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Measuring Congestion for Strategic Highway Investment for Tomorrow (SHIFT) Implementation (PL-32)

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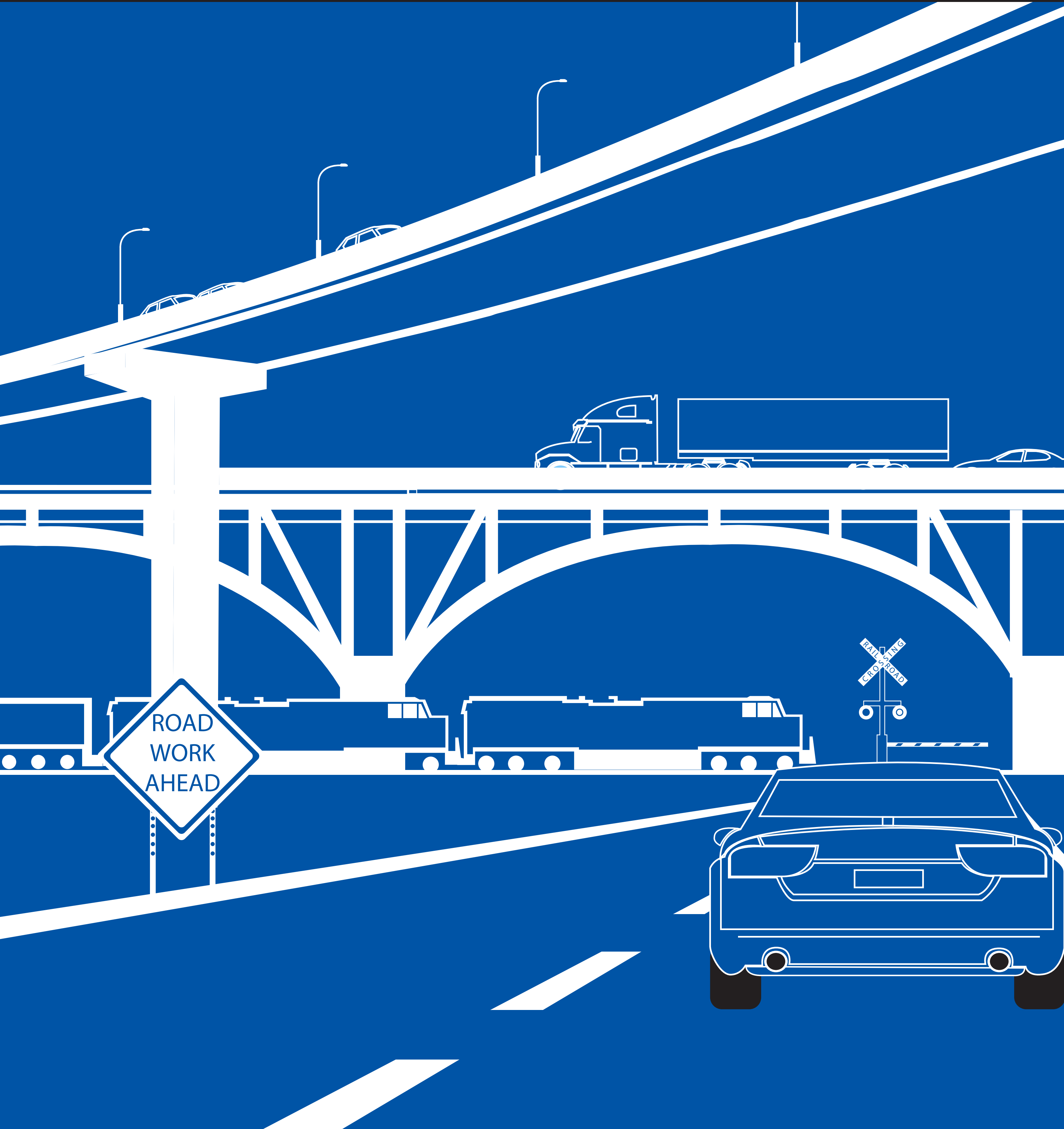

Kentucky Transportation Center
College of Engineering, University of Kentucky, Lexington, Kentucky

in cooperation with
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Commonwealth of Kentucky

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Kentucky Transportation Center • University of Kentucky
176 Raymond Building • Lexington, KY 40506 • 859.257.6898 • www.ktc.uky.edu

University of
Kentucky

Research Report
KTC-19-20/PL32-1F

Measuring Congestion for Strategic Highway Investment for Tomorrow (SHIFT) Implementation (PL-32)

Mei Chen
Department of Civil Engineering

Xu Zhang
Kentucky Transportation Center

Fahmida Rahman
Department of Civil Engineering

Jacob Brashear
Department of Civil Engineering

and

Reginald Souleyrette
Department of Civil Engineering

Kentucky Transportation Center
College of Engineering
University of Kentucky
Lexington, Kentucky

In Cooperation With
Kentucky Transportation Cabinet
Commonwealth of Kentucky

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Executive Summary

The Kentucky Transportation Cabinet (KYTC) has moved toward a data-driven decision-making process, the Strategic Highway Investment Formula for Tomorrow (SHIFT), to allocate funds for highway improvement projects. SHIFT requires that candidate projects be scored on five critical metrics: safety, asset management, congestion, economic growth, and benefit/cost analysis.

The measure of congestion used in SHIFT 2018 was a combination of volume-to-service flow ratio (VSF) and design hourly volume (DHV). VSF is a traditional performance measure developed based on limited data, primarily for sketch planning purposes. However, it does not accurately reflect the dynamics of traffic congestion of many facilities.

This report presents a framework for integrating third-party speed data (acquired from HERE Technologies) into traditional congestion performance measures for use in SHIFT 2020. The speed data came from aggregated GPS-based vehicle locations at various temporal and spatial resolutions collected from 2015 to 2017. Data assessments undertaken by the research team found these data offer adequate coverages for monitoring congestion performance on most highways in Kentucky, except for some rural low-volume roads.

An automated process was developed to conflate HERE's proprietary network, to which the speed data are attached, and KYTC's Highway Information System (HIS) network. Spatial integration lets the Cabinet link speed data to a state-maintained inventory database, enabling additional applications beyond those addressed in this study, such as the calibration and validation of travel demand models.

The research team evaluated several performance measures that could potentially be applied in Kentucky. Based on this assessment, Vehicle Hours of Delay (VHD) is recommended as the best measure for quantifying congestion on a highway section. Two other measures – Vehicle Hours of Delay Per Mile (VHDPM) and Average Hours of Delay (AHD) – may be considered alongside VHD when performing network screening to identify bottlenecks. The research team, based on feedback from Cabinet work groups, developed a procedure for estimating VHD on highway improvement projects. A white paper in Appendix A documents this procedure.

1. Introduction

1.1 Background

The Kentucky Transportation Cabinet (KYTC) recently adopted the Strategic Highway Investment Formula for Tomorrow (SHIFT) model for prioritizing transportation projects. SHIFT is a data-driven process for project identification and selection. One criterion used to score projects is congestion, which is measured using a combination of volume-to-service flow ratio (VSF) and design hourly volume (DHV). VSF is a measure developed based on limited data primarily for sketch planning purposes. A recent study found VSF does not accurately reflect traffic congestion dynamics on many of Kentucky's facilities. For some roads, measured speeds and estimated VSF often give very different levels of service.

KYTC has acquired speed data generated by probe vehicles at the link level for 2015 through 2017 for all Kentucky highways. The data contain link speeds daily in 5-minute epochs, where available. Such data have proven valuable for generating travel time reliability performance measures, identifying bottlenecks, enhancing performance measures for project selection and incident management, and calibrating and validating travel models.

1.2 Objectives

This study develops a framework to integrate speed data into traditional congestion performance measures. Kentucky Transportation Center (KTC) researchers evaluated available data and the current methodology used to derive congestion performance measures. They also investigated ways to enhance congestion measures using speed data acquired as part of this study. Researchers sought to create measures that reflect the operating condition throughout the analysis period and offer a uniform scale that allows direct comparison of congestion levels among different facility types.

The study's major components are listed below. The scope was established based on a discussion during the SHIFT Congestion Workgroup meeting on December 15, 2017.

- Data acquisition and processing
    - Request for Proposals (RFP) and vendor/product selection with KYTC input.
    - Assess data temporal and spatial accuracy as well as coverage and resolution.
    - Network conflation.
    - Aggregation to annual statistics.
- Develop an enhanced congestion performance measure
    - Review the state-of-the-practice on congestion performance measures at state Department of Transportation (DOTs), with a focus on measures incorporating travel time data.
    - Investigate how to set the reference speed for travel time-based congestion measures, such as the travel time index (TTI). Ensure that the congestion measure adopts the same scale across all facility types.
    - Investigate the applicability of calculating a congestion measure using speed data for different sample pools based on their coverages. Determine how much data are needed to produce a credible measure of congestion.

    - Investigate ways to measure congestion on ramps and provide a list of needed data items. This is to address the lack of data for ramps, even though interchanges are often congestion hotspots.
    - Evaluate the consistency among potential performance measures, including VSF, TTI, density, percent free-flow travel time, and level of service.
- Develop a procedure to incorporate speed data into congestion performance measures. Include a method to address situations beyond the applicability of speed data.
- Develop a tool for calculating the measure of congestion annually or biennially.

The results documented in this report will facilitate KYTC's efforts to evaluate congestion on all roads as well as on proposed projects submitted for funding consideration.

2. Data Acquisition and Analysis

2.1 Data Sources

Major data sources for this study included HERE Technologies, a third-party data provider which supplied historical speed data, and KYTC's Highway Information System (HIS), from which data on roadway geometrics, condition, and usage were obtained.

2.1.1 Speed Data

Archived speed data from 2015 to 2017 for all Kentucky roadways were acquired from HERE Technologies. Speeds are referenced to HERE 2017Q3 map links and are available in 5-min and 60-min epochs for each day. Speeds are available for all vehicles, cars only, and trucks only.

2.1.2 Highway Inventory Data

Traditional methodologies require a number of data items on roadway geometrics, condition, and usage. Table 1 lists required data items for capacity estimation (*1*).

Table 1 List of Data Items Required

Items	Facility Type	Freeway	Multi-lane	Rural One/Two Lane	Rural Three Lane	Signal	Stop	Urban 1/2/3 Lane
Pavement type	•							
Facility type	•	•	•	•	•	•		•
Area type	•	•				•	•	
At grade signal	•							
At grade stop	•		•	•	•			
At grade other			•	•	•			
Section length	•	•	•		•			
Through lanes	•	•	•		•	•	•	•
Median type	•		•		•			
Median width	•		•		•			
Access control	•							
Terrain type		•	•	•	•			
AADT		•	•	•	•	•	•	
K factor		•	•	•	•	•	•	
D factor		•	•	•	•	•	•	
Functional system						•	•	
Peak lanes		•	•			•	•	•
Lane width		•	•	•	•	•		•
Right shoulder width		•	•	•	•			
Left shoulder width			•		•			
Peak truck percentage		•	•	•	•	•	•	•
Daily truck percentage				•	•			
Interchanges		•						

Items	Facility Type	Freeway	Multi-lane	Rural One/Two Lane	Rural Three Lane	Signal	Stop	Urban 1/2/3 Lane
Speed limit			•		•			
Percent of passing				•	•			
Truck climbing lane				•	•			
Turning lanes						•	•	
Peak parking						•		•
Green ratio						•		

KYTC supplied KTC researchers with a copy of the HIS extract containing all required data items.

2.2 Data Quality Statistics

Similar to Planning Studies 24 and 27 (*2; 3*), the research team evaluated probe speed coverage to understand data quality, particularly temporal and spatial coverages. Quality measures are shown in Table 2. Because 1-hour interval data were used to generate performance measures for the SHIFT process, evaluation focused on speed data from all vehicles at 1-hour intervals.

Table 2 Sample Adequacy Measures

Measure	Description
TotalIntervals_Ideal	Number of 1-hour intervals in the time period of interest. For example, there are 365 days × 24 hours = 8,760 1-hour intervals in one year.
TotalIntervals_Sampled	Number of 1-hour intervals with probe data during the time period of interest.
PcntInterval_Sampled	Percentage of 1-hour intervals with probe data during the time period of interest. It is calculated as: 100*TotalIntervals_Sampled/TotalIntervals_Ideal

Based on the quality measures derived for each link, Table 3 shows the distribution of the directional-miles of Kentucky roadways with different temporal coverage ranges for 2015 to 2017. Temporal coverage of probe speeds was measured by PcntInterval_Sampled, as defined in Table 2. For example, a temporal coverage range of (1, 2) indicates probe speeds were available for 1%–2% of the 8,760 intervals. This equates to approximately 88–175 1-hour intervals. According to Table 3, in 2015 11.96% of the total directional-miles had speed data at this temporal coverage range. The percentage increased to 12.37% in 2016 and 12.61% in 2017. For 2015-2017 data, there were 168,275.3 total directional miles in the conflated network, a significant increase over the 53,157.7 miles for 2013–2014 data and 53,188.1 miles for 2011–2012 data. However, the increase in lane miles is mostly the result of the conflation process for 2015–2017 data, which used the AllRds file in HIS. This file contains significantly more roadways than the Highway Performance Monitoring System (HPMS) file used for the conflation processes on 2011–2012 and 2013–2014 data.

Table 3 shows slight improvements in data availability from 2015 to 2017. While the percentages of directional miles in higher temporal coverage ranges increased, percentages decreased for lower temporal coverage ranges.

Table 3 Sample Coverage Distribution of Link-Referenced Data

Temporal Coverage Range	2015	2016	2017
0	4.19	3.35	3.26
(0,0.012]	2.9	2.38	2.32
(0.012,0.5]	34.66	31.13	30.7
(0.5,1]	12.33	12.02	11.86
(1,2]	11.96	12.37	12.61
(2,5]	12.99	14.62	14.69
(5,10]	6.58	7.87	7.99
(10,20]	5.25	5.89	5.95
(20,50]	5.6	5.97	6.22
(50,100]	3.55	4.4	4.39

2.3 Data Adequacy Evaluation

Speed data may not be available at all segments for all time periods because they are based on passively collected location data from GPS-enabled devices. For rural low-volume roads, speed data can be sparse. As Section 2.2 shows, data availability varies significantly across facilities. Before using speed data to develop congestion performance measures, one must determine if the data available for a given segment adequately represent the speed profile observed during the analysis period.

This section describes the bootstrapping approach the research team used to determine the minimum data availability rate required to produce reliable travel time and congestion measures. *Availability rate* refers to the percentage of time periods (e.g., 5-minute or 1-hour epochs) throughout a year during which speed data are available. For example, if speed data are obtained at 5-minute epochs, there should be $12 \times 24 \times 365 = 105{,}120$ epochs in a year and – ideally – the same number of speed records. If only 4,000 speed records are available for a year, the availability rate is: $\frac{4000}{105120} = 3.8\%$. The bootstrapping approach was adopted to determine the minimum availability rate that produces a statistically representative distribution of the true speed distribution. The results from bootstrap sampling can help establish a coverage threshold for future acquisitions.

Bootstrapping uses resampling with replacement to create multiple bootstrap replications from an original dataset. The number of observations in successive bootstrap replications are equal to a predefined sample size. For example, for a dataset with 15 samples, $t = (t_1, t_2 \ldots t_{15})$, an individual replication for a predetermined 12 samples could be $t* = (t_1, t_2, t_1, t_1, t_3, t_5, t_7, t_7, t_8, t_9, t_{11}, t_{14})$. This resampling procedure is executed m times to create m replications. This sampling method is used to create replications of the original speed dataset.

After extracting speed data for each road segment during the non-holiday weekday afternoon peak (3 pm to 6 pm), the bootstrapping method was applied to the original speed datasets with varying availability rates (x%). The procedure accounts for the distribution of the sample mean ($\bar{y}$) of replicated samples to calculate the margin of error (ME) at the 95% confidence level. The minimum availability rate that yields an acceptable error (±5% in this case) was thus identified. Figure 1 presents this methodological framework.

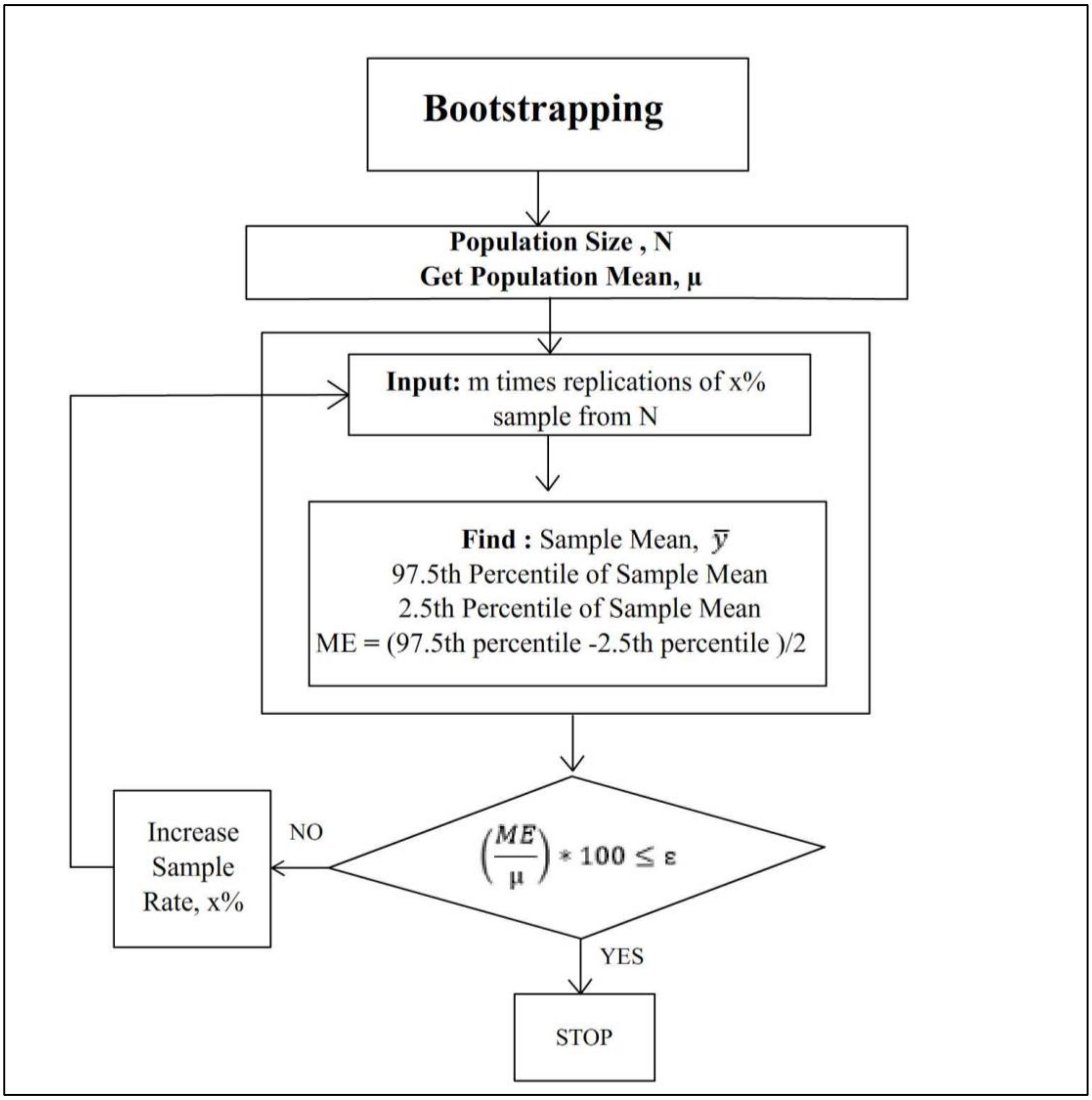


Figure 1 Methodological Framework for Minimum Availability Rate

Some studies have evaluated the application of bootstrapping to obtain accurate estimates of statistical measures. In (*4*), the authors applied bootstrapping to assess the accuracy of travel time reliability measures to avoid the requirement of a specific distribution function. The method was adopted to address the concern that the travel time distribution may not strictly follow a normal distribution (*5*-*7*). Various travel time reliability measures, including standard deviation, coefficient of variation, buffer time index (BTI), and planning time index (PTI) were evaluated. In another study, bootstrapping was used to obtain the full distribution of various parameters as well as associated confidence intervals, which were later used as a stopping rule in simulation analysis (*8*).

For this study, bootstrapping was applied to uninterrupted and interrupted facilities separately, because these facility types have distinct traffic flow characteristics. Uninterrupted facilities include freeways, rural one/two/three lane roads, urban one/two/three lane roads, and multilane roads. Interrupted facilities include signal- and stop sign-controlled facilities. The minimum availability rate results were obtained for both interrupted and uninterrupted segments.

Analyses showed that for freeways, multilane highways, and rural two-lane roads, the minimum availability rates are 8%, 5%, and 9%, respectively. Speed data for 2015-2017 show that 99.8% of the freeway miles, 90.8% of multilane highway miles, and 47.5% of the rural two-lane highway miles meet these criteria.

Bootstrapping was also applied to interrupted facilities using the data for the 3 pm–6 pm period on weekdays. These facilities tend to have less probe data coverage. After extensive analysis, it was determined that for both interrupted and uninterrupted facilities, a 10% minimum data availability should be chosen. About 3% for stop sign controlled miles and 60% of signal controlled miles meet this criterion. Table 4 lists the recommended minimum availability rates for Kentucky facilities and the summary of directional miles meet the criterion.

Table 4 Minimum Availability Rate Required

Facility Type	Minimum Availability Rate Required	Total Segments	Total Directional Miles Meeting Criterion
Uninterrupted Facilities	10%	11,082	25,842
Interrupted Facilities	10%	11,146	7778

2.4 Network Conflation

Network conflation is required to link speed data from HERE with state-maintained attributes such as functional class, geometric condition, traffic control, and volume for several applications, including performance measures, model calibration, and validation. Because of discrepancies in the referencing systems and segmentations of the datasets, conflation is a very challenging task. The geometric discrepancy between the two networks and large network size amplify the difficulty of developing an accurate and efficient conflation process. Table 5 compares the two networks.

Table 5 Comparison of AllRds and HERE Networks

Network	KYTC AllRds	HERE Streets
Referencing System	Linear Referencing with RT_Unique and Milepoints	Unique Numerical IDs
Direction Definition	Cardinal/Non-Cardinal	F/T based on latitude/longitude of endpoints
Number of Links	388,203	591,835
Directional Mileage	169,816 miles	194,661 miles

An earlier project developed a method that first converted the HERE network into a point layer. Then midpoint data were matched to the nearest HPMS links. Since only spatial distance was used, the method did not perform very well at intersections and interchanges. Nor did it perform well at locations where streets are close to one another; extensive quality assurance was needed as a result (*9*). For this study, a new intersection-based approach using a set of geometric and non-spatial attributes and fuzzy logic inference was developed. It has been proved to be robust and accurate in performing the conflation task.

Figure 2 illustrates the geometric discrepancies by overlapping the KYTC and HERE networks. AllRds is represented by solid red lines while HERE Streets is represented by blue dotted lines. While some disparities exist, such as missing links in either network and coding divided highways, most roads match well and are segmented at the same locations (i.e., intersections). This observation inspired the design of the node-based conflation process developed for this study. The basic idea of this process is to match end nodes (i.e., intersections) first and then match the links and their directions in between two nodes. Figure 3 depicts the conflation process.

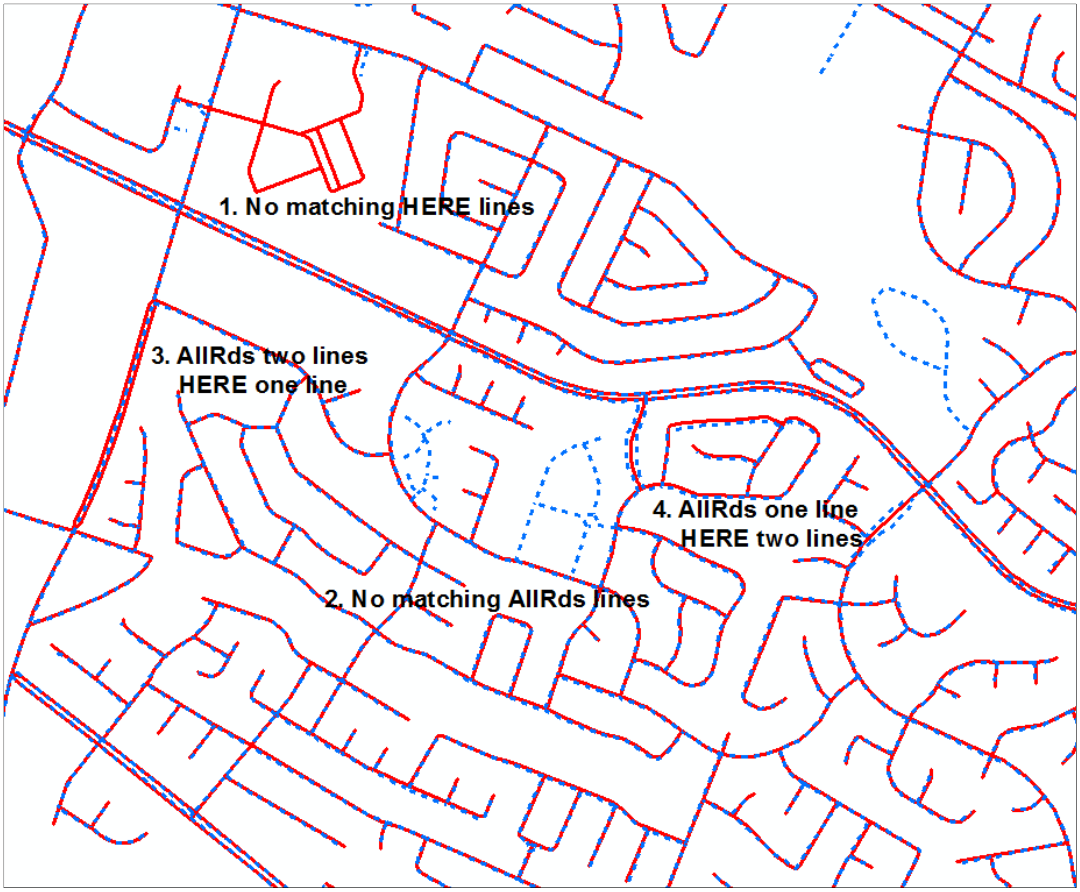


Figure 2 Geometric Discrepancies between AllRds and HERE Networks

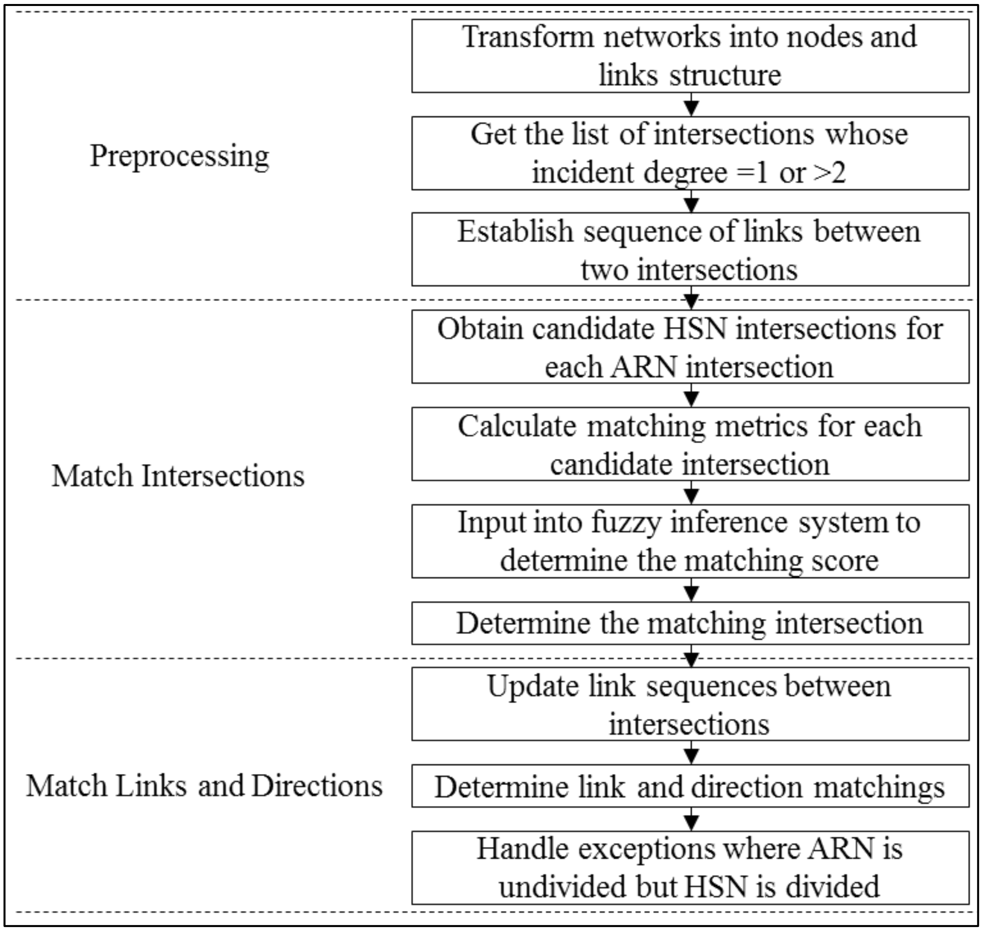


Figure 3 Overall Conflation Process

2.4.1 Preprocessing

Preprocessing transforms AllRds and HERE line features into directed graphs with a structure consisting of nodes and links. This structure is critical for establishing network connectivity and locating intersections, which are needed during subsequent steps. Preprocessing is performed in ArcGIS using several tools, including Line to Points, Add XY Coordinates, Near, and Locate Features Along Routes.

2.4.2 Matching Intersections

While the topologies of AllRds and HERE networks are very similar, their network segmentations are quite different. This prohibits directly matching current links because there is no one-to-one relationship between two networks. Since the network topologies are quite similar, the intersection locations are very similar; thus it is more likely to find a one-to-one match for intersections. Figure 4 illustrates the closeness between intersections from the two networks. AllRds intersections are represented by red nodes while the HERE intersections are denoted by blue nodes.

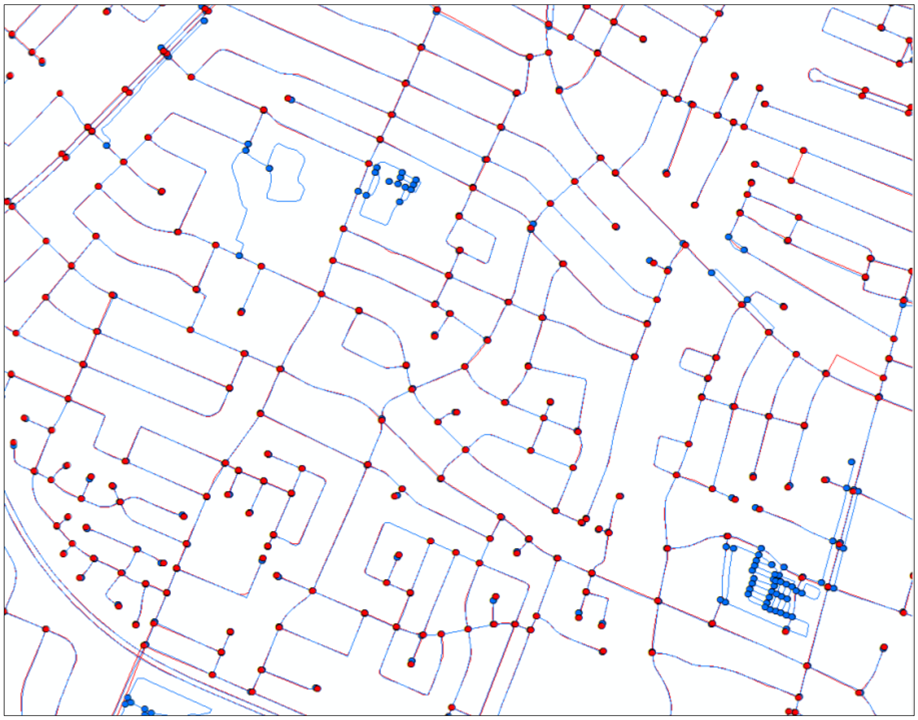


Figure 4 Closeness of Intersections in AllRds and HERE Networks

Shorter intermediate links are consolidated into a longer segment bound by two intersections, as shown in Figure 5 (*10*). When aggregating shorter links, their sequence along the segment is also recorded as it is needed for link and direction matching.

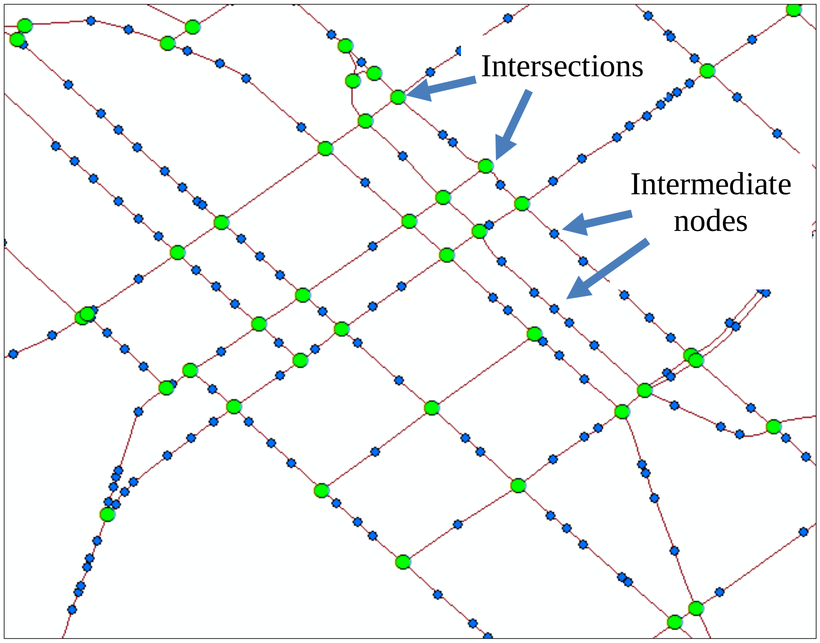


Figure 5 Examples of Node Types

After obtaining intersections and link sequences, matches between AllRds and HERE intersections are identified. Due to the complications shown in Figure 6, a more robust method is desirable to account for the uncertainties and imprecisions associated with the two networks.

Figure 6 Example Locations with Complications

A fuzzy logic inference algorithm is introduced to the matching process to address the uncertainties in both network geometries and road names while simultaneously considering both criteria. Fuzzy logic performs well in ambiguous and uncertain situations. It also works very well with variables having different scales, which is the case with the conflation task. The algorithm first transforms numerical values into linguistic terms via predefined membership functions and then applies reasoning rules to combine different variables to achieve a final weighted value. For example, the following rule can be defined in the algorithm: if the distance is very close and road names are very similar, the matching score is high. Figure 7 sketches out the matching process used by the fuzzy logic algorithm.

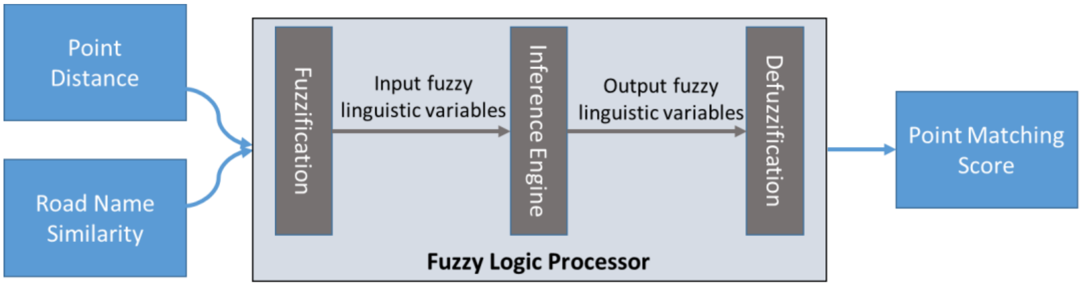


Figure 7 Fuzzy Logic Inference Process

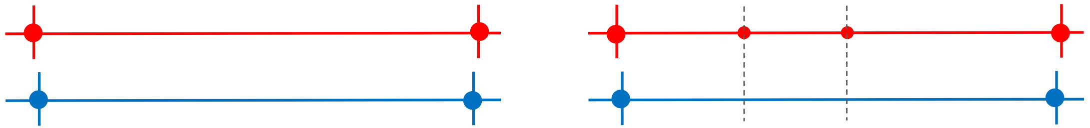
During the matching process, a list of candidate intersections from the HERE network is first obtained for each AllRds intersection. For each candidate intersection, the fuzzy logic process is then applied, by entering the distance between the candidate intersection and AllRds intersection and the road name similarity of AllRds and HERE segments. After going through the inference engine, a linguistic term for the matching quality is determined (e.g., high, medium, or low). The linguistic result is converted to a numerical value via a defuzzification function, which is the overall matching score for the candidate intersection. Once the matching scores are obtained for all candidate intersections, the highest scoring one is selected as the optimal match.

2.4.3 Link and Direction Matching

The goal of this step is to determine the correspondence of links and associated directions based on the intersections matched in the previous step. With the known sequence of HERE links, the milepoints associated with the beginning and ending points of each link can be determined. Four scenarios can arise when matching links and associated milepoints (Figure 8). The simplest scenario is one-to-one matching, (i.e., one HERE link is matched to one AllRds link). In this case, the HERE link is assigned to the AllRds link without further processing. The second simplest scenario is many-to-one matching. In this scenario, one HERE link is assigned to multiple AllRds links, but the milepoints from those links can be directly used. A more complicated scenario is one-to-many matching, where the AllRds link is split in accordance with the sequence and lengths of HERE links; then, HERE links are matched with split AllRds links correspondingly. The most complicated scenario arises when both AllRds and HERE segments return multiple links – many-to-many matching. Under this scenario, both AllRds and HERE links are further split according to the length and sequence of their respective links, a procedure similar to finding the smallest common denominator. The split AllRds and HERE links are then integrated accordingly.

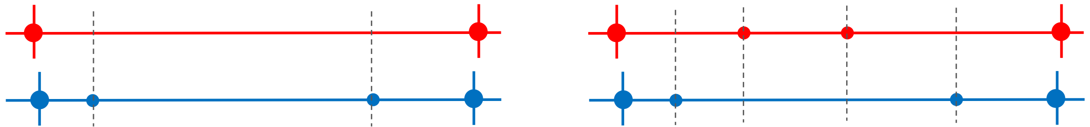
When matching links, the F or T direction of each link from the HERE network should also be matched with the cardinal or non-cardinal direction of each link from the AllRds network. The rules used to determine the direction by the respective network are as follows:

- For AllRds, the direction is cardinal if milepoints along the link increase. Otherwise, the direction is non-cardinal;
- For HERE, the direction is F if it travels from the reference endpoint to the non-reference endpoint. Otherwise, the direction is T.



(a) one to one

(b) many to one



(c) one to many

(d) many to many

Figure 8 Four Link Matching Scenarios

The reference endpoint and non-reference endpoint are decided using the following rules:

- The reference endpoint is the endpoint with the lower latitude.
- If the latitudes of both endpoints are the same, the reference endpoint is the endpoint with the lower longitude.

Figure 9 illustrates how directions are determined based on these rules. Milepoints along the AllRds link are obtained through preprocessing, which creates and assigns milepoints along the link at intervals equal to 1/10th of the link's total length.

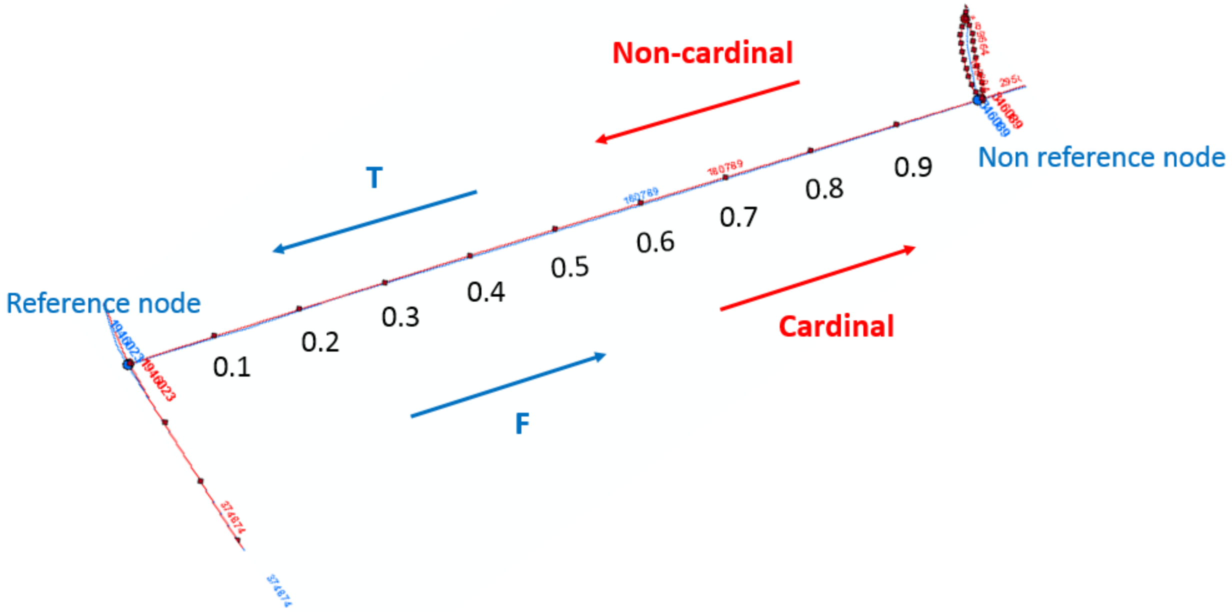


Figure 9 Illustration of AllRds and HERE Directionalities

2.4.4 Handling the Exceptions

The conflation methodology functions well except in the following situations:

- When a roadway is only present in AllRds but not the HERE network, two ends of the AllRds segment may be matched to the same HERE intersection;
- A road section is undivided in AllRds while divided in the HERE network.

To address the first issue, HERE links that are close to the subject AllRds segment are designated in a list of candidate links. Because the candidates may involve irrelevant links from intersecting and/or parallel streets due to their close proximity, two criteria are employed to filter out unlikely links: road name similarity (as previously discussed) and the angle between candidate HERE links and the subject AllRds segment. Using the ArcGIS Locate Features Along Routes tool, remaining links are assigned milepoints and their sequence determined. Lastly, the previous procedure is applied to determine the correspondences of links as well as their directions.

To handle the second issue, the conflation table generated from the previous steps is first needed to identify problematic locations and to obtain matched HERE and AllRds link information (e.g., RT_unique, milepoints, cardinal/non-cardinal direction, F/T direction). That information is used to select candidate links within a certain area of the target AllRds segment that are not included in the conflation table. This ensures only links in the missing direction remain in the candidate list. Road name similarity and angular difference criteria are applied to filter out unlikely links. Finally, the associated beginning and ending milepoints are obtained for each remaining link.

3. Congestion Performance Measures

This chapter reviews performance measures other state DOTs use to quantify congestion. Later, performance measures that can be developed for Kentucky highways are documented, with an emphasis on identifying threshold speed values to distinguish congested from uncongested conditions.

3.1 Review of Current Practice

This section summarizes current congestion measurement practices in peer states. The research team first reviewed documents pertaining to the network screening, needs identification, or adequacy/sufficiency rating. If none of these documents were available, researchers searched for relevant guidelines related to project prioritization or project selection. Further, the state's long-range transportation plan and the plan's congestion measures plan were reviewed. Methodologies and data used for measuring congestion to perform network screening and project selection are discussed below.

3.1.1 Network Screening

Seven DOTs publish documentation on network screening or the need identification process on their web sites.

Florida developed a quality/level of service handbook, consistent with *Highway Capacity Manual* (HCM) methodologies, to quantify the service provided by its multimodal transportation system (*11*). The level of service (LOS), as defined in the HCM, is used as the performance measure. The handbook is used for 1) generalized planning involving broader area-wide analyses and 2) initial problem identification and conceptual planning, which focuses on the facility level and is more detailed than generalized planning. The conceptual planning approach can be used to identify needs if the generalized planning approach is not considered detailed enough.

Iowa (*12*), Ohio (*13*), and Oklahoma (*14*) evaluate current congestion conditions and capacity needs across the state highway system based on the volume-to-capacity (V/C) ratio. Tennessee developed a highway deficiency analysis tool and uses the V/C and delay measures to evaluate systemwide highway conditions (*15*). South Carolina uses two performance measures – the LOS from its statewide travel demand model and vehicle hours lost based on INRIX probe data – to evaluate conditions on the state's Strategic Corridor Network(*16*).

Oregon's hybrid approach combines the Highway Economic Requirements System (HERS-ST) and archived real-time data (when available) to generate performance measures, including TTI, BTI, travel delay, V/C, travel time, and speed (*17; 18*).

3.1.2 Project Selection

Methods used for project prioritization are the same as those used for statewide network screening. States often use travel demand models to generate future volume and performance as an input into the HCM-based approach.

3.1.2.1 Highway Capacity Manual based Methods

HCM-based methods have been widely applied for the analysis of highway performance using more established data sources, such as roadway geometries and traffic volumes. Key congestion measures include V/C, LOS, and delay. Some states use more than one performance measure.

Many states utilize V/C to measure congestion: Alabama (*19*), Indiana (*20*), North Carolina (*21*), Utah (*22*), Arizona (*23*), Alaska (*24*), Connecticut (*25*), Illinois (*26*), Kansas (*27*), Maine (*28*), New Hampshire (*29*), and Rhode Island (*30*).

LOS is a qualitative measure of highway operating condition based on metrics such as density, speed, and delay. The states that utilize LOS include Delaware (*31*), Georgia (*32*), Michigan (*33*), Missouri (*34*), Mississippi (*35*), Montana (*36*), New Jersey (*37*), South Dakota (*38*), and Vermont (*39*).

The following states use delay as a performance measure: Illinois (*26*), Delaware (*31*), Hawaii (*40*), Massachusetts (*41*), Pennsylvania (*42*), Rhode Island (*30*), Texas (*43*), Virginia (*44*), and Washington (*45*).

3.1.2.2 Highway Economic Requirements System Method (HERS-ST)

The FHWA developed HERS-ST as an optimization framework to assist transportation agencies in developing highway investment programs and evaluating the relationship between investment levels and improvements in highway system performance. HERS-ST uses standard HPMS data items to assess a highway system's conditions and deficiencies. The speed model in HERS-ST can generate various performance measures, including travel time, speed, and delay. Several states such as Louisiana and West Virginia have relied on the HERS-ST method to generate performance measures, such as V/C and delay, used in the project prioritization process (*46; 47*). However, the FHWA no longer supports the program.

3.1.2.3 Travel Time-Based Methods

Some DOTs have begun to use emerging data sources, such as probe vehicle speed data, to develop travel time-based metrics. These data reflect operating conditions and provide insight into traffic dynamics unavailable from the traditional HCM-based method. Measures of congestion and travel time reliability used at state DOTs include:

- TTI: The ratio of travel time for a given time period to the free-flow travel time. It measures the severity of congestion during the peak period.
- PTI: The ratio of the 95th percentile travel time to the free-flow travel time. It represents the travel time needed to ensure a 95% chance of on-time arrival.
- BTI: The ratio of the difference between the 95th percentile travel time and the average travel time to the average travel time. It represents how much extra time (expressed as a percentage) that travelers add to their average travel time to ensure on-time arrivals at 95% of the time.
- Delay: A measure of the additional travel time experienced by a vehicle/passenger or a group of vehicles/passengers due to recurring or non-recurring events. It is the difference between experienced travel time and free-flow travel time.

States using travel time-based methods include California (*48*), Colorado (*49*), Minnesota (*50*), and Wisconsin (*51*). Other states, such as Wyoming (*52*), New Mexico (*53*), and Nebraska (*54*), are working to establish data-driven procedures according to their long-range transportation plans.

3.1.2.4 Hybrid Approach

Some states use a combination of traditional methods and travel time-based methods. Arkansas uses a combination of V/C, derived from the HCM method, and TTI when travel time data are available (*55*). Florida relies on three sources to evaluate the mobility conditions of its Strategic Intermodal System: 1) probe vehicle data to identify bottlenecks based on PTI and frequency of congestion, 2) a predictive model developed in-house to generate PTI, and 3) the HCM method to evaluate V/C and delay (*56*).

The following bullets offer additional details on how states using travel time-based measures handle data coverage issues.

- Arkansas (*55*) uses NPMRDS data to generate TTI for its National Highway System (NHS). Although TTI is included as a mobility measure, no score is given to TTI in its rating system.
- California (*48*) relies on PeMS to report delay and BTI. If no data are available for a segment, it is assumed that the delay is below the lowest threshold, and the BTI is below the threshold considered as reliable.
- Minnesota (*50*) only reports speeds on Twin Cities metro area freeways and the Interregional Corridor System where data are available. It is investigating using probe data to expand the reporting coverage. The agency is also expecting to adopt new congestion measures in response to MAP-21 requirements.
- Colorado (*49*) uses PTI as a congestion measure only for the NHS. There is no mention of what to do with unavailable or inadequate data or non-NHS highways.
- Florida (*56*) only considers the segments on its Strategic Intermodal System and where there are enough data to develop a bottleneck ranking. Segments with no data or inadequate data are not considered bottleneck and receive a score of 0. A predictive model developed by the agency is used to generate PTI for all the segments.
- Oregon (*17*) has a more comprehensive description of its approach. Case studies by Eisele et al. (*18*) in showed that HERS-ST-estimated results are similar to ATR speeds, thus the model shows promise for statewide application. The need exists to investigate data quality issues (especially AADT and number of lanes), as well as to perform a sensitivity analysis, to better understand HERS-ST.

To summarize, evaluating congestion at network or project level requires either a data-driven speed approach or traditional methods (e.g., HERS-ST). The adaptation of congestion measures varies across state DOTs. Overall, congestion measures, (e.g., V/C ratio, LOS, Delay, TTI, PTI, BTI) are widely used by agencies to measure congestion.

3.2 Congestion Measures

As the last section demonstrated, DOTs use a number of congestion measures. V/C ratio, LOS, Delay, AADT, Person Throughput, Travel Time, Speed, TTI, PTI, and BTI are used for network screening and project selection. This section lists several commonly used measures that can be developed for Kentucky highways.

Delay is frequently used as a measure of congestion. Delay is the additional time required to complete a trip over what would be required in uncongested conditions. A threshold speed value that differentiates congested and uncongested conditions must be determined before estimating delay. This threshold value is referred to as the reference speed.

3.2.1 Reference Speeds

A critical step in measuring congestion is to set the reference speed. When speed falls below the reference speed, a roadway is considered congested. Analysis has been carried out on the test network based on the 2017 HIS extract, with reference speed investigated for different facility types. However, a reasonable amount of speed data is not available for all facilities, especially during nighttime hours, which affects the accuracy of the reference speed. To balance data from nighttime and daytime periods, several reference speeds were tested for each facility type.

Based on analysis and discussion with KYTC congestion workgroups, Table 6 lists recommended definitions of reference speeds for Kentucky roadways. Adequate speed data were used to calculate the reference speed. With respect to data adequacy, a threshold value of a minimum 10% availability was used to align with previous analysis on 'Minimum Availability Rate' (see Chapter 2).

Table 6 Reference Speed

Facility Type	Reference Speed
Freeways	The 85th percentile speed of all speed data
Non-freeways	The average speed during weekday daytime (6am-8pm)

3.2.2 Performance Measures

After establishing the reference speed, the research team calculated a number of performance measures. These measures were generated from integrated speed and HIS data. Calculations were first performed at the segment level for a typical weekday and then aggregated into annual statistics. In Kentucky, many rural and low-volume roads appear to lack adequate speed data, especially for the nighttime hours. Based on the data quality assessment, these measures were aggregated for daytime hours (6 am–8 pm) only.

As a preliminary step, researchers tested a number of performance measures, and eventually narrowed down the list of potential congestion measures for use in Kentucky to those described in the following sections.

3.2.2.1 Vehicle Hours of Delay (VHD)

Delay is the time spent traveling a segment in excess of the reference travel time. Individual vehicle delay for the i_{th} hour (D_i) is defined as:

$$D_i = \frac{L}{S_i} - \frac{L}{RS}$$

where: L = Segment Length, S_i = Average Speed for the i_{th} hour, and RS = Reference Speed. Vehicle hours of delay for the i_{th} hour (VHD_i) are estimated as:

$$VHD_i = V_i \times D_i$$

in which V_i = Volume for the i_{th} hour.

Total VHD for a typical weekday during the 6 am-8 pm interval (the 14-hour daytime period) is estimated as:

$$VHD = \sum_i VHD_i$$

VHD measures the total delay experienced by all vehicles traveling a highway segment.

3.2.2.2 Vehicle Hours of Delay per Mile (VHDPM)

VHDPM is VHD per unit length (e.g., 1 mile) of a segment. It is calculated as:

$$VHDPM = \frac{VHD}{L}$$

3.2.2.3 Average Hours of Delay (AHD)

AHD measures the delay experienced by a vehicle traveling one mile on a segment. It is the ratio of total VHD to Vehicle Miles Traveled (VMT) over the same period, as defined below:

$$AHD = \frac{VHD}{VMT}$$

and

$$VMT = \sum_i V_i \times L$$

The research team recommends using VHD to rank projects where the project length has been pre-determined. VHDPM and AHD are more suitable for systemwide screening to identify bottlenecks.

3.3 Adapted HERS-ST Model

An adapted HERS-ST speed model was used to estimate speed when probe vehicle speed data for the roadways were deemed inadequate. The results were used to estimate VHD for these roads.

Most data items required to implement the HERS-ST model are similar to those listed in Table 1. Data on pavement roughness (IRI or PSR), grade, and curve lengths are needed as well. The free-flow speed (FFS) model in HERS-ST was adapted. Conceptually, FFS is defined as the speed at which traffic is light and vehicle speed is restricted by geometric conditions and traffic control devices, but not the presence of other vehicles. In HERS-ST, FFS is determined using three inputs: 1) maximum allowable speed on a curve (VCURVE), 2) maximum allowable ride-severity speed (VROUGH), and 3) maximum speed resulting from the speed limit (VSPLIM):

$$FFS = \frac{e^{\sigma^2/2}}{(VCURVE^{-1/\beta} + VROUGH^{-1/\beta} + VSPLIM^{-1/\beta})^{\beta}}$$

Recommended default model parameter values are $\sigma = 0.1$ and $\beta = 0.1$. In this study, the FFS model was calibrated using measured speeds to enhance its performance.

The FFS (or FFSUP) generated by the model was compared with reference speeds based on speed data. Notably, the model does not account for the impact of narrow lanes when estimating FFS. While this apparently does not pose a problem for freeways and multilane highways, it tends to produce significant overestimates of FFS for rural two-lane roads with narrow lanes. Therefore, a lane width adjustment factor based on the HCM was included to further adjust FFS. For interrupted facilities (i.e., signal- and stop sign-controlled facilities) the effect of traffic control devices was accounted for by adding a zero-volume delay to the FFS model. For signal controlled facilities,

$$ZVDSIG = 0.0687\left(1 - e^{-NSIG/24.4}\right)$$

where; ZVDSIG is zero volume delay in hours per vehicle-mile traveled, while NSIG is the number of signals per mile. For stop-sign controlled facilities,

$$ZVDSTP = NSTP(1.9 + 0.067FFS)$$

in which ZVDSTP is zero volume delay due to stop sign in hours per 1000 vehicle miles, and NSTP is the number of stop signs per mile. This is adapted from the HERS-ST speed model for stop sign-controlled delay by setting the volume to zero. Therefore, the adjusted FFS for the signal-controlled facility can be estimated as $1/(\frac{1}{FFS} + ZVDSIG)$ and that for the stop-controlled facility would be $1/(1/FFS + ZVDSTP/1000)$.

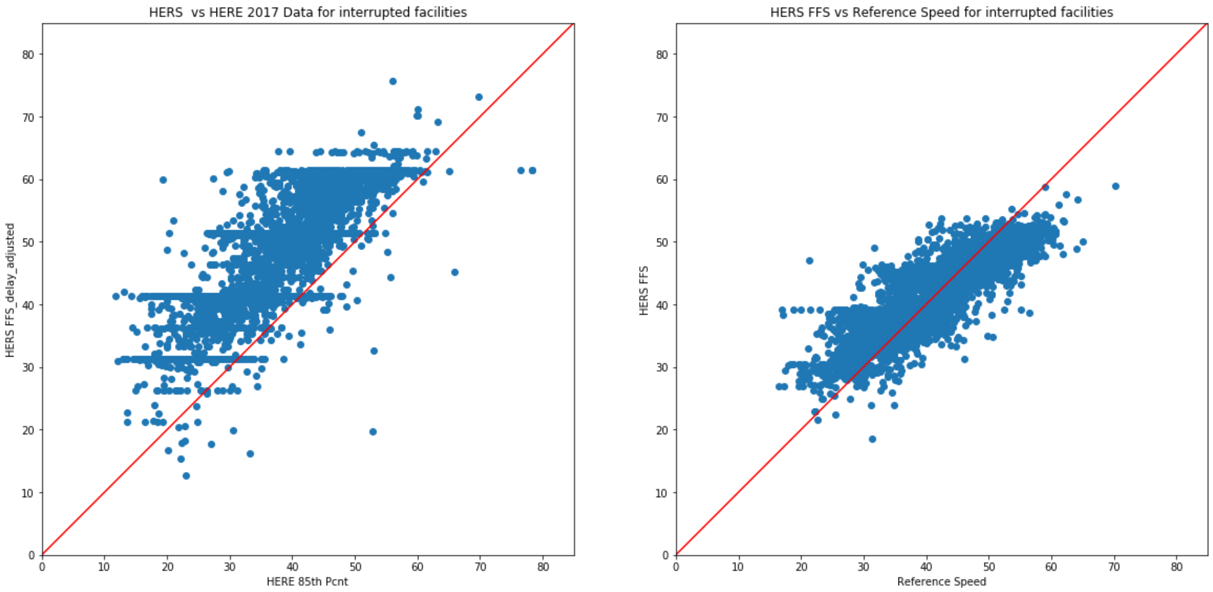
Based on these adaptations, the FFS model was calibrated using the reference speeds calculated from speed data. The goal is to find values of σ and β that produce the best fit between the modeled FFS and measured reference speed. The process only used data from segments with adequate speed data coverages, and calibration was performed separately for interrupted and uninterrupted facilities. Table 7 lists the resulting parameters.

Table 7 FFS Calibration Results

Facility Type	σ	β
Uninterrupted Facilities	0.1427	0.2092
Interrupted Facilities	0.3907	0.18378

To evaluate the calibrated FFF model's performance, reference speeds from measured data were compared with the modeled FFS for interrupted facilities and uninterrupted facilities.

Figure 10 presents the results for interrupted facilities. The horizontal axis indicates the measured reference speed while the vertical axis represents model output. Ideally, the plots should align well with the red diagonal line. Where dots are located above the red line the model overestimates FFS; and where dots are below the red line shows where the model underestimates FFS. The model calibrated with local data clearly outperformed the one with default parameter (σ and β) values.



Before Calibration

After Calibration

Figure 10 Model and Measured FFS Speed Comparison for Interrupted Facilities

The results from the calibrated model were used to estimate hourly (congested) speeds by adapting an hourly speed estimation process from Margiotta et al. (*57*). Previously, Chen and Gong (*58*) demonstrated that the HERS-ST speed model provides a statistically accurate estimate of speed for different facility types. The procedure for estimating the daily average speed can be found in their study. The research team incorporated the methodology in Margiotta et al. (*57*) to calculate hourly speeds for segments with inadequate data. **Error! Reference source not found.** outlines the procedure.

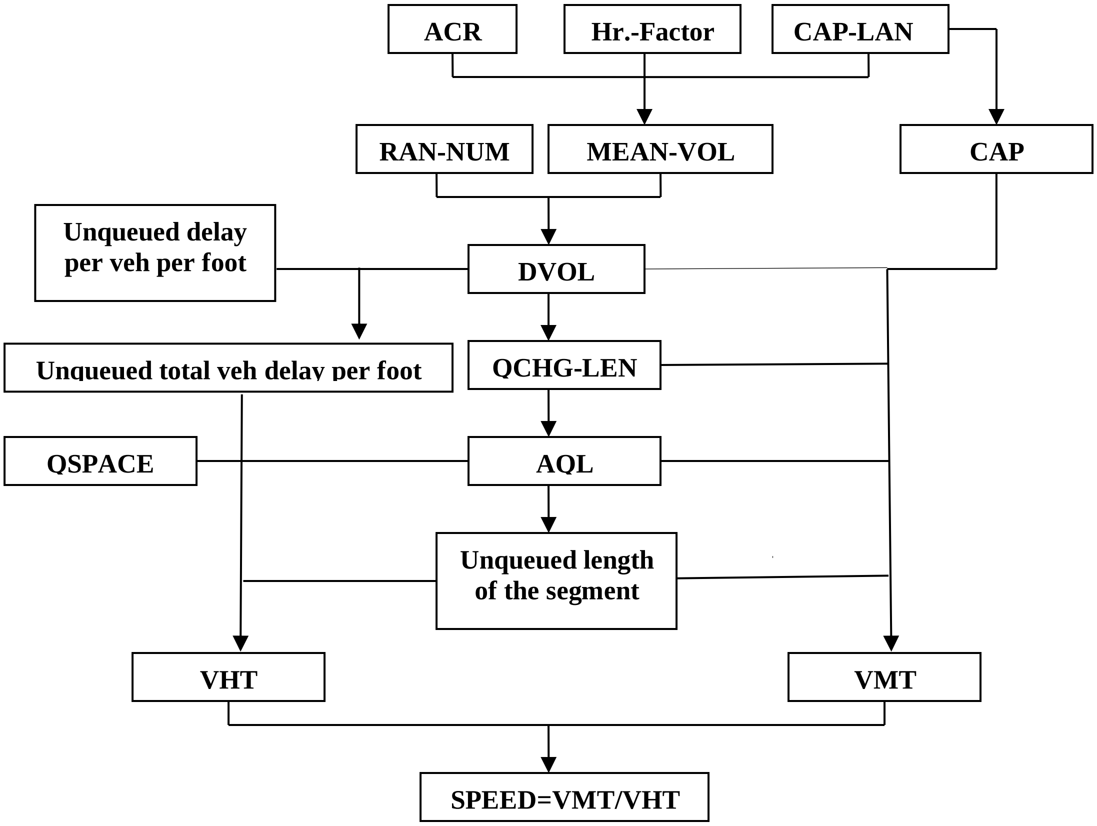


Figure 11 Hourly Speed Estimation

In **Error! Reference source not found.**,

ACR = the AADT to capacity ratio for the segment
Hr.-Factor = hourly factor
CAP-LAN = capacity per lane per direction
RAN-NUM = random number seed
MEAN-VOL = mean hourly volume
CAP = bottleneck capacity
DVOL = demand volume for this hour (in vehicles)
QCHG-LEN = queue length
QSPACE = spacing of vehicles in the queue (in feet per vehicle)
AQL = average queue length during the hour (in feet)
VMT = vehicle-miles of travel
VHT = vehicle-hours of travel

For each hour of the day, speed is estimated from VMT and VHT. Both of these are estimated separately for queued and unqueued portions of the segment:

$$\text{Speed} = \text{VMT}/\text{VHT}$$

On the unqueued portion, VMT is determined by the length of unqueued portion and volume. VHT is derived from the unqueued segment length, hourly volume, and unqueued delay. On the queued portion, VMT is computed using the average queue length during the hour and bottleneck capacity. VHT is obtained from the average queue length during the hour and vehicle spacing in the queue. Calculations are performed using the following equations:

$$\mathrm{VMT} = \{(\mathrm{UQL} \times \mathrm{DVOL}) + (\mathrm{AQL} \times \mathrm{CAP})\}/5280$$

$$\mathrm{VHT} = (\mathrm{UQL} \times \mathrm{DVOL} \times \mathrm{UQDEL}) + (\mathrm{AQL}/\mathrm{QSPACE})$$

where:

UQL	=	length of the segment that is not queued (in feet)
DVOL	=	demand volume for this hour (in vehicles)
AQL	=	average queue length during the hour (in feet)
CAP	=	bottleneck capacity
UQDEL	=	unqueued delay (in hours per vehicle-foot)
QSPACE	=	spacing of vehicles in the queue (in feet per vehicle)

The second term in the VHT equation is derived from estimating the queued VHT (QVHT) based on the queued VMT (QVMT) and queue speed.

$$\mathrm{QVHT} = \mathrm{QVMT}/\text{Queue Speed}$$

where:

QVMT = AQL*CAP (the second term in the VMT equation)
Queue Speed = CAP*QSPACE

Accordingly,

QVHT = (AQL*CAP) /(CAP*QSPACE) = AQL/QSPACE

Hourly demand is estimated from AADT and the hourly distribution factor. To account for stochastic variations in traffic, a random factor is introduced. It is assumed that the actual hourly demand varies within a range of 10 vehicles to 1.5 times of average hourly demand.

Average queue length and unqueued delay are two important variables to estimate. The estimation procedures for these variables are described in detail in the following two sections.

3.3.1 Average Queue Length

Average queue length is calculated using queue lengths at the start and the end of the hour, the length of the link, and the length of the overflow (defined as the difference between demand and segment capacity). In this model, average queue length is considered when the queue lengths at the start and the end fall under these scenarios.

3.3.1.1 No Initial Queue

When queue length at the start of the hour is zero, if the queue length at end does not exceed the length of the link, average queue length is half of the queue length at end of the hour. Otherwise, the following equation is used:

$$\mathrm{AQL} = \mathrm{Link\_len} \times (\mathrm{Link\_len}/(2 \times \mathrm{Qs\_len}) + (1 - \mathrm{Link\_len}/\mathrm{Qe\_len}))$$

where:

Link_len = the length of the link
Qs_len = the length at start of time interval
Qe_len = the length at end of time interval

3.3.1.2 Initial Queue Occupying Part of Segment

When queue length at the start of the hour is less than the length of the link, the following three scenarios must be considered:

(1) If queue length at end of the hour is less than the length of the link but not equal to zero, average queue length is the average of the queue lengths at the start of the hour and the end of the hour.
(2) If queue length at end of the hour is zero, average queue length is computed with the following equation:

$$\mathrm{AQL} = (\mathrm{Qs\_len}/\mathrm{Qo\_len}) \times \mathrm{Qs\_len}/2$$

where:

Qo_len = the length of overflow (from the previous hour)

(3) If queue length at the end of the hour is greater than the length of the link, AQL is calculated with the following equation:

$$\begin{aligned}\mathrm{AQL} = {} & (\mathrm{Link\_len} - \mathrm{Qs\_len}) \times (\mathrm{Link\_len} + \mathrm{Qs\_len})/(2 \times \mathrm{Qo\_len}) + \\ & \mathrm{Link\_len} \times (1 - (\mathrm{Link\_len} - \mathrm{Qs\_len})/\mathrm{Qo\_len})\end{aligned}$$

3.3.1.3 Initial Queue Occupying Entire Segment

When queue length at the start of the hour exceeds the length of the link, three scenarios must be evaluated:

(1) If queue length at end of the hour exceeds the length of the link, average queue length is equal to the length of the link;
(2) If queue length at the end of the hour is zero, the following equation is used to estimate AQL:

$$\mathrm{AQL} = (\mathrm{Link\_len}/\mathrm{Qo\_len}) \times (\mathrm{Qs\_len} - \mathrm{Link\_len}/2)$$

(3) If queue length at the end of the hour is less than the length of the link but not equal to zero, AQL is calculated with the following equation:

$$\begin{aligned}\mathrