic default capacity for freeway links could conceivably reduce or eliminate this discrepancy.

The simulation tool results for the intersection and the arterial street deviate to a greater extent from HCS and Synchro results than before under free-flow conditions. This appears to be due to the impact of queue blockages of the left and right turn lanes at the signals. HCS and Synchro assume that all of the demand can reach each turn lane. SimTraffic, CORSIM, and Vissim found that that was frequently not the case. Thus the latter tools predict higher delays and slower speeds than HCS and Synchro.

Table 23. Basic Freeway Section Results – At Theoretical HCM Capacity.

Freeway Section	HCS	Synchro	SimTraffic	CORSIM	Vissim	Q-Paramics	Aimsun
Vehicles Enter	6,901	N/A	5,085	6,353	6,822	6,603	6,910
Vehicles Exit	6,901	N/A	5,032	6,348	6,817	6,601	6,691
VMT (v-mi)	7,131	N/A	5,254	6,564	7,022	6,818	7,282
VHT (v-h)	140	N/A	115	121	134	136	142
SMS (mph)	51	N/A	46	54	53	51	51
Density (v/ln-mi)	45	N/A	36	39	43	43	44
HCM LOS	E	N/A	E	E	E	E	E

- All simulation tool results are the average of 5 runs with varying random number seeds.

- Simulation tools not calibrated. All parameters at default. Note that Aimsun, Q-Paramics, and S-Paramics were produced by their respective vendors and not the authors of this report. Note that Vissim results are based on corrections to author's initial coding by the vendor.

- Shaded cells are not directly output by the tool. Entries in these cells were computed manually by the analyst based on other outputs provided by the tool.

- Resource limitations restricted tests of at-capacity conditions to HCS, SimTraffic, CORSIM, Vissim, Q-Paramics, and Aimsun.

Table 24. Freeway Facility Results – At Theoretical HCM Capacity.

Freeway Facility	HCS	Synchro	SimTraffic	CORSIM	Vissim	Q-Paramics	Aimsun
Vehicles Enter	6,900	N/A	6,990	6,502	6,916	6,603	6,995
Vehicles Exit	6,900	N/A	5,032	6,438	6,548	6,504	6,585
VMT (v-mi)	18,830	N/A	14,141	17,619	18,999	18,023	20,357
VHT (v-h)	363	N/A	1,273	408	362	347	392
SMS (mph)	52	N/A	11	43	52	52	52

- All simulation tool results are the average of 5 runs with varying random number seeds.

- Simulation tools not calibrated. All parameters at default. Note that Aimsun, Q-Paramics, and S-Paramics were produced by their respective vendors and not the authors of this report. Note that Vissim results are based on corrections to author's initial coding by the vendor.

- Shaded cells are not directly output by the tool. Entries in these cells were computed manually by the analyst based on other outputs provided by the tool.

- Resource limitations restricted tests of at-capacity conditions to HCS, SimTraffic, CORSIM, Vissim, Q-Paramics, and Aimsun.

Table 25. Signalized Intersection Results – At Theoretical HCM Capacity.

Intersect MOES	HCS	Synchro	SimTraffic	CORSIM	Vissim	Q-Paramics	Aimsun
Vehicles Enter	4,468	4,468	3,311	?	?	?	3,340
Vehicles Exit	4,468	4,468	3,185	3,737	3,460	2,817	2,887
Delay/Vehicle (s)	86	81	604	142	145	167	397
EBT Q 50% (ft)	420	256	3,128	2,625	784	559	653
HCM LOS	F	F	F	F	F	F	F

- All simulation tool results are the average of 5 runs with varying random number seeds.

- Simulation tools not calibrated. All parameters at default. Note that Aimsun, Q-Paramics, and S-Paramics were produced by their respective vendors and not the authors of this report. Note that Vissim results are based on corrections to author's initial coding by the vendor.

- Shaded cells are not directly output by the tool. Entries in these cells were computed manually by the analyst based on other outputs provided by the tool.

- Resource limitations restricted tests of at-capacity conditions to HCS, SimTraffic, CORSIM, Vissim, Q-Paramics, and Aimsun.

Table 26. Arterial Street Results – At Theoretical HCM Capacity.

EB Arterial	HCS	Synchro	SimTraffic	CORSIM	Vissim	Q-Paramics	Aimsun
Art Speed mph	15	19	17	15	16	17	18
Art LOS	D	C	D	D	D	D	C

- For eastbound direction of one-mile long section of Arterial between First and Second Street signals.

- All simulation tool results are the average of 5 runs with varying random number seeds.

- Simulation tools not calibrated. All parameters at default. Note that Aimsun, Q-Paramics, and S-Paramics were produced by their respective vendors and not the authors of this report. Note that Vissim results are based on corrections to author's initial coding by the vendor.

- Shaded cells are not directly output by the tool. Entries in these cells were computed manually by the analyst based on other outputs provided by the tool.

- Resource limitations restricted tests of at-capacity conditions to HCS, SimTraffic, CORSIM, Vissim, Q-Paramics, and Aimsun.

4.3 CONCLUSIONS

This section highlights the conclusions of our evaluation of the computation of MOEs by seven typical traffic analysis tools (HCS, Synchro, DynaSmart, SimTraffic, Vissim, Paramics, Aimsun).

Computation of HCM Level of Service

Of the analysis tools considered here, HCS, Synchro, and Paramics report HCM level of service letter grades. The other tools report MOEs that users may be tempted to convert into HCM LOS grades.

The HCS and Synchro are relatively faithful to the HCM LOS method and criteria since they are inherently macroscopic analysis tools. Paramics differs in its LOS letter grade assignments because it is a microscopic tool and its outputs are not as directly comparable to HCM LOS criteria. The discussion below highlights these differences.

Freeway LOS – Most microscopic tools output mean vehicle density but not in terms of passenger car units.

Paramics provides for a user input PCE adjustment by vehicle type to convert vehicle density into passenger car unit density. Thus the Paramics PCU densities are closer to the HCM densities. However the PCE adjustment is universal rather than link-specific (and thus not sensitive to grades).

Intersection LOS – All microsimulation tools tally approach delay for the links approaching the intersection. CORSIM is the only one that tallies control delay, which includes the delay after passing through the intersection to resume free-flow speed. Also, HCM control delay excludes vehicles not going through the intersection that become entangled in the queue for the intersection.

Arterial LOS – Only SimTraffic directly reports the arterial level of service grade. Paths can be identified in the other microsimulation tools and the mean speed of through traffic reported.

Two-Lane Highway LOS – Paramics reports percent time delay for two-lane rural roads. But, since Paramics (like all of the other microsimulation tools evaluated here) does not model passing in opposing lanes, the model is of limited use for modeling two-lane rural roads.

Computation of Volume Capacity Ratio

Only HCS and Synchro, among the tools evaluated here, output volume/capacity ratios. It is not practical for the microsimulation tools to output this measure. It would require multiple runs to identify the capacity of a link or node.

Computation of Speed and Travel Time

The computation of speed and travel time is generally similar for all of the microsimulation tools. The difference is whether or not the delays incurred by vehicles denied entry to the network during the simulation are included in the accumulated vehicle travel time (VHT) and whether or not that additional delay also is included in the computed mean speed for the system. Most developers have elected to exclude vehicles not on the network from the computation of mean network speed.

Some microsimulation tools compute mean link speeds by dividing accumulated vehicle miles traveled on the link by the vehicle hours traveled on the link (excluding delays incurred by vehicles denied entry to the link). It is unclear whether or not the other tools take the simple mean of the vehicle speeds on the link.

Computation of Delay

The definition of delay varies among the microsimulation tools. The result is that some of the tools generate delay even under free-flow conditions.

Most microscopic tools compare the actual travel speed to the free-flow speed over the length of the link (or trip) to determine delay. However, the mean speed of vehicles under free-flow conditions is often five mph below the coded free-flow speed for the link. Thus delay is guaranteed under even free-flow conditions. It would be better to compare actual speed to the desired speed.

The computation of mean delay runs into the problem of defining the number of vehicles by which to divide the total delay. Most microsimulation tools, in order to save on computer storage requirements, do not keep a running tally of the number of vehicles for which the various statistics are accumulated each instant within the simulation period. So, in order to arrive at the number of vehicles on the link for computing link averages most tools use one or more vehicle counts for the link after the simulation is done.

Some tools use just the number of vehicles exiting the link during the analysis period. Others add to that the vehicles remaining on the link at the end of the analysis period. Still others add the average of the vehicles on the link at the start of the period and the end of the period. This counting issue is illustrated below.
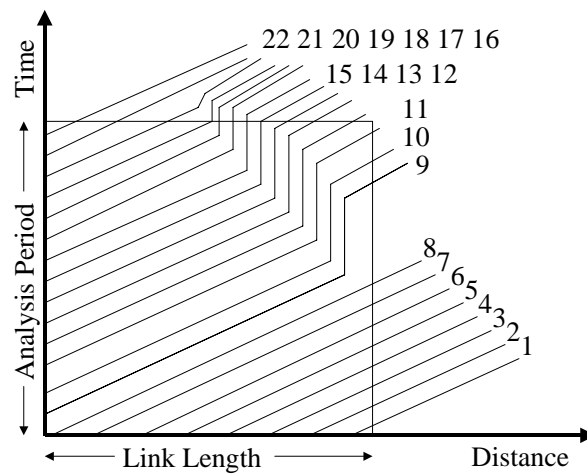
Figure 4. Counting Vehicles on a Link.

As shown above, a total of 22 vehicle traces (the diagonal lines in the figure) take place somewhere on the link at some time during the analysis period (the square box in the figure).

Some of the microscopic tools may use 22 vehicle traces to accumulate VMT, VHT, delay, queues, and stops on the link during the analysis period. Others use only the 11 vehicle traces that exit the link during the simulation period. An additional difficulty comes in the computation of the mean delay and mean stops.

A total of 14 vehicles actually entered the link during the analysis period (22 traces minus 8 already on the link at the start of the analysis period). A total of 11 vehicles exit the link during the analysis period. Eleven vehicles remain on the link at the end of the simulation period. Only 3 vehicles actually enter and leave the link within the simulation period.

Some microsimulation tools will divide the accumulated delay by the 11 exiting vehicles. Others will divide the accumulated delay by 22, the 11 exiting plus 11 remaining vehicles on the link.

Incidentally, this counting problem also makes it difficult to define the volume (flow rate) on a link. If we stand at the start of link we would count 14 vehicles passing by during the analysis period. If we stand at the end of the link we would have counted 11 vehicles passing by. If we stand in the middle we would have counted 15 vehicles passing by during the analysis period. The problem is that we are attempting to apply a point measurement (volume) to a link.

Computation of Queue

The different microsimulation tools apply different definitions of queuing vehicles. SimTraffic and CORSIM use predefined maximum speeds and acceleration rates to identify stopped and queuing vehicles. Aimsun, Paramics, and Vissim allow the user to select their own definition of queuing vehicles.

Some tools provide the mean and maximum number of vehicles queued at any instant. Others provide the distance to the farthest upstream point of the queue, the back of queue. The difference between the two can be seen in the above figure. The maximum back of queue within the analysis period is nine vehicles back from the stop bar, however the maximum queue at any instant in time is five vehicles.

The mean queues and 95 percentile queues estimated by microsimulation tools generally differ from those provided by HCM type tools for signals in that the microsimulation tools measure the average queue across both green and red signal intervals. Traditional HCM tools compute the mean queue for signals for only the red signal intervals.

The difference can be illustrated by Figure 4. Counting Vehicles on a Link. The queue does not start until the signal turns red, about half way through the analysis period. During this red time the mean queue is about four vehicles long. If we add in the zero queues experienced during the green time, the mean queue for the analysis period is two vehicles.

Computation of Stops

The different microsimulation tools include differing degrees of "slow" vehicles in their definition of stopped vehicles. Some tools document these definitions in their Users Guides. Others do not.

Aimsun, Paramics, and Vissim allow the analyst to set their own definition of when a slow vehicle is stopped and when it ceases to be stopped. CORSIM and SimTraffic have these values preset.

Again the mean number of stops per vehicle varies according to how the microsimulation tool determines how many vehicles should be used to compute the mean.

Computation of Density

Most all microsimulation tools output density in terms of mixed vehicles per lane-mile. One, Paramics allows the user to apply PCEs by vehicle type to output density in terms of passenger car units. These PCEs however apply systemwide and are not link or facility type-specific.

Paramics also adds the density of the vehicles at the end of the simulation period to the mean density of vehicles during the simulation period (rather than averaging the two). This results in double the density. This double counting can be turned off by the analyst.

Computation of Travel Time Variance

None of the tools directly output reliability of travel times (variance of travel times). The microsimulation tools can be run several times to obtain some variance estimates. Several microsimulation tools have tools for computing the variance from several runs. However, the variance built in to the microsimulation tools is generally limited to the pulsing of traffic within the simulation period and variations in driver behavior.

Random day-to-day variations in demand and uncertainty in the estimated mean demand are not incorporated in these tools.

Also, these tools do not incorporate random day-to-day variations in capacity due to random incidents.

Thus the variance in travel times produced by microsimulation tools would be expected to be less than that exhibited in the real world.

5.0 CRITIQUE OF CURRENT MOE ESTIMATION METHODS

This chapter highlights the limitations of current MOEs and their computation.

5.1 LIMITATIONS IN HOW MOES ARE CURRENTLY COMPUTED

Our ability to measure the MOEs in the field and the ability of simulation tools to estimate the MOEs are both severely strained by extreme congestion (See Table 27. Strengths and Weaknesses of Common MOEs, and Table 28. Common Limitations of MOEs in Practice).

Under severe congestion conditions it is very difficult to study a large enough geographic area over a long enough analysis period to ensure that congestion does not extend back beyond the limits of the study area and congestion is not present at the start or the end of the analysis period. Thus most simulation modeling of severe congestion conditions usually has queues that extend beyond the temporal and physical limits of the model.

Failure to include in the MOEs the queues that stretch beyond the geographic and the temporal bounds of the study area will bias the computation of travel time, speed, and delay, making capacity improvements within the study area appear to perform worse than no improvements.

There also are problems with reporting queues that extend beyond the turn bay and/or beyond the link. Only one simulation tool will track the buildup of queues beyond the subject link, and none of them will track congestion beyond the temporal or geographic limits of the model. With one exception, the reported queue is, by definition, never longer than the storage capacity of the turn bay or the link. Thus, the analyst cannot rely upon the reported queue length to identify queue overflow problems. The analyst must find the upstream links and review the reported queues there.

5.2 INHERENT LIMITATIONS OF CURRENT MOES

Most MOEs are satisfactory measures of traffic performance for uncongested conditions. Travel time, delay, queues, stops, density, and travel time variance all increase as traffic demand increases relative to capacity and traffic operations worsen.

Among these MOEs, speed is a less satisfactory indicator of how close a facility is to breakdown, because speed is comparatively insensitive to changing traffic flow rates until capacity is reached.

Most all of the MOEs tend to break down under extreme congestion conditions. Speed, density, stops, and travel time variance are invariant under "parking lot" conditions where no movement is possible (speed equals zero, density equals jam density, and travel time variance is zero). The only MOEs that continue to function under parking lot conditions are travel time and delay, which continue to increase over the length of the analysis period.

Table 27. Strengths and Weaknesses of Common MOEs.

MOE	Strengths	Weaknesses
HCM Level of Service	• Widely known and used. • Readily understood by Decision-Makers. • Most LOSs can be either estimated or measured in field.	• Totally loses sensitivity once LOS "F" (capacity) is reached. • LOS measures not available for many situations (e.g., local residential streets, rural highways with signals, etc.). • Average delay, average density used in LOS, miss hot spots. • Misleading on extent of time which given LOS is present at location in network (peak 15 minutes versus 2 ½ hours.
Volume/ Capacity	• Readily understandable. • Gives indication of how close to breakdown.	• Expensive to measure in field once v/c1. (must gather queue data).
Travel Time	• Can be directly measured in field. • Indicates relative benefits of alternatives.	• Must be related to some standard in order to determine if result is good or bad. • Expensive to measure in field.
Speed	• Can be directly measured in field. • Indicates relative benefits of alternatives.	• Must be related to some standard in order to determine if result is good or bad. • Expensive to measure in field.
Delay	• Can be directly measured in field. • Indicates relative benefits of alternatives.	• Must be related to some standard in order to determine if result is good or bad. • Expensive to measure in field. • Definitional issues.
Queue	• Can be directly measured in field. • Indicates relative benefits of alternatives.	• Must be related to some standard in order to determine if result is good or bad. • Expensive to measure in field. • Definitional issues.
Stops	• Can be directly measured in field. • Indicates relative benefits of alternatives.	• Must be related to some standard in order to determine if result is good or bad. • Expensive to measure in field. • Definitional issues.
Density	• Can be directly measured in field. • Indicates relative benefits of alternatives.	• Must be related to some standard in order to determine if result is good or bad. • Expensive to measure in field. • Definitional issues.
Travel Time Variance	• Can be directly measured in field. • Indicates relative benefits of alternatives.	• Must be related to some standard in order to determine if result is good or bad. • Expensive to measure in field. • Definitional issues.

Table 28. Common Limitations of MOEs in Practice.

Building Blocks of Performance Measurement Systems

MOE	Limitations
Travel Time	• Treatment of delays and travel time for incomplete trips or trips that cannot start within the analysis period is an issue. • Difficult for a decision-maker to interpret (no value of time is obviously too high or too low without knowing more about the trip characteristics).
Speed	• Treatment of incomplete or un-begun trips is an issue, as for travel time. • Interpretation is facility specific. Low speed may be quite acceptable on an arterial, but not on a freeway. • Once all vehicles come to a stop, the mean speed conveys no further information on the severity of congestion (speed cannot go below zero). • Speed is a poor indicator of how close the facility is to breakdown (capacity).
Delay	• Treatment of incomplete trips or trips that have not started is an issue. • Definition of free-flow speed, against which delay is measured, is a problem. Some use the posted speed limit for the free-flow speed; others use the mean speed under very low flow conditions (can be higher or lower than the posted speed limit).
Queue	• Definition of when vehicle joins a queue and when it leaves a queue is a problem. • Interpretation is road segment and facility specific. Queues are normal for signals, but queues that overflow turn bays or block cross streets are not desirable. • Tallying of queued vehicles unable to enter the road segment is an issue for many tools. Many tools cannot report a queue longer than the storage capacity of the road segment or turn bay. • Tallying of vehicles, which have not been able to enter the road network during the analysis period, is an issue.
Stops	• Definition of what minimum speed is a stop is an issue. (One reviewer has recommended that stop time be tallied only for full stops, zero mph, to better match two-fluid models of traffic flow.) • Since tallying of stops is normally suspended while a vehicle is moving up within a queue, the definition of a queue is an issue. • Once all vehicles are queued on a road segment, further increases in congestion have no effect on stops.
Density	• Once all vehicles are queued, then further increases in congestion have no effect on density.
Travel Time Variance	• Rarely used due to difficulty of computation. Prediction tools are close to non-existent. • Once all vehicles are queued on a road segment, the variation in travel time tends to drop towards zero. Variance will tend to peak when the volume is around capacity.

Table 28. Common Limitations of MOEs in Practice (continued)

Indicators of Performance

MOE	Limitations
HCM Level of Service	• HCM LOS is designed to convey how close the facility is to reaching capacity or unacceptable LOS. Once LOS "F" reached, HCM LOS letter grades give no further information on relative severity of different degrees of congestion. • HCM LOS ratings do not exist for several situations: roundabouts, collector/distributor roads, local residential streets.
Volume/ Capacity	• Cannot measure in field or simulate volumes passing a given point that are greater than capacity (measured v/c is always less than 1.00). In such situations, must add to the measured flow rate the buildup in the queue.

6.0 RECOMMENDED MOES

This chapter presents the recommended set of MOEs along with their recommended method of computation and interpretation.

6.1 RECOMMENDED SYSTEM OF KEY SYSTEMWIDE MOES

Traffic operations analyses can generate a great deal of numerical output. Any one of the numerical outputs can be important to the analyst depending upon the purpose and scope of the analysis and the alternatives being evaluated. The set of key systemwide MOEs recommended below is designed to be the "starting set" but not the end all set of MOEs for any traffic operations analysis.

This basic set is kind of like the first set of exams given to every patient when they first check into the emergency room. It does not matter what the patient's complaint, the same four measurements are gathered and reported for every emergency room patient: temperature, pulse, blood pressure, and blood oxygen. These four basic indicators give the doctors a basic understanding of the general health of the patient, and some indication of general fields to investigate for the source of the problem. But they are not the definitive diagnostic tests. They are not the MRIs, X-Rays, or exploratory surgery that come later.

Similarly, our basic system MOEs are designed to be that first round of tests every traffic engineer and planner should perform to assess the general health of his or her transportation system. They give an indication of the overall health of the system, and how serious the problems are. But they do not necessarily tell the engineer/planner precisely what is wrong. That is the purpose of additional analyses and additional tests.

So this basic set of MOEs is not designed to replace the more detailed intersection and segment MOEs engineers and planners already are accustomed to perform to diagnose and solve traffic operations problems on the transportation system. This basic set is designed to help the engineer/planner and decision-maker rapidly assess the state of the system and identify key avenues of additional analysis to better identify needed improvements.

This basic set of MOEs also is good for rapidly assessing the benefits of alternative improvements at the system level, in a form readily understandable by the decision-maker.

The basic set of MOEs for decision-making consists of five basic measures:

1. Throughput;

2. Mean Delay;

3. Travel Time Index;

4. Oversaturated Freeway Segments; and

5. Surface Street Intersections with Turn Bay Overflows and Exit Blockages.

Each of these basic MOEs is highlighted in Table 29. Key Measures of Effectiveness for Decision-Making. Their use, definition, computation, reporting, and interpretation are presented in this table.

Table 29. Key Measures of Effectiveness for Decision-Making

Decision MOE	Use/Description/Interpretation
Throughput (Vehicles/hr) and Percent Incomplete Trips	• Use – Provides a measure of the relative productivity of the system compared to an alternative. This MOE is also required to compute mean delay. • Definition – The number of vehicles present at the start plus those attempting to enter and successfully entering the system during the analysis period. • Computation – At start of analysis period tally number of vehicles present within system. During analysis period tally number of vehicles attempting to enter the system but never successfully enter. Tally number of vehicles that both enter and exit the system during the analysis period. Tally number of vehicles entering the system during the analysis period that are remaining on system at end of analysis period. • Reporting – Number of vehicles at start that successfully exit system during analysis period (V1). Number of vehicles at start that fail to exit the system during the analysis period (V2). Number of vehicles that entered but did not exit during the analysis period (V3). Number of vehicle generated but never entered the system during the analysis period (V4). Number of vehicles that successfully both entered and exited the system during the analysis period (V5). Report the percent of incomplete trips as the ratio of (V1+V2+V3+V4)/ (V1+V2+V3+V4+V5). • Interpretation – The throughput is compared for different alternatives to determine the relative productivity of each alternative. Higher values are desired. If the ratio of incomplete trips exceeds 5 percent then the decision-maker should consider lengthening the analysis period or investigate the MOEs computed for solely the through trips (V5) to see if they might better represent system performance.

Table 29. Key Measures of Effectiveness for Decision-Making (continued)

Decision MOE	Use/Description/Interpretation
Delay/Trip	• Use – Comparison of traveler perceptions of average traffic performance of alternatives. • Definition – The travel time (for all vehicles entering and attempting to enter the system during the analysis period) minus the theoretical travel time at the free-flow speed. This difference is divided by the number of vehicle trips to obtain mean delay per trip. The free-flow speed is defined as the minimum of the maximum safe speed or the analyst coded speed limit. Note that turning vehicles at an intersection would have a lower maximum safe speed than through vehicles. • Computation – Accumulate distance traveled (VMT) and time expended (VHT) each second by vehicles on system (or attempting to enter system) during analysis period. Simultaneously accumulate theoretical VHT that would have been expended if vehicle had been able to travel the same VMT at free-flow speed. At the end of the analysis period the free-flow VHT is subtracted from the accumulated VHT to obtain Delay VHY. The Delay VHT is converted to seconds and then divided by the total number of vehicle trips over which the delay was accumulated (V1+V2+V3+V4+V5). If the number of incomplete trips (V1+V2+V3+V4) is greater than 5 percent of all trips, then either the analysis period should be lengthened, or Delay VHT should be accumulated separately for through trips (V5) and averaged over only the through trips (V5). • Reporting – Delay is reported in vehicle hours traveled (VHT) and mean seconds per trip. If incomplete trips account for over 5 percent of all trips, that should be noted. • Interpretation – Subjective. If trips are long in system, then high mean delays may be acceptable. If trips are short, even low mean delay may be unacceptable.

Table 29. Key Measures of Effectiveness for Decision-Making (continued)

Decision MOE	Use/Description/Interpretation
Travel Time Index	• Use – To determine if facility operation during peak periods is unacceptably worse than for off-peak periods.
	• Definition – Ratio of observed vehicle-hours traveled (VHT) to theoretical VHT at free-flow speed for same VMT.
	• Computation – See notes above on computation of mean delay. The travel time index is the accumulated VHT divided by the theoretical free-flow VHT.
	• Reporting – System travel time index plus a few words qualifying the result, such as "Good," "Bad."
	• Interpretation –
	– The TTI minus 1.00 gives the mean delay as a percentage of the mean trip time.
	– The inverse of the TTI gives the mean speed as a percentage of the free-flow speed for the system.
	– For an entire metropolitan area (including local streets, arterials, and freeways) a peak period TTI of 1.4 or better was typical of 90 percent of the metropolitan areas of United States in 2005.
	– For more focused systems of mixed freeway and arterial facilities (no local streets) a TTI of under 2.5 is roughly indicative of generally uncongested conditions and good signal coordination.
	– For a system of solely unsignalized facilities (freeways, highways, 2-lane rural roads) a TTI of over 1.4 is indicative of a facility that is over-capacity for the entire length of analysis period.
	– A qualifier of "Good" for TTIs <= 1.5, "Potentially Acceptable" for TTIs between 1.5 and 2.5, and "Less Desirable" for TTIs > 2.5 would help the decision-makers.

Table 29. Key Measures of Effectiveness for Decision-Making (continued)

Decision MOE	Use/Description/Interpretation
Freeways: Percent Breakdowns	• Use – To identify geographic and temporal extent of unsatisfactory operations for freeways in system.

• Description – Breakdown is defined as a density of traffic greater than the density typical of capacity flow rate conditions. This is equivalent to HCM LOS F definition. Two percents are computed:

   – Maximum percent of directional freeway miles at LOS F at any onetime during the analysis period.

   – Percent of analysis period when any directional freeway segment is at LOS F.

• Computation – Determine maximum LOS "E" density for each directional freeway segment in system according to the Highway Capacity Manual. Determine PCE values for each vehicle type in system for each directional freeway segment according to the Highway Capacity Manual. For each second in the analysis period tally number of vehicles on directional segment and multiply by appropriate PCE value to obtain equivalent PCUs. At end of model run compute 15 minute running averages of PCUs for each directional segment. Identify start and end times when 15 minute average PCU exceeds HCM LOS E maximum density. Find earliest start time of LOS F and latest end time of LOS F for system. The percent duration of LOS "F" is equal to the latest end time minus the earliest start time of LOS F, divided by the length of the analysis period.

The maximum percent LOS "F" is the maximum number of directional segment miles operating at LOS "F" (averaged over 15 minutes) at any one time divided by the total directional miles of freeway in the system.

• Interpretation – The geographic and temporal percents LOS "F" are indicators of congested freeway operations. The lower, the better.

Table 29. Key Measures of Effectiveness for Decision-Making (continued)

Decision MOE	Use/Description/Interpretation

Surface Street: Percent of Intersections Exits Blocked	• Use – To identify geographic and temporal extent of unsatisfactory operations for urban streets in system. Intersection exit blockages due to downstream queues extending back to an upstream intersection reduce through capacity and are potential safety concerns.
	
	• Definition – Two percents are computed:
	
	  – Maximum percent of intersection exits that are blocked at any onetime during the analysis period.
	
	  – Percent of analysis period when any intersection exit is blocked.
	
	• Computation – For every directional street link and for each second in the analysis period compare the distance of back bumper of last car in any lane of the directional street link to the total estimated distance to the nearest upstream intersection (If the upstream node has only one link feeding the subject downstream link, that node is not an intersection. Abandon the test on the subject link and perform the test instead on the upstream link.). Determine if the back of queue is within 25 feet of storage length of the directional link.
	
	  – Accumulate number of seconds during analysis period when one or more directional links are full. The percent of the analysis period with one or more full directional links is the number of seconds when one or more directional links are full divided by the number of seconds in the analysis period.
	
	  – Tally number of directional links meeting this "full" criterion at any one time. The maximum percent full links is the maximum number of full directional links at any one time divided by the total number of directional street links (exclude freeway links which have their own LOS F test) in the system.
	
	• Report – Maximum percent of full directional street links at any one time. Percent of analysis period during which one or more directional street links are "full."
	
	• Interpretation – The geographic and temporal percents of "full" links are indicators of potential capacity and safety problems. The lower, the better. Since a common goal for designs of new turn bays is to provide storage for the 95-percentile demand per cycle, a goal of no more than 5 percent of the analysis period with full street links would be desirable for a new design.

There are, of course, many other MOEs that every good planning or engineering study also will want to consider, such as, user benefits, user costs, fuel consumption, noise, air pollutant emissions, and safety. However, the five basic system MOEs listed above will give the decision-maker and the analyst a good idea of how well the system is performing and how one alternative improvement compares to another. The text below describes them in more detail.

Throughput

Throughput is an indicator of the productivity of the system. It tells the analyst how many vehicles were processed by the system during the analysis period. A related indicator is the percent of trips that were initiated during the analysis period but could not

be completed during the analysis period. Throughput plus the percent incomplete trips tell the analyst how good a job the system is doing at moving vehicles.

If the analyst's goal is to move people rather than just vehicles, throughput and percent incomplete can be computed based on person trips rather than vehicle trips. It is a straight forward conversion requiring only knowledge of the vehicle occupancy (number of person per vehicle).

Throughput is defined as the number of distinct vehicles (or people) able to enter or exit the system during the analysis period. To aid its interpretation, the throughput should be divided into five components according to whether or not the vehicle entered, exited, never entered, or never exited the system during the analysis period (see Figure 5. Illustration of Different Components of Throughput).
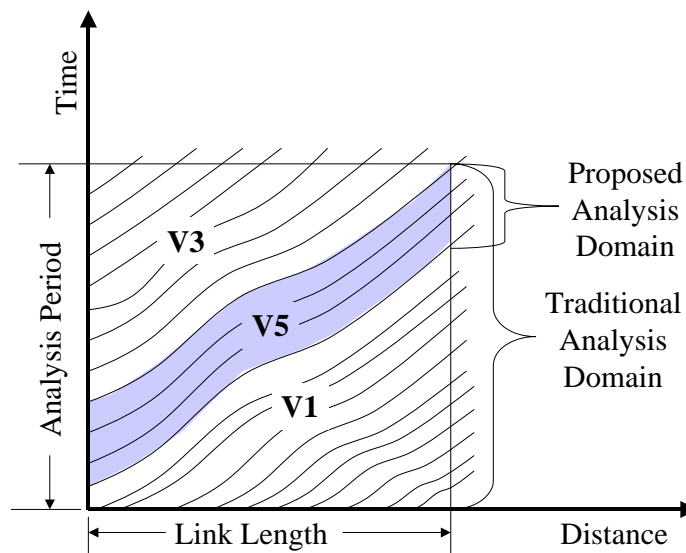
Figure 5. Illustration of Different Components of Throughput.

Vehicles Class I = Vehicles that were present at the start of the analysis period and were able to successfully exit the system before the end of the analysis period.

Vehicle Class II (not shown in figure) = Vehicles that were present at the start of the analysis period but were unable to successfully exit the system before the end of the analysis period. Except for severe congestion cases or very short analysis periods, this class of vehicles is usually zero.

Vehicles Class III = Vehicles that were able to enter the system during the analysis period but were unable to successfully exit the system before the end of the analysis period.

Vehicles Class IV (not shown) = Vehicles that tried to enter the system during the analysis period but were completely unsuccessful. While it frequently happens that vehicles are temporarily delayed from entering the system due to congestion, only extreme congestion (or a very short analysis period) would cause vehicles to be totally

barred from entering the system during the analysis period. Thus, the number of vehicles in this class of vehicles is usually zero as well.

Vehicles Class V = Vehicles that entered during the analysis period and were able to successfully exit the system before the end of the analysis period.

The percent of incomplete trips will be the sum of vehicle classes 1, 2, 3, and 4, divided by the sum of all vehicle classes (1+2+3+4+5).

If the percent of incomplete trips is greater than five percent of total trips during the analysis period, the analyst should lengthen the analysis period so that more complete trips are reflected in the computed MOEs for the system.

If it is not feasible to further lengthen the analysis period, the analyst must carefully evaluate the MOEs computed for the incomplete trips against the MOEs computed for the complete trips and decide which is the most relevant measure of system operations, or select a weighting system for combining the MOEs for incomplete and complete trips.

Generally, higher throughputs and lower percentages of incomplete trips are desired since they reflect the productivity of the transportation system.

Mean Delay

Mean delay is an attempt to couch delay measurements in terms that a typical driver might understand, mean seconds delay per trip. However, it must be recognized that the same number of seconds of delay will be more important for a short trip, and less important for a long trips.

One issue with delay is the yardstick to measure it against. Common practice would be to measure actual travel time against a theoretical travel time at free-flow speeds, when congestion is nonexistent. However, an agency may have a different standard against which it wishes to measure system performance.

This report has adopted the common measure of free-flow travel time against which to measure delay, but other yardsticks are certainly possible.

Free-flow speed is often defined as the speed of traffic at very low-flow conditions (when the flow rate is so low that changes in the flow rate have no significant effect on average travel speed). This may require a field measurement of prevailing speeds under low-flow conditions, so often planners will simply use the posted speed limit as a proxy for the free-flow speed.

Free-flow speeds may indeed be higher or lower than the posted speed limit. A poorly enforced speed limit may not be obeyed. The maximum safe speed on curves and in turns at an intersection also should be taken into account in determining the free-flow speed. It is up to the analyst to determine the desired target against which to compute delay.

The accumulated travel time of all vehicles on the system should be accumulated during the analysis period. At the same time the theoretical travel time to go the same distance traveled should be accumulated as well.

At the end of the analysis period the analyst (or software tool) subtracts the accumulated vehicle hours traveled at the theoretical free-flow speed (the free-flow VHT) from the accumulated vehicle hours traveled (VHT) to get the total delay in terms of vehicle hours (the Delay VHT).

The delay VHT is converted to seconds and then divided by the number of vehicle-trips to obtain mean delay per vehicle-trip.

If the analyst wants person-trip delay, the vehicles are multiplied by the vehicle occupancy while the theoretical free-flow and actual VHTs are accumulated. The result is person hours traveled (PHT). Delay is computed as before and then divided by the total number of person-trips during the analysis period.

If the percent of incomplete trips (described above under throughput) is greater than five percent, then the analyst should extend the duration of the analysis period. If this is not feasible, then the analyst should accumulate VHT (or PHT) by the five vehicle-trip classes described above under throughput and compute the mean delay separately for each vehicle-trip class. The analyst then needs to evaluate the results and decide how to present them.

Generally less delay is preferable, however; specific thresholds of acceptable or unacceptable delay are not available. The Highway Capacity Manual publishes mean delay level of service thresholds for signals and unsignalized intersections but not for segments of streets. The results might be roughly compared to the HCM thresholds, but one should not expect an exact equivalence due to differences in the definition of delay between the Highway Capacity Manual and the method used here.

The Travel Time Index (TTI)

The Texas Transportation Institutes Travel Time Index (TTI) indicates the extra delay associated with congestion on the system. The TTI is the ratio of the peak-period travel time to the free-flow travel time. Values of TTI for urban areas in the United States range from 1.05 (Anchorage, Alaska) to 1.75 (Los Angeles, California).

Typical TTIs at capacity are shown below for uninterrupted flow facilities, arterials with poor signal coordination, and arterials with good signal coordination.

An individual freeway or conventional highway with a TTI of greater than 1.4 is over capacity. An individual signalized arterial with a TTI greater than 2.5 either has poorly coordinated signals or is over capacity, or both.

Table 30. TTIs Per HCM – Freeways and Highways.

HCM Facility Type	Miles per Hour		Hours/Miles		Travel Time Index at Capacity
	Free-Flow Speed	Speed at Capacity	Free-Flow Travel Time Rate (T0)	Capacity Travel Time Rate (TC)	
Freeway	75	53.3	0.0133	0.0188	1.41
	70	53.3	0.0143	0.0188	1.31
	65	52.2	0.0154	0.0192	1.25
	60	51.1	0.0167	0.0196	1.17
	55	50.0	0.0182	0.0200	1.10
Multi-Lane Highway	60	55.0	0.0167	0.0182	1.09
	55	51.2	0.0182	0.0195	1.07
	50	47.5	0.0200	0.0211	1.05
	45	42.2	0.0222	0.0237	1.07
Two-Lane Rural Road	55	40.0	0.0182	0.0250	1.38

Sources:

1. Freeways: Exhibit 23-2 HCM.

2. Multi-Lane Highways: Exhibit 21-2 HCM.

3. Two-lane Highways: Exhibit 20-2, HCM.

Table 31. TTIs Per HCM – Arterials – Uncoordinated Signals.

Arterial Class	Speed Limit (mph)	Signals/mi	Miles per Hour		TTI		
			Zero vph	Capacity	0vph/lim	Cap/0vph	Cap/Lim
1	55	1	32.9	22.4	1.67	1.47	2.45
1	50	2	31.5	21.7	1.59	1.45	2.30
1	45	4	20.4	12.9	2.21	1.58	3.49
2	45	2	29.0	20.5	1.55	1.41	2.20
2	40	4	19.7	12.6	2.03	1.56	3.17
2	35	5	16.7	10.5	2.10	1.59	3.34
3	35	4	18.7	12.2	1.87	1.53	2.87
3	30	6	14.5	9.0	2.06	1.62	3.35
4	35	4	18.5	12.1	1.89	1.53	2.89
4	30	6	14.1	8.8	2.13	1.60	3.41
4	25	8	10.4	6.5	2.40	1.59	3.82

Source: FDOT ARTPLAN Modified by Dowling 6/22/06.

Assumptions: 120 second signal cycle, 0.45 g/c through, no coordination.

Table 32. TTIs Per HCM – Arterials – Coordinated Signals.

Arterial Class	Speed Limit (mph)	Signals/mi	Miles per Hour		TTI		
			Zero Vph	Capacity	0vph/lim	Cap/0vph	Cap/Lim
1	55	1	32.9	22.4	1.67	1.47	2.45
1	50	2	31.5	21.7	1.59	1.45	2.30
1	45	4	24.9	16.3	1.80	1.53	2.76
2	45	2	29.0	20.5	1.55	1.41	2.20
2	40	4	24.0	15.9	1.67	1.51	2.52
2	35	5	20.5	13.3	1.70	1.54	2.63
3	35	4	22.5	15.2	1.56	1.48	2.30
3	30	6	19.0	12.2	1.58	1.56	2.46
4	35	4	22.2	15.1	1.58	1.47	2.32
4	30	6	18.3	11.9	1.64	1.54	2.53
4	25	8	15.5	10.4	1.61	1.49	2.40

Source: FDOT ARTPLAN Modified by Dowling 6/22/06.

Assumptions: 80-120 second signal cycle, 0.45 g/c through, coordination if >=4 sig/mi.

Freeway Segments at Breakdowns

Freeway breakdown occurs when the demand exceeds the capacity of the freeway. This can be most reliably measured by identifying the density per lane of traffic when the freeway is flowing at capacity and then comparing the observed density to the density at capacity. If the observed density is greater than the density at capacity, then the freeway is considered to be oversaturated or in "breakdown" condition.

The Highway Capacity Manual applies the level of service "F" label to passenger car unit densities exceeding capacity that last for at least 15 minutes. For the purpose of this system MOE, we have relaxed the requirement that the density persist for at least 15 minutes, so that we can catch even transient breakdowns in freeway operations.

The geographic extent and duration of freeway segments operating at Highway Capacity Manual Level of Service "F" densities during the analysis period are indicators of the severity of freeway congestion on the system during the analysis period.

This MOE might be more appropriately displayed as a two-dimensional time-space plot showing the portion of the time-space box taken up by congestion. However, this report attempts to identify two dimensions that might indicate the maximum extent and duration of congestion. One measure is the maximum percent of the analysis period when any freeway segment in the system is at level of service "F." The other measure is the maximum percent of freeway miles that are congested at any one time during the analysis period. The first measure attempts to get at the maximum duration of congestion on the freeway system. The second measure attempts to get at the maximum geographic extent of the freeway congestion.

Both measures require the identification of which directional freeway segments are operating at LOS "F" densities for continuous 15-minute periods at each second of the analysis period (A 15-minute running average density is computed each second of the analysis). The number of vehicles must be converted to equivalent passenger car units (PCUs) using the passenger car equivalents in the Highway Capacity Manual. These equivalents vary by vehicle type and grade (or general terrain: level, rolling, mountainous).

Once the timing and location of level of service "F" conditions have been identified, it is then just a matter of processing the data to find the maximum length of time when at least one freeway segment is congested, and the maximum number of freeway-miles of segments that are congested at any one time during the analysis period.

To help the decision-maker appreciate the relative magnitude of the problem, the results are reported as a percentage of the total freeway-miles in the system and a percentage of the total analysis period.

Generally lower percentages of Level of Service "F" are preferred.

Surface Street Backups and Overflows

Surface street backups and turn bay overflows are indicators of the extent to which capacity destructive queues are present on the surface streets of the system. These excessive queuing situations also are indicative of potential safety problems where vehicles queue back into an upstream intersection or vehicles queue back out of a turn bay and into a through traffic lane.

A surface street backup is one where a downstream queue backs up in one or more through lanes to an upstream intersection, reducing its capacity. For want of a more descriptive term, these are called, "Intersection Exit Blockages." They occur when the number of vehicles queued in any one lane on a street exceed its storage capacity. Additional vehicles must wait for the queue to reduce a bit before they can move through the upstream intersection.

Turn bay overflows are situations where the number of vehicles waiting to make a left or right turn exceeds the storage capacity of the turn bay. Waiting vehicles must back up into the through lanes, reducing through capacity at the intersection.

As for freeway Level of Service F, this MOE might be more appropriately displayed as a couple of two-dimensional time-space plots (one for street backups affecting upstream intersections, the other for turn bay overflows) showing the portion of the time-space box taken up by excessive queuing. However, this report attempts to identify two dimensions that might indicate the maximum extent and duration of excessive queuing. One measure is the maximum percent of the analysis period when any turn bay or street segment in the system is experiencing queue overflows. The other measure is the maximum percent of directional street segments that have queue overflows at any one time during the analysis period. The first measure attempts to get at the maximum duration of street and turn bay

queue overflows on the street system. The second measure attempts to get at the maximum geographic extent of the queue overflows.

Both measures require the identification of which directional street segments and turn bays have queues that exceed the storage length at any second in the analysis period.

Since most simulation tools cannot identify queues that exceed the storage capacity (the excess vehicles are reported as queued on the upstream link), the criterion selected is whether or not the queue is "close" to storage capacity of the link or turn bay. The estimated storage length for one vehicle of 25 feet is subtracted from the storage capacity. If the queue exceeds the storage length minus 25 feet, it is considered as if it has actually exceeded the available storage length. This measure no doubt slightly over estimates the actual occurrences of queue overflows, but it is only off by one vehicle length.

Once the timing and location of queue overflow conditions have been identified, it is then just a matter of processing the data to find the maximum length of time when at least one directional street segment or turn bay is overflowing, and the maximum number of directional street links or turn bays with overflow queues at any one time during the analysis period.

To help the decision-maker appreciate the relative magnitude of the problem, the results are reported as a percentage of the total directional street segments (or turn bays) in the system and a percentage of the total analysis period.

Generally lower percentages of queue overflow are preferred. Since it is common to design new turn bays for the 95 percentile traffic surge each cycle, it is suggested that 5 percent queue overflows during the analysis period might be a good target for a new design. No guidance is provided for existing systems, which may routinely experience more frequent queue overflows, and still be quite acceptable to the local populace.

6.2 COMPARISON OF MOES BETWEEN ANALYSIS TOOLS

Since each analysis tool has slightly different definitions of what constitutes stopped and queued vehicles and because the tools also vary in the determination of which vehicles to include in the computations (vehicles that both entered and exited during the analysis period, vehicles that did neither, or vehicles that either entered or exited but not both during the analysis period), it is not feasible for an analyst to take the macroscopic output from one tool, apply a conversion factor (or equation) and compare the results to that of another tool. The analyst simply does not have access to sufficient data at the macroscopic level to be able to compare MOEs across tools.

The lowest common denominator for all analytical tools is the vehicle trajectories output. This is a microscopic output. With this output the analyst can compute macroscopic MOEs from any tool in a consistent manner. Then it is indeed possible to compare vehicle performance results across different analytical tools, through the computation of macroscopic MOEs from microscopic vehicle trajectory data.

6.3 MOES FOR FUTURE RESEARCH

The technical review suggested four additional key MOEs that are likely to be valuable to decision-makers but could not be included at this time due to several uncertainties about them requiring more research and additional practical experience in order to better define them. They are:

- Buffer Index;

- Fuel Consumption Ratio;

- NO_x Emissions Ratio; and

- Safety.

The Buffer Index

The buffer index shows how much earlier a travel must start the trip (as a percentage of the trip duration) to have a 95 percent chance of arriving on time. It is computed according to the following formula:

$$Buffer\ \text{Index}\ (\%) = \left[\frac{\begin{array}{c} \text{95th Percentile Travel Time} \\ \text{(minutes)} \end{array} - \begin{array}{c} Average\ \text{Travel Time} \\ \text{(minutes)} \end{array}}{\begin{array}{c} \text{Average Travel Time} \\ \text{(minutes)} \end{array}} \right] \times 100\% \qquad \textbf{Equation 69}$$

There are a dozen different measures of travel-time reliability (see "Selecting Travel Reliability Measures," by J. Lomax, D.L. Schrank, S.M. Turner, R. Margiotta, Report, Texas Transportation Institute, May 2003.)

The buffer index was selected because it is similar to the decisions a traveler has to make, "How much extra time do I have to allow in order to be sure of getting there on time?" Related measures include standard deviation, variance, and several other indicators or travel-time reliability.

Difficulties with implementing the buffer index at this time include a lack of understanding of the true variability of traffic operations when considering variance in demand, probability of capacity reducing incidents, and the inherent variability of driver behavior for any given situation. More research is needed to better understand how much of this total variability is included in microsimulation models, and how much is still missing.

Fuel Consumption Ratio

The Fuel Consumption Ratio would be used to identify the excess fuel consumption caused by unsatisfactory system operation. It is the ratio of fuel consumed to fuel that would have been consumed if all travel could have been made at most fuel efficient speed for vehicles without stops.

Fuel consumption can be expressed as power consumption (Kilowatt hours or British Thermal Units). Gallons of gasoline equivalent was selected since it generates a ready visual image of fuel consumption for decision-makers.

While tools do exist to compute fuel consumption from VMT and speed, the key issue with this MOE is that tools and procedures do not exist for computing the theoretical optimal fuel consumption for a system.

The NO_x Ratio

The NO_x ratio is defined as the kilograms of nitrous oxide emissions divided by the theoretical minimum NO_x emissions that would occur at ideal vehicle operating speeds on the system.

Vehicles actually emit a wide range of pollutants (Carbon Monoxide, Nitrous Oxides, Hydrocarbons, etc.). Nitrous Oxides (NO_x) was selected as an indicator pollutant since it is the one most likely to be controlled in a nonattainment basin.

Vehicle-Specific Power (VSP) may be an alternative measure that closely follows NO_x emission rates. VSP requires assumptions about drag and rolling resistance, Weight drops out because VSP is normalized by mass. Using typical value of coefficients, in SI units the equation becomes:

VSP (kW/metric Ton) = v * (1.04*a + 9.81*grade(%) + 0.132) + 0.00121*v^3   **Equation 70**

Where:

V   = Velocity (km/hr).
A   = Acceleration.

Source: Nam, Proof of Concept Investigation for the Physical Emission Rate Estimator (PERE) to be Used in MOVES [report EPA420-R-03-005]. 2003, U.S. EPA (page 7).

Issues with the NO_x ratio or other air pollutant emission proxy such as VSP is the lack of agreement on how best to compute air pollutant emissions or proxies from microsimulation data. The standard methods generally use average speed and VMT, but upcoming methods rely on data that can only come from vehicle trajectories. There also is a lack of information as to the accuracy of vehicle accelerations predicted by microsimulation models.

Safety

Safety is one field where a great deal of research will be needed to develop tools for translating traffic operations results into indicators of relative safety. One promising approach is to use microsimulation to tally the frequency of conflicts or close encounters in the traffic stream. However, this approach is still under development and more time will be needed to determine how best to incorporate safety into traffic operations analysis.

7.0 PRACTICAL APPLICATION RESULTS

The purpose of the practical application task is to demonstrate through case studies the validity of the approach(s) recommended in the previous chapter. The intent is to use existing real-world data to demonstrate how transportation professionals should generate and interpret the basic system MOEs recommended by this study.

7.1 SELECTION OF CASE STUDIES

The original hypothesis of this research was that a set of procedures could be developed to convert the MOEs reported for typical microscopic and macroscopic traffic analysis tools into a consistent set of MOEs comparable to the Highway Capacity Manual. The investigation into how various tools compute the standard MOEs discovered that there is a wide range of methods used to compute and average the standard MOEs, and these methods diverge at the microscopic level. The reports produced by typical traffic analysis tools do not provide sufficient microscopic information to enable the analyst to convert the MOEs produced by one tool into the equivalent MOEs produced by another tool.

Consequently, the recommended approach for achieving consistent MOE results across various analytical tools is to compute the MOEs directly from vehicle trajectory data produced by the tool, rather than trying to correct aggregate MOE results reported by each microscopic or macroscopic tool.

One advantage of this approach is that vehicle trajectory data is the lowest common denominator shared by all microscopic and mesoscopic tools. A single procedure for computing MOEs directly from vehicle trajectory data is applicable to all micro and mesoscopic tools. The procedures identified in this report can be automated today through the use of commonly available analytical tools (ACCESS and EXCEL for example) or in the future through procedures built into each tool to process vehicle trajectory data.

Since none of the macroscopic tools and few of the microscopic tools produce vehicle trajectory data readily accessible to the average user, these cases studies use vehicle trajectory data measured directly in the field. The FHWA NGSIM program has developed three datasets of tenth-second vehicle trajectory data. Two of these vehicle trajectory data sets were selected for use in the case studies:

1.   The I-80 Freeway – Emeryville, California; and

2.   Lankershim Boulevard – Los Angeles, California.

7.2 THE I-80 FREEWAY CASE STUDY

The I-80 data set consists of tenth-second vehicle trajectories for a 1,650-foot-long section of the I-80 eastbound freeway between Powell Street and Ashby Avenue in Emeryville, California. The section is a 5-lane plus HOV lane weaving section of freeway with a one lane on ramp merge point for Powell Street about 420 feet into the section. The grade is nominally 0 percent in this section.

Vehicle trajectory data was gathered for three 15-minute periods on the afternoon of April 13, 2005. The 5:15 p.m. through 5:30 p.m. period was selected for the case study as likely to have the most congestion.

Further details on the data set can be found in: Cambridge Systematics, NGSIM I-80 Data Analysis (5:15 p.m. to 5:30 p.m.) Summary Report, December 2005, available on the NGSIM web site (http://www.ngsim.fhwa.dot.gov/). Table 33. I-80 Data Dictionary, defines the data fields in this data set.

The MOE results for the I-80 data set are shown in Table 34. I-80 Decision-Maker MOEs.

A single ACCESS query of the I-80 vehicle trajectory database provided most of the decision-maker MOEs. This query identified the first millisecond and the last millisecond when the vehicle was present anywhere on the system for those milliseconds within the analysis period. The starting and end "Y" position for each vehicle also was identified in the same query.

The query was output to a spreadsheet, which then computed the VMT and VHT for each vehicle. Each vehicle and the VMT and VHT it generated was separated into five categories:

1. Vehicles already present at the start of the analysis period that were able to exit the system before the end of the analysis period.

2. Vehicles already present at the start of the analysis period that were still within the system at the end of the analysis period.

3. Vehicles still present on the system at the end of the analysis period, but which were not present at the start.

4. Vehicles completely denied entry to the system during the entire analysis period. (The NGSIM datasets do not include these vehicles so they had to be estimated for the purpose of the case study.)

5. Vehicles successfully entering and exiting the system during the analysis period.

Travel Time Index (Trip Time/Ideal Trip Time)

Computation Notes – The travel time index was computed by taking the ratio of the sum of the VHT traveled for all 5 vehicle categories to the ideal free-flow VHT. The ideal free-flow VHT was computed by dividing the sum of the VMT accumulated by all 5 vehicle categories by the posted speed limit of 65 mph.

The NGSIM dataset does not include vehicles unable to enter the system, so the vehicle hours accumulated by vehicles denied entry to the system had to be estimated. Since the study section had a mean density of close to 100 vehicles per mile per lane over the entire analysis period, it was assumed that the queue extended beyond the start of the study segment for the entire analysis period. Based on personal knowledge of the freeway

section, it was estimated that the queue of vehicles waiting to enter the study section extended back about 1 mile and persisted in steady state throughout the entire analysis period. The VHT of delay for vehicles temporarily delayed from entering the study section was therefore estimated at 100 vehicles/mile/lane x 4 lanes x 1 mile x 0.25 hrs = 100 VHT (See Table 35. Adjustment to TTI Computation for Delayed Entry to System (I-80)).

The vehicle hours accumulated for vehicles entering the system during the analysis period (Vehicle categories 3 and 5) were split into two subcategories. The first subcategory represents the VHT accumulated within the study section. The second subcategory represents the estimated VHT accumulated by the same vehicles waiting their turn to enter the study section during the analysis period.

The final TTI is then the ratio of the posted speed limit to the final adjusted mean speed for all vehicles taking into account the delays to vehicles queued waiting to enter the system during the analysis period.

Interpretation – The value of 18.69 for the TTI is very high, quite a bit higher than the metropolitan areawide TTIs reported by the Texas transportation Institute, which in 2005 ranged from 1.05 (Anchorage, Alaska) to 1.75 (Los Angeles, CA) (Source: The 2005 Urban Mobility Report by David Schrank and Tim Lomax of the Texas Transportation Institute, May 2005, http://mobility.tamu.edu).

The TTI also is quite a bit higher than the TTIs at capacity flows computed using the Highway Capacity Manual method for freeways.

Throughput (vph)

Computation Notes – The system throughput is the total number of vehicles able to exit the system during the analysis period, including vehicles present anywhere in the system at the start of the analysis period. The throughput is normalized to an hourly rate by dividing the number of vehicles by the number of hours in the analysis period.

The throughput was the sum of vehicle categories 1 and 5, all vehicles able to exit the system during the analysis period.

Interpretation – Throughput is a solely a function of demand until demand starts approaching capacity. Then it is a function of solely capacity. A throughput of 6,844 vph is equivalent to 1,141 vph/lane for a 6-lane freeway, which is less than 60 percent of the potential capacity of this freeway. The throughput is constrained by a downstream bottleneck. Throughput is useful for comparing alternative improvements.

Freeway MOEs – Maximum Extent Breakdowns (%/dir.miles)

An ACCESS query grouping PCEs present on the segment for each millisecond of the analysis period was exported to an EXCEL spreadsheet. Within the spreadsheet the PCUs per lane-mile were compared to the Highway Capacity Manual density thresholds for LOS "F" on freeways (43 pcu/lane-mile).

The mean density the full length of the analysis period and across all lanes and for the full length of the study section exceeded the LOS "F" density of 43 pcus/lane/mile. Thus the study section reached 100 percent LOS "F."

Freeway MOEs – Duration of Breakdowns (%/Time)

The total milliseconds where PCUs per lane-mile were greater than the Highway Capacity Manual density thresholds for LOS "F" on freeways (43 pcu/lane-mile) was divided by the total milliseconds in the analysis period to obtain the percent duration. Since the duration was 100 percent of the analysis period, the study section is considered severely congested.

Surface Street MOEs – Street Segment Overflows

The surface street MOEs are not applicable to the I-80 data set.

Table 33. I-80 Data Dictionary.

Field	Name	Definition	Used in Case Study
1	Vehicle ID	Preliminary ID number assigned to each vehicle trajectory during first pass recording trajectories. Several ID numbers dropped during manual reconnection of broken trajectories.	Yes
2	Frame ID	Frame ID Number.	No
3	Total Frames	Number of frames vehicle is visible.	No
4	Global Time	Number of milliseconds after Midnight, January 1, 1970 Greenwich Standard Time.	Yes
5	Local X	Lateral (X) coordinate of the front center of the vehicle with respect to the left-most edge of the section in the direction of travel.	Yes
6	Local Y	Longitudinal (Y) coordinate of the front center of the vehicle with respect to the entry edge of the section in the direction of travel.	Yes
7	Global X	CA State Plane NAD83 coordinate.	No
8	Global Y	CA State Plane NAD83 coordinate.	No
9	Vehicle Length	Feet.	No
10	Vehicle Width	Feet.	No
11	Vehicle Class	1 = motorcycle, 2 = auto, 3 = truck.	Yes
12	Vehicle Velocity	Feet per second.	Yes
13	Vehicle Acceleration	Feet per second squared.	Yes

Table 33. I-80 Data Dictionary (continued)

Field	Name	Definition	Used in Case Study
14	Lane Identification	Lane 1 = farthest left.	No[a]
		Lane 6 = farthest right.	
		Lane 7 = on-ramp.	
		Lane 9 = shoulder on the right-side	
15-18		Additional data on leading vehicle, following vehicle, and headway	No

Source: Cambridge Systematics – NGSIM Data Dictionary.

[a] Although not used in this particular test, it would be handy to have the lane identification in the MOE dataset, so that the difference between HOV and non-HOV lane operation could be evaluated.

Table 34. I-80 Decision-Maker MOEs.

Decision-Maker MOEs	Value	Interpretation
Travel Time Index (Trip Time/Ideal Trip Time)	18.69	Severely congested. Quite a bit higher than HCM TTI at capacity. See table below.
Throughput (vph)	6,844	Operating at about 50 percent of capacity for 6-lane freeway.
Freeway MOEs		
Maximum Extent Breakdowns (%/dir.miles)	100%	Severely congested.
Duration of Breakdowns (%/Time)	100%	Severely congested.
Surface Street MOEs		
Maximum Street Segment Overflows	N/A	
Maximum Segment Overflows (%/segs)	N/A	
Duration Segment Overflows (%/time)	N/A	
Maximum Turn Bay Overflows	N/A	
Maximum Turn Bay Overflows (%/bays)	N/A	
Duration Turn Bay Overflows (%/time)	N/A	

Table 35. Adjustment to TTI Computation for Delayed Entry to System (I-80).

Vehicle Group	Component	Value
V1 (vehicles present in system at start of period and successfully exiting before end of period)		138
V2 (vehicles present in system at start of period but unable to exit before end of period)		0
V3 (vehicles entering system during period but unable to exit before end of period))		79
V4 (vehicles denied entry for entire period)		0
V5 (vehicles successfully entering and exiting during the period)		1,573
V (total vehicles)		1,790
VMT1 (vehicles at start and successfully exiting)		28.25
VMT2 (vehicles at start unable to exit)		0.00
VMT3 (vehicles at end, but not at start)		17.90
VMT4 (vehicles denied entry)		0.00
VMT5 (vehicles successfully entering and exiting)		461.33
VMT (total vehicles)		507.47
VHT1 (vehicles at start and successfully exiting)		2.30
VHT2 (vehicles at start unable to exit)		0.00
VHT3 (vehicles at end, but not at start)		7.27
VHT3A (accumulated on Network)	2.49	
VHT3B (accumulated waiting to enter Network) (manual adjustment)	4.78	
VHT4 (accumulated while vehicle denied entry)		0
VHT5 (vehicles successfully entering and exiting)		136.38
VHT5A (accumulated on Network)	41.29	
VHT5B (accumulated waiting to enter Network) (manual adjustment)	95.09	
VHT (total vehicles)		145.94
MPH1 (vehicles at start and successfully exiting)		12.30
MPH2 (vehicles at start unable to exit)		0.00
MPH3 (vehicles at end, but not at start)		2.46
MPH4 (while vehicles denied entry)		0.00
MPH5 (vehicles successfully entering and exiting)		3.38
MPH (total vehicles)		3.48

VMT = Vehicle miles traveled (VMT1, VMT2, etc., are VMT for respective vehicle group).

VHT = Vehicle hours traveled.

MPH = Mean speed (miles per hour).

TTI = FFS/MPH where FFS equals free flow speed and MPH equals adjusted mean speed for all vehicles.

7.3 THE LANKERSHIM CASE STUDY DATA SET

The Lankershim data set consists of tenth-second vehicle trajectories for a 1,600-foot-long bidirectional section of Lankershim Boulevard between Valley Heart Drive and the U.S. 101 freeway in California. The section includes 4 closely spaced signalized intersections. The arterial has three to four through lanes in each direction with left and right turn bays many of the intersections. The posted speed limit is 35 mph.

Adjacent land uses include: Bus Terminal, Metro station, 36 story office building, Metro station and office building parking lots and garages, and Universal Studios parking lot.

Vehicle trajectory data was available for two 15-minute periods on the morning of June 16, 2005. The 8:30 a.m. to 8:45 a.m. period was selected for the case study as likely to have the most congestion.

Further details on the data set can be found in: Cambridge Systematics, *NGSIM I-80 Data Analysis (8:30 a.m. to 8:45 a.m.) Summary Report*, March 2006, available on the NGSIM web site (http://www.ngsim.fhwa.dot.gov/). A data dictionary listing the contents of this dataset is provided in Table 36. Lankershim Data Dictionary.

The MOE results for the Lankershim data set are shown in Table 37. Lankershim Decision-Maker MOEs.

Decision-Maker MOE Results

A single ACCESS query of the Lankershim vehicle trajectory database provided most of the decision-maker MOEs. This query identified the first millisecond and the last millisecond when the vehicle was present anywhere on the system for those milliseconds within the analysis period. The starting and end "Y" position for each vehicle also was identified in the same query.

The query was output to a spreadsheet, which then computed the VMT and VHT for each vehicle. Each vehicle and the VMT and VHT it generated was separated into five categories:

1. Vehicles already present at the start of the analysis period that were able to exit the system before the end of the analysis period.

2. Vehicles already present at the start of the analysis period that were still within the system at the end of the analysis period.

3. Vehicles still present on the system at the end of the analysis period, but which were not present at the start.

4. Vehicles completely denied entry to the system during the entire analysis period. (The NGSIM datasets do not include these vehicles so they had to be estimated for the purpose of the case study.)

5. Vehicles successfully entering and exiting the system during the analysis period.

Since the NGSIM dataset does not include vehicles unable to enter the system, the vehicle hours accumulated by vehicles denied entry to the system had to be estimated. Since the queues in the system did not fill up the street segments very often during the analysis period (less than 12 percent of the time), the vehicle hours of delay for denied entry vehicles was assumed to be zero. No adjustment was necessary.

Table 36. Lankershim Data Dictionary.

Field	Name	Definition	Used in Case Study
1	Vehicle ID	Preliminary ID number assigned to each vehicle trajectory during first pass recording trajectories. Several ID numbers dropped during manual reconnection of broken trajectories.	Yes
2	Frame ID	Frame ID Number.	No
3	Total Frames	Number of frames vehicle is visible.	No
4	Global Time	Number of milliseconds after Midnight, January 1, 1970 Greenwich Standard Time.	Yes
5	Local X	Lateral (X) coordinate of the front center of the vehicle – perpendicular to the median of the Lankershim Boulevard. Vehicles traveling on the east side of the median have positive Local X values, while those traveling on the west side of the median have negative Local X values.	Yes
6	Local Y	Longitudinal (Y) coordinate of the front center of the vehicle along the median of the Lankershim Boulevard. The start point is at the southern boundary of the study area.	Yes
7	Global X	CA State Plane NAD83 coordinate.	No
8	Global Y	CA State Plane NAD83 coordinate.	No
9	Vehicle Length	Feet.	No
10	Vehicle Width	Feet.	No
11	Vehicle Class	1 = motorcycle, 2 = auto, 3 = truck.	Yes
12	Vehicle Velocity	Instantaneous feet per second.	Yes
13	Vehicle Acceleration	Instantaneous feet per second squared.	Yes
14	Lane Identification	Current lane position of vehicle. Lane numbering is incremented from the left-most lane, except for locations where left-turn or right-turn bays exist. Left-turn bays are numbered starting from 11 and are incremented from the left-most left-turn bay. Right-turn bays are numbered starting from 31 and are incremented from the left-most right-turn bay. The left-turn bay mid-block between intersections 3 and 4 is numbered 101.	Yes
15	Origin Zone		No
16	Destination		No
17	Intersection	From south to north, intersection numbers.	Yes
18	Section	From south to north, section number.	Yes
19	Direction	Moving direction of the vehicle. 1 – eastbound (EB), 2 – northbound (NB), 3 – westbound (WB), 4 – southbound (SB).	Yes
20	Movement	Movement of the vehicle. 1 – through (TH), 2 – left-turn (LT), 3 – right-turn (RT).	No
21-24		Additional data on leading vehicle, following vehicle, and headway.	No

Source: Cambridge Systematics – NGSIM Data Dictionary.

Table 37. Lankershim Decision-Maker MOEs

Decision-Maker MOEs	Value	Interpretation
Travel Time Index (Trip Time/Ideal Trip Time)	2.58	Better than typical for an uncoordinated arterial operating at capacity.
Throughput (vph)	4,212	Useful for comparing the productivity of alternative improvements.
Freeway MOEs		
Maximum Extent Breakdowns (%/dir.miles)	N/A	N/A
Duration of Breakdowns (%/Time)	N/A	N/A
Surface Street MOEs		
Maximum Street Segment Overflows	2	Two segments to investigate.
Maximum Segment Overflows (%/segs)	33%	Significant fraction of system under stress.
Duration Segment Overflows (%/time)	20%	Problems endure longer than peak 15 minutes of hour.
Maximum Turn Bay Overflows	2	Two problem spots to investigate.
Maximum Turn Bay Overflows (%/bays)	40%	Significant fraction of turn bays have problems.
Duration Turn Bay Overflows (%/time)	12%	Greater than design standard of 5 percent implied by 95 Percentile Turn Bay Length design standard.

Travel Time Index (Trip Time/Ideal Trip Time)

Computation Notes – The travel time index was computed by taking the ratio of the sum of the VHT traveled for all 5 vehicle categories to the ideal free-flow VHT. No adjustment to the TTI was necessary for vehicles delayed from entering the system during the analysis period, because queues did not extend beyond the physical limits of the study area. The ideal free-flow VHT was computed by dividing the sum of the VMT accumulated by all 5 vehicle categories by the posted speed limit of 35 mph.

Interpretation – The value of 2.58 for the TTI is quite a bit higher than the metropolitan areawide TTIs reported by the Texas transportation Institute, which in 2005 ranged from 1.05 (Anchorage, Alaska) to 1.75 (Los Angeles, California) (Source: The 2005 Urban Mobility Report by David Schrank and Tim Lomax of the Texas Transportation Institute, May 2005, http://mobility.tamu.edu.).

According to the Highway Capacity Manual method the TTI for an urban arterial would range from 1.9 to 2.1 under free-flow uncoordinated conditions and from 2.9 to 3.3 under capacity flow uncoordinated conditions for a Class II/Class III arterial. Since the computed TTI of 2.58 falls below the values at capacity for uncoordinated arterials, the arterial traffic operation is considered to be generally good.

Throughput (vph)

Computation Notes – The system throughput is the total number of vehicles able to exit the system during the analysis period, including vehicles present anywhere in the system at the start of the analysis period. The throughput is normalized to an hourly rate by dividing the number of vehicles by the number of hours in the analysis period.

The throughput was the sum of vehicle categories 1 and 5, all vehicles able to exit the system during the analysis period.

Interpretation – Throughput is solely a function of demand until demand approaches capacity. Then it is a function of solely capacity. A throughput of 4,212 vph is equivalent to 702 vph/lane for a 6-lane arterial, which is slightly below the planning capacity for a signalized intersection (planning capacity would be 750 vph/ln = 1,500 vphgl * 0.50 g/c). Throughput is useful for comparing alternative improvements.

Freeway MOEs – Maximum Extent Breakdowns (%/dir.miles)

This MOE is not applicable to the Lankershim data set.

Freeway MOEs – Duration of Breakdowns (%/Time)

This MOE is not applicable to the Lankershim data set.

Surface Street MOEs – Street Segment Overflows

Computation Notes – A specialized set of segment by segment, direction by direction set of ACCESS queries were required to identify street segments where the queues of vehicles had filled up one or more through lanes on the street.

First a query was conducted to identify the maximum and minimum "Y" coordinates for each vehicle on each direction of each street segment. The results were exported to an EXCEL spreadsheet where a pivot table was used to compute the average maximum and average minimum "Y" coordinates for each direction of each street segment. The average was used because of slight differences in the starting and end "Y" coordinates for each lane of each segment.

The average maximum "Y" was subtracted from average minimum "Y" for each direction of each segment to obtain the mean segment length by direction. Since vehicles that cannot fit within the segment are never recorded, the target queue length for determining if a segment is full was set at 25 feet less than the actual length of the segment. If the queue extends to within 25 feet of the back of the segment, the segment is considered to be full, for all practical purposes.

However, the "Y" coordinates in the data set represent the position of the front of the vehicle, not the back, so the target length of the segment (for determining when the queue filled up the segment) was reduced by a further 25 feet. Thus the target "Y" coordinate for

determining if the vehicle queue in any lane had filled up the segment was the "Y" coordinate of the back of the link minus 50 feet.

A separate query was then conducted in ACCESS for each direction of each segment. For each millisecond of the analysis period, if the "Y" coordinate of any vehicle exceeded the maximum "Y" coordinate minus 50 feet for that direction of that segment, and the vehicle was traveling at that moment at a speed of less than 7 fps, with an acceleration of less than +2 fpss, then one or more lanes of that direction of the segment was considered to be "blocked" with queuing vehicles (even if not other queuing vehicle is present in the lane in front of the queued vehicle).

The number of segments "blocked" at any millisecond of the analysis period was tallied to obtain the maximum number of blocked directional segments for the analysis period.

The duration of blocked directional segments within the system during the analysis period was obtained by summing up the number of millisecond snapshots where at least one directional segment was blocked.

Interpretation – The percentage of street segments subject to risk of overflow is relatively high (33 percent), with at least one segment subject to risk of overflow 20 percent of the analysis period. Since standard practice is to design turn bays so that they have less than a 5 percent risk of overflowing during the peak hour, the 20 percent overflow for an individual street segment would be undesirable for a new design.

Surface Street MOEs – Turn Bay Overflows

Computation Notes – Given the tediousness of the approach used to arrive at the segment blockages, an alternative approach was tried to identify turn bay overflows.

An ACCESS query was launched to report all instances of queued vehicles (speeds less than 7 fps and acceleration less than +2 fpss) within all turn bays of the system. The maximum and minimum "Y" coordinate was reported for the queued vehicles each millisecond within the turn bay. The query result was exported to a spreadsheet.

The difference between maximum and minimum "Y" coordinates for each turn bay for each millisecond was compared to the nominal storage length for the turn bay reported in the NGSIM data collection report, less 25 feet (50 feet was not subtracted from the storage length because several turn bays are only 70 feet long. Subtracting 50 feet from the storage length would have resulted in these turn bays being reported as at risk of overflow every time a single vehicle entered the bay).

Note that this method was easier to implement with an ACCESS query, but it only gets the maximum number of vehicles in queue in the lane at any one time, not the maximum back of queue. Consequently, the method described above for identifying street segment backups is preferable because of its superior accuracy at identifying queue overflow problems.

A pivot table was used to tally up the number of milliseconds during the analysis period that each turn bay was at risk of overflowing.

The maximum duration of turn bay overflows was estimated to be the longest duration of overflows for the turn bays. The maximum number of turn bays at risk of overflow at any one time during the analysis period was estimated by visual inspection of the turn bay query results. (It would have been more accurate to plot the turn bay overflows by millisecond through the analysis period and identify the maximum impacted at any one time and the total number of milliseconds of the analysis period when any of the turn bays was at risk of overflowing, however; resource and time limitations caused the author to select these two shortcuts for approximating the maximum duration and extent of turn bay overflows.)

Interpretation – The maximum number of turn bays at risk of overflowing at any one time is quite high (40 percent). Also, the percent of time when one or more turn bays is at risk of overflowing (12 percent) is higher than 5 percent risk that standard practice would call for in the design of new turn bays.

7.4 CONCLUSIONS FROM CASE STUDIES

The above practical applications have demonstrated how vehicle trajectory data can be post-processed to yield key basic measures of effectiveness useful for transportation operations analysis and decision-makers. People more familiar with database processing than the author can no doubt find betters ways to process the trajectory data than were used in these examples. However, the practical applications have illustrated the feasibility of using off-the-shelf database programs to generate MOEs from vehicle trajectory data.

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