Traffic Flow Measures Implementation Guide
Traffic Flow Measures

Traffic flow performance measures encompass the following:

Travel Time – Facility
Travel Time – Trip
Speed
Recurring Delay
Extent of Congestion – Spatial
Extent of Congestion – Temporal
Throughput – Person
Throughput – Vehicle
Travel Time - Reliability

First and foremost, the implementation guide for traffic flow measures addresses the issues related to the collection of quality travel time and volume data. Such data is the basis upon which calculations of all traffic flow measures are contingent. Emerging technologies aim to not only replace traditional inductive loop sensor mechanisms, but to directly measure and continuously monitor travel time using vehicle probe methods rather than imputing travel time from spot speed measures. Guidance for the implementation of effective traffic flow data collection is addressed in four areas:

Establish Traffic Data Specifications

Traffic flow data will support numerous measures and applications. Understanding the data requirements of various applications and fundamental accuracy relationships related to sample sizes is necessary in planning an effective data collection system.

Select Appropriate Technology and Methods

Not only are technologies proliferating to procure speed, travel time, and volume data, but new business models are emerging that provide data without the need to invest in sensors and other associated infrastructure. The new business models as well as the new sensor technologies promise to reduce cost, minimize maintenance, and minimize intrusion into the roadway while providing timely and accurate data. As a result of the growing options to procure data, organizations are faced with a matrix of choices between old and new technologies and methods, each with differing accuracy, quality control issues, and cost implications. Assistance navigating this matrix is the primary focus of this section.

Plan for Quality Control and System Maintenance

One of the themes that emerged from the pilot test results of the National NCHRP project was the need to develop a quality control plan for the data collection process, regardless of the technology. The plan covers various aspects of data quality such as preventative maintenance, sensor calibration, data error checking, and accuracy validation.

Data Processing and Archiving Considerations

Any data collection system requires basic information technology (IT) resources such as data logging, archiving, backup, recovery, and querying tools in order to preserve the data for applications such as planning and design. This section address IT resource requirements for consideration in planning and design of data collection.

These four areas provide the basis from which to collect quality data for use in developing the various traffic flow performance measures. Following these sections, guidelines and issues specific to individual traffic flow measures are provided. Within each section additional resources helpful to the implementation may also be cited.

Establish Traffic Data Specifications

Transportation agencies are being driven to consider new methods and technologies of traffic data collection in order to reduce costs while simultaneously expanding geographic coverage. Rather than application-specific data collection, new systems can provide comprehensive traffic monitoring to support both new and legacy applications. To enable such an approach, the most stringent accuracy and timeliness data specifications govern the overall data collection system design.

Table A1 provides a framework to characterize the accuracy specifications for various applications of the NTOC performance measures. This table depicts an accuracy range for each measure in four different classes of applications: Traffic Engineering, Transportation Planning, and operations applications of Traffic Management and Traveler Information. The acceptable accuracy ranges resulted from collaboration with transportation professionals from State DOTs, MPOs, cities, academia and industry during the NCHRP study. If the error in the performance measure is greater than that specified in the range, the application will be adversely affected. For example, 20% error is often cited as the maximum allowed error in travel time estimates for traveler information applications such as travel times displayed on changeable message signs. If the error in estimated travel time exceeds 20%, the public will quickly lose confidence in the information source, undermining the support and utility of the system. If the error in the performance measure is less than the specified range, it is still useful for the application, but the application does not benefit appreciably from the increased accuracy.

[Note that Transportation Planning encompasses any type of planning or long-range monitoring activity. The year to year fluctuation in corridor travel times falls into this category. The grayed sections imply that the performance measure may not be applicable to the intended application.]

TABLE A1 Performance Measure Accuracy Requirements for Various Applications

<table>
<tr><th rowspan="3">Performance Measure</th><th colspan="4">Types of Applications</th></tr>
<tr><th rowspan="2">Traffic Engineering</th><th rowspan="2">Transportation Planning</th><th colspan="2">Operations</th></tr>
<tr><th>Traffic Management</th><th>Traveler Information</th></tr>
<tr><td>Customer Satisfaction</td><td rowspan="2">5% - 10%</td><td rowspan="2">5% - 20%</td><td></td><td rowspan="4"></td></tr>
<tr><td>Incident Duration</td><td>5% - 10%</td></tr>
<tr><td>Throughput - Vehicle</td><td>1% - 5%</td><td>2% - 10%</td><td>5% - 10%</td></tr>
<tr><td>Throughput - Person</td><td>2% - 5%</td><td>5% - 10%</td><td>5% - 15%</td></tr>
<tr><td>Speed</td><td rowspan="3">1% - 5%</td><td rowspan="3">2% - 10%</td><td rowspan="3">5% - 10%</td><td rowspan="3">5% - 20%</td></tr>
<tr><td>Travel Time - Facility</td></tr>
<tr><td>Travel Time - Trip</td></tr>
<tr><td>Travel Time - Reliability</td><td rowspan="3">5% - 10%</td><td rowspan="3">5% - 15%</td><td rowspan="3">5% - 10%</td><td rowspan="3">10% - 20%</td></tr>
<tr><td>Recurring & Non-Recurring Delay</td></tr>
<tr><td>Extent of Congestion Spatial & Temporal</td></tr>
</table>

Traffic data quality is fundamentally dependent on two items. The first is the fidelity of the sensor, method, or process used in the detection and collection of traffic data. The second factor is the number of data samples or measurements used to estimate average flow conditions. The variability of traffic flow governs how accurately sample data reflects actual flow conditions. Assuming that the detection error is negligible, the accuracy of the flow data is dependent only on the variability of traffic flow (such as the standard deviation of speed, travel time, or volume) and the number of samples taken. Sample size considerations are critical whenever periodic data sampling is performed in lieu of deploying a system that continuously measures and logs traffic data. However, knowledge of the standard deviation of traffic flow parameters of varying conditions also provides valuable insight from which to evaluate the accuracy claims of more complex methods and technologies.

Figure A1 reflects the results of an analysis conducted during the NCHRP project depicting the underlying variability of freeway traffic speed for a specific facility. The objective of the analysis was to characterize the sample standard deviation of speed and volume under varying throughput conditions. The major finding of the analysis was that the standard deviation of these parameters varied significantly with vehicle throughput. As shown in Figure A1, at flows between 0 to 500 vehicles per hour per lane (vphpl) the standard deviation of speed is relatively high. This high variability results from differences in individual driver control characteristics during extremely light traffic. In the middle flow regime, between 500 and 1200 vphpl, variability is minimized as traffic tends to self regulate speed but is not subject to congestion. The standard deviation in speed again increases above 1200 vphpl where traffic flow becomes subject to congestion. Previously literature suggested a standard deviation of 5 mph to be adequate for all roadway types and AADT ranges. The analysis revealed a characteristic patterns in standard deviation as a function of traffic volume (vphpl) on arterials and freeways, and for both speed and volume measurements. Appendix D to the full NCRHP study report contains a full account of the analysis.

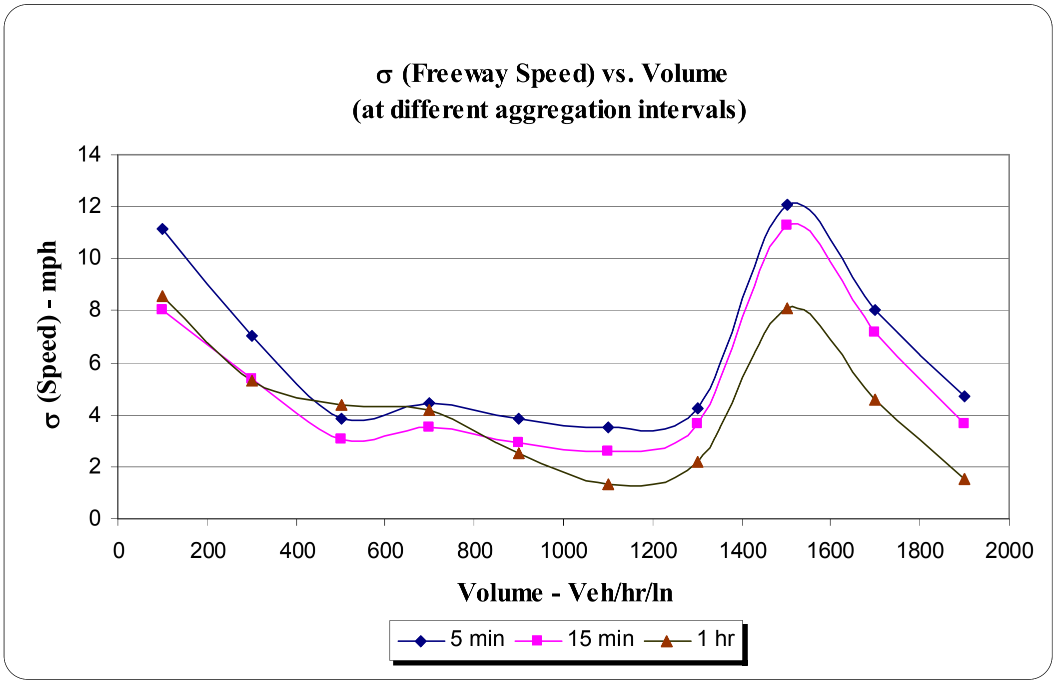

Figure A1. Standard Deviation of Freeway Speeds as a Function of Volume. Analysis depicts results for 5 minute, 15 minute, and 1 hour volume aggregation summary levels.

Knowledge of the standard deviation of traffic, as depicted in Table A1, allows for the direct computation of minimum sample sizes to estimate traffic flow parameters of specified accuracy and within known confidence limits. The results of the analysis were compiled into four tables below. The tables reflect the minimum sample size needed at various flow levels to estimate speed and volume for freeways and arterials for common confidence levels and accuracy specifications. Note that on the volume tables, the coefficient of variation is specified rather than a standard deviation.

TABLE A2 Minimum Sample Sizes for Determining Arterial Speed

Volume (veh/hr/ln)	Std. Dev. (mph)	**90% confidence level** Error Tolerance			**95% confidence level** Error Tolerance		
		± 2 mph	± 3 mph	± 4 mph	± 2 mph	± 3 mph	± 4 mph
0 - 200	14	134	60	34	189	84	48
200 - 400	7	34	15	9	48	21	12
400 - 600	7	34	15	9	48	21	12
600 - 800	7	34	15	9	48	21	12
800 - 1000	7	34	15	9	48	21	12
1000 - 1200	7	34	15	9	48	21	12
1200 - 1400	13	116	52	29	163	73	41
1400 - 1600	13	116	52	29	163	73	41
1600 - 1800	14	134	60	34	189	84	48

TABLE A3 Minimum Sample Sizes for Determining Freeway Speed

Volume (veh/hr/ln)	Std. Dev. (mph)	**90% confidence level** Error Tolerance			**95% confidence level** Error Tolerance		
		± 2 mph	± 3 mph	± 4 mph	± 2 mph	± 3 mph	± 4 mph
0 - 200	11	83	37	21	117	52	30
200 - 400	8	44	20	11	62	28	16
400 - 600	5	18	8	5	25	11	7
600 - 800	5	18	8	5	25	11	7
800 - 1000	5	18	8	5	25	11	7
1000 - 1200	5	18	8	5	25	11	7
1200 - 1400	5	18	8	5	25	11	7
1400 - 1600	9	56	25	14	78	35	20
1600 - 1800	9	56	25	14	78	35	20
1800 - 2000	8	44	20	11	62	28	16

TABLE A4 Minimum Sample Sizes for Determining Arterial Volume

Volume (veh/hr/ln)	Coefficient of Variation	**90% confidence level** Error Tolerance			**95% confidence level** Error Tolerance		
		5%	10%	20%	5%	10%	20%
0 - 200	1.00	1089	273	69	1537	385	97
200 - 400	0.26	74	19	5	104	26	7
400 - 600	0.18	36	9	3	50	13	4
600 - 800	0.14	22	6	2	31	8	2
800 - 1000	0.12	16	4	1	23	6	2
1000 - 1200	0.10	11	3	1	16	4	1
1200 - 1400	0.11	14	4	1	19	5	2
1400 - 1600	0.07	6	2	1	8	2	1
1600 - 1800	0.06	4	1	1	6	2	1

TABLE A5 Minimum Sample Sizes for Determining Freeway Volume

Volume (veh/hr/ln)	Coefficient of Variation	**90% confidence level** Error Tolerance			**95% confidence level** Error Tolerance		
		5%	10%	20%	5%	10%	20%
0 - 200	0.45	221	56	14	312	78	20
200 - 400	0.30	99	25	7	139	35	9
400 - 600	0.22	53	14	4	75	19	5
600 - 800	0.15	25	7	2	35	9	3
800 - 1000	0.19	40	10	3	56	14	4
1000 - 1200	0.12	16	4	1	23	6	2
1200 - 1400	0.12	16	4	1	23	6	2
1400 - 1600	0.12	16	4	1	23	6	2
1600 - 1800	0.11	14	4	1	19	5	2
1800 - 2000	0.09	9	3	1	13	4	1
2000 - 2200	0.09	9	3	1	13	4	1
2200 - 2400	0.07	6	2	1	8	2	1
2400 - 2600	0.07	6	2	1	8	2	1

General Guidelines for Establishing Traffic Data Specifications

- Identify all intended applications that will make use of traffic flow data
- Characterize the accuracy and timeliness data specifications required for each application.
  - Use Table A1 as a general guide for accuracy requirements.
  - Consult with application owners for acceptable data quality requirements.
  - Consider impact on application as accuracy degrades
  - Determine latency requirements – does the application require:
    - Data archive
    - Data within an hour
    - Data within five minutes
    - Real-time Data
  - Consider impact on application as latency degrades
- Develop a list of the most stringent data requirements from the set of supported applications
- Estimate minimum sample-sizes for speed, volume, and travel-time (assuming space-mean speed equivalent) based on Tables A2 through A5
- Document any uncommon or peculiar application requirements that may have impact on the data collection system.

Additional Resources:

Select Appropriate Methods and Technology

Traffic flow data collection can be broken into three primary classes. Table A6 lists these classes of data collection technologies and their associated characteristics. These classes include *fixed sensors*, *floating car methods*, and *vehicle probe technologies*.

A fixed sensor includes any type of electronic sensing device installed in a specified location to collect speed, volume and/or occupancy data. Although a variety of technologies are available, inductive loops are the oldest and most prevalent. Single loop configurations directly measure volume and occupancy. Speed is inferred from single loop configurations by assuming an average vehicle length. Speed estimates from single loops are accurate to 5 or 10 mph in free-flow steady speed conditions. Such accuracies are indicative of any technology whose base measurements are volume counts and occupancy. Inaccuracies arise not from the electronic sensing equipment, but from the uncertainties inherent in converting volume and occupancy into speed data. Dual loop arrangements measure speed directly, achieving accuracies of 1 to 2 mph.

Contrast of Data Collection Methods

Method	Sub-Method	Base Measurements	Typcial Sampling Paragmeters	Freeway Use	Arterial Use	Performance Measures Supported: Speed	Travel Timie	TT - Reliability	Recurring Delay	Non-Recurring Delay	Extent of Congestion	Throughput	Costs	Primary Deployment Issues
Fixed Sensor	Single Loops	Volume & Occupancy	5 Minute	✓		X	X	X	X	X	X	X	$7500 to $20000 per site depending on availability of existing structures	Costs, Sensor Density, Maintenance, Quality Control
	Dual Loops	Volume, Occupancy, & Speed	5 Minute	✓		X	X	X	X	X	X	X		
	Cross-Fire Radar	Volume, Occupancy, & possibly Speed	5 Minute	✓		X	X	X	X	X	X	X		
	Video Cameras	Volume, Occupancy & Possibly Speed	5 Minute	✓		X	X	X	X	X	X	X		
Floating Car	GPS Instrumented	Travel Time	8-10 Runs per year, per corridor	✓	✓	X	X		X		X		Budget $300 to $500 per mile	Minimum Sampling Parameters
Vehicle Probe	Toll-Tag Transponder	Travel Time	1-5 minute	✓	✓	X	X	X	X	X	X		$15000 per site per direction (exclusive of structures)	Density of Toll-Tags and Cost of Equipment
	Fleet GPS Data		5 - 15 minutes	✓	?	X	X	X	X	X	X		$500 - $1000 / mile / year	Data Latency and Sampling Density
	Cell Phone Probes		1-10 minutes	✓	?	X	X	X	X	X	X		$500 - $1000 / mile / year	Accuracy, Privacy, and Business Model Sustainability

TABLE A6 Traffic Flow Data Collection Methods and Technologies

Data from fixed sensor networks share common attributes regardless of the sensor technology. Because speed is measured at a particular point in the roadway, fixed sensors are effective only in places where spot speed measurements are a good indicator of overall traffic flow. This assumption is valid in most freeway environments. The progression of traffic flow on arterials, however, is dependent primarily on signals and other traffic control devices at intersections. Spot speed measurements, no matter how accurate, provide insufficient information to assess travel time or delay on arterials. As such, fixed sensors networks are not recommended for assessing space-mean speed or travel time on arterial networks. Note, however, that fixed sensors are effective and required to obtain volume measures on such roadways.

Installation costs for a fixed sensor network are estimated between $7,500 and $20,000 per site. The range in cost is due primarily to the extent of which existing infrastructure can be reused. Reuse of existing poles and sign trusses, and existing power and communications feeds reduce cost. Methods and technology that allow for reuse of existing infrastructure, though more expensive, may prove the more cost effective overall.

During the pilot test, sensor spacing ranged from 1/3 mile up to 3 miles on some networks, with 1/2 mile and 1/3 mile being the most prevalent. The relationship between sensor density and the accuracy of the estimated travel time from the sensors has been the subject of previous research efforts, as well as the relationship between travel time accuracy and the type of algorithm used to infer travel time from spot speed measurements. The results from the pilot test indicated that most organizations use a relatively simple algorithm to estimate travel time from spot speed measures, and that the primary benefit of dense sensor spacing is immunity from sensor outages.

The foremost challenge in deploying fixed sensor networks is an effective quality control program to address maintenance, calibration, and error detection – as will be discussed later.

Floating car methods use dedicated vehicles and drivers to sample travel time in the traffic stream. The dates and times of sampling are chosen to be representative of average conditions for the period of interest. Sample sizes are determined to ensure that the results are statistically representative of the population. Floating car methods are not adaptable to real-time data, nor is it recommended for travel time reliability due to the amount of data required.

Advancements in technology over the past decade have enabled additional vehicle probe methods as alternatives to fixed sensor networks. These alternatives fall generally into three categories. *Fleet GPS Data* refers to the reuse of automated vehicle location data derived from fleets whose vehicles periodically report position and trajectory from onboard Global Positioning System equipment. *Cell Phone Probes* estimate traffic flow based on geolocation data harvested from the cellular phone infrastructure. *Toll-Tag Transponders* estimate average travel time based on a sample of vehicles equipped with toll-tag transponders. Implementation of automated toll-tag methods is restricted to toll facilities served by such technology, or roadways in the immediate vicinity of such toll facilities.

The data in Table A7 for *Fleet GPS Data* and *Cell Phone Probe*s are based on recent projects at the Wisconsin DOT, I-95 Corridor Coalition and the Georgia DOT. Although still considered unproven, such technologies are theoretically capable of monitoring traffic flow on large geographic extents at a much reduced cost and without the need to deploy additional sensing equipment in the right-of-way. Early results indicate that such methods are viable alternatives for freeway monitoring. Effectiveness on arterials has yet to be verified with field data. Such new methods present not only technology risks, but also introduce risks associated with new procurement methods, outsourcing, and data rights and data licensing issues.

Floating car and vehicle probe methods provide direct measures of travel time. As such, these methods are applicable to arterials as well as to freeway environments. However, fixed sensors are still needed on arterial to provide volume data.

General Guidelines for Selecting Appropriate Methods and Technology

- Determine methods and technologies available to meet data specifications based on attributes in Table A2.
- Consider legacy data collection systems
  - Is the legacy system capable of being upgraded to meet latency and/or accuracy requirements?
  - Can the legacy system be extended to provide required geographic coverage?
  - Determine costs and technical issues involved in upgrading or expanding coverage
- Consider ownership versus outsourcing options
  - Outsourced data collection:
    - Relieves the burden of system upkeep and maintenance
    - Data ownership is negotiable, data rights and data licensing are key issues
  - Agency owned system

        - Maintenance and calibration are the burden of the agency
        - Data ownership is inherent
- Consider fixed sensor versus vehicle probe concepts
    - Fixed sensors attributes
        - Requires access to and deployment on right-of-way
        - Travel time is inferred from speed measurements
        - Provides volume measurements
        - Speed data should not be used to estimate travel time on arterials
    - Vehicle probe attributes
        - Travel time is sampled directly
        - Volume information is unavailable or of minimal accuracy
        - May not require roadside deployed equipment
- Analyze risks associated with various approaches:
    - Technology risks associated with new or unproven equipment or methods
    - Risk associated with a new company or business model
    - Business relationship risks associated with dependence on multiple entities, most notable in Cell Phone Probes and Fleet GPS Data

Additional Resources:

To educate the transportation community on the latest sensor technologies, the Federal Highway Administration (FHWA) recently published a revised and restructured edition of the *Traffic Detector Handbook*. It is a two-volume, comprehensive reference on sensors for traffic management on surface streets, arterials, and freeways and reflects the evolution, maturation, and state of the practice of sensor hardware and installations. Volume one can be accessed online at http://www.tfhrc.gov/its/pubs/06108/.

Turner, Shawn M. et al, *Travel Time Data Collection Handbook*, FHWA,1998
Last updated in 1998, this reference provides guidance to transportation professionals and practitioners for the collection, reduction, and presentation of travel time data. It is available online at http://www.fhwa.dot.gov/ohim/timedata.htm.

An example of Data Rights and Data Licensing suitable for out-sourced data collection is available from the recent I-95 Corridor Coalition Vehicle Probe Request for Proposals (RFP), under section 6.0 starting on page 29. The RFP is available at http://www.catt.umd.edu/research/i95_vehicle_probe.html

Data and information for new and emerging technologies is quickly outdated. If considering such technologies, research the latest deployments for recent information and lessons learned.

Quality Control Plan

Regardless of the technology or method of procurement, a quality control plan is essential to long term viability of the data collection system. Although the implementation of the quality control plan will vary with the selection of type of data collection system, the basic principles remain the same. The quality control plan should address the methods, time table, required resources, and actions necessary to maintain minimum accuracy and timeliness specifications. Quality control plans for agency owned systems will emphasize maintenance, calibration, and error checking whereas outsourced data collection will emphasize validation procedures and contractual responsibilities.

General Guidelines for Quality Control Plan

- Data Validation
  Validation encompasses the methods to ensure the data delivered from the system or contractor meets the specifications required for the application. Validation should be independent of the data collection process, objectively performed, and fairly assessed. The quality control plan should address:
  - Time and frequency of validation efforts
  - Data items and specifications to be validation
  - Methods, standards, and procedures used in the validation process
  - Qualifications of personnel, if any
  - Data source/s used for comparison (Also referred to as ground truth)
  - Acceptable ranges for various parameters and specifications
  - Implications if data fails validation
    - Contractual consequences
    - Impact on applications
- Maintenance and Calibration
  Maintenance and calibration is primarily applicable to fixed sensor networks owned and maintained by transportation agencies. The plan should address:
  - Organization and/or people responsible for system maintenance & calibration
  - Frequency and timing of preventative maintenance and calibration
  - Preventative maintenance and calibration procedures
  - Resource requirements in terms of manpower, equipment, and costs
- Error Checking
  Error checking refers to examining the data for reasonableness. It is applicable to both agency owned and out-sourced systems. The quality control plan should include:
  - Valid ranges for each data item
  - Any characteristic data patterns that would indicate sensor or system failure
  - Actions to take when or if errors are detected
  - Acceptable or expected error rates
- Considerations for agency owned systems considerations
  - Budget and plan adequately for maintenance, calibration and validation activities. In the absence of any supporting data, estimate and budget ten percent of procurement cost for these activities on a yearly basis.
  - Assess manpower and equipment resources
    - Identify responsible offices for various activities
    - Consider outsourcing all or part of the maintenance and calibration
  - Determine lifecycle cost inclusive of quality control activities of the system
- Consideration for outsourced data collection (contractual arrangements)
  - Determine consequences for poor data quality
    - Consider making payment contingent on validated data quality
    - Consider termination or renegotiation if data is of insufficient quality

        - Consider terms and conditions of corrective action
    - Include validation methods, procedures and standards in the contract (if possible.)
    - Determine how disagreements will be arbitrated

Additional Resources:

Error checking:
Turner, Shawn M., *Guidelines for Developing ITS Data Archiving Systems*, Texas Transportation Institute, Report 2127-3, 2001 available online at http://tti.tamu.edu/documents/2127-3.pdf Chapter 3 contains a summary of quality control for archived data that is applicable to quality control plans.

An example of contractual terms and conditions related to data quality is available from the recent I-95 Corridor Coalition Vehicle Probe Request for Proposals (RFP). Invoicing for services, described in section G on page 35, is contingent upon validation of data accuracy and latency as specified in section C, subsection 3.1 starting on page 19. The RFP is available at http://www.catt.umd.edu/research/i95_vehicle_probe.html

Data Processing and Archiving Considerations

A system that plans for the long term storage, indexing, querying, backup, retrieval, and distribution of data will minimize system overhead and maximize the investment in the data collection system over the life of the system. A robust processing and archiving architecture will minimize maintenance burdens and maximize the reuse of the data for other applications requiring archive data. This includes not only planning and design purposes, but also forensics, data-mining, and research. This section address IT resource requirements for consideration in planning and design of data collection.

General Guidelines for Data Processing and Archiving Considerations

- Storage requirements
    - Determine yearly storage requirements
    - How long will the data be stored? (most likely the in perpetuity)
- Archiving considerations
    - What mechanism will be used to access archived data? (Database, data files, spreadsheets)
    - At what resolution will the data be stored? (Spatial and Temporal)
    - Are their restrictions on the access and distribution of data? This is critical if any data is licensed or purchased from a vendor.
    - How will the archive be backed-up to insure availability for years to come?
- Indexing considerations
    - What are the most likely ways to query the data
        - Time, Space, Facility Names, Linear Referencing System
- Create comprehensive system and data documentation
    - Data structures, schemas, file formats, logging procedures, quality procedures and metrics.

- Estimate costs
    - Equipment
    - Manpower resources
    - Software

Additional Resources for the Procurement of Traffic Flow Data
The procurement of traffic data collection systems can be a complex and present multiple risks. Depending on the amount of interval resources and level of expertise within the organization, consider the use of professional resources such as consultants or university research centers for the following tasks:

- Development of detailed specifications for data collection
- Development of custom quality control procedures
- Independent data quality validation
- System design and procurement

NCHRP 560, Guide to Contracting ITS Projects provides a structured process to determine what type of procurement is suitable (and how to effectively utilize external resources) depending on the complexity of the procurement and availability internal resources expertise.

Guidance Specific to Performance Measures

Travel Time – Facility

Travel time is the primary and dominant traffic flow performance measure in use to reflect user experience. Its ease of application and inherent understanding by the traveling public provides the greatest benefit for application and reporting purposes. Travel time serves as the basis for delay and reliability measures as well as effectively and easily communicates system status to the public using simple reporting mechanisms.

- Travel time is foremost indicator of the quality of traffic flow currently in use.
- Travel time is a prime indicator of congestion. The primary application of the travel time measure for half of the pilot test submittals was congestion tracking.
    - Travel time is typically summarized in 15 minute intervals during peak periods of traffic, such as AM and PM rush hours.
    - Peak periods differ for various regions and networks. Peak periods should be assessed individually for each region.
- Direct measures of travel time are effective on arterial networks. Spot speed measurements are not an effective to estimate travel time on arterials.

Travel Time – Trip

This measure was included in the NTOC set to reflect overall, multi-modal trip efficiency. Technology is not readily available to monitor end-to-end trip travel times on anything except special study purposes.

Speed

Spot speed measurements are useful in so far as they reflect space-mean speed of the traffic flow, and thus a reflect travel time on the facility.

- The primary application of speed data from a fixed-sensor network is to color code a speed map for a public traveler information web site.
- Consider reuse of speed data from continuous count stations for operations purposes.

Throughput – Vehicle

Methods and technology to collect volume counts for vehicles are well established. Although new technologies are entering the market for volume counts, these offerings represent only are only additional sensor options, not new methods. Throughput metrics, particularly in the transportation planning, are useful to support long range planning, travel demand modeling, HPMS and other applications.

- Volume data is essential for the computation of other operations performance measures.
- Vehicle throughput as an operational performance measure is an effective indicator of facility utilization. Although not reflective of performance from a user's point of view, capacity utilization provides an essential management perspective for decision making and resource management.

Throughput - Person

Person throughput measures for roadways are accomplished by factoring vehicle volume measures with occupancy factors.

- Person throughput measures require periodic, location specific occupancy surveys to obtain customized occupancy factors to apply to traffic volume counts.
- Person throughput measures are effective to assess performance of HOV lanes.

Extent of Congestion Measures – Spatial and Temporal

It is unclear if the NTOC defined Extent of Congestion measures effectively capture and convey congestion information in time and space. Continued monitoring of research in this area as well as continued experimentation alternative extent of congestion measures is recommended.

- Extent of Congestion measures as defined by NTOC do not have widespread use. During pilot testing no organization periodically reported the measure, only experimental calculations were submitted.
- Comparable measures that attempt to capture the geographic and time extents of congestion are in use. Such measures use various speed thresholds and/or methods of calculation peculiar to the organization. The most commonly used metric is the percent of time speed falls below 35 MPH. This threshold is roughly equivalent to twice the NTOC travel time threshold of 30% increase in travel time.
- Extent of Congestion Measures are contingent upon determining an 'Unconstrained Travel Time'. Unconstrained travel time for freeways is based on off-peak traffic characteristics, while for arterials is must be based more on professional judgment since delay is a factor primarily of signal timing.

The results of the pilot tests for extent of the extent of congestion measures revealed that the current NTOC definition may not provide the utility needed to quantify spatial and temporal extents of congestion. However, no equivalent measure has proliferated. Each entity appears to be experimenting with various combinations of travel time, speed, and throughput to define an effective congestion measure. Of particular note is the Washington DOT's capacity utilization graphics, referred to as 'Lost Productivity.'

Travel Time – Reliability

The implementation of the reliability measures has quickly proliferated and has been consistently implemented. As a consequence, reliability measures are expected to grow in use and importance in determining funding and policy. Reliability reflects the users experience of having to plan for the consequences of congestion.

- The explicit nature of the definition of travel time reliability provides for consistent implementation across various organizations.
- Metrics for reporting reliability in the pilot data included 95^{th} percentile travel time, Planning Time Index (PTI), and Buffer Time Index (BTI).

Recurring Delay

- Delay is frequently used to assess a monetary value (or penalty) for the adverse effects of congestion.
- Varying definitions of unconstrained travel time are in use. WSDOT uses a travel time equivalent of maximum throughput, which is approximately 51 MPH. Colorado uses off-peak travel times which creates problems for arterial networks. WFRC intends to use posted speed, or equivalent based on functional class of roadway.
- Determine a consistent method for determination of unconstrained travel time, preferably in agreement with the NTOC defined measures. (See definitions)
- Metrics and aggregation level of reporting vary, though this does not appear to present a problem due to the cumulative nature of the delay metric.

Delay – Nonrecurring : No examples of non-recurring delay were submitted as part of the pilot tests, although some data submitted for incident duration could be construed as such. Although a clear concept, direct measures of nonrecurring delay such have not emerged as effective performance measures. The project concludes that non-recurring delay should be omitted from the list of core operations performance measures.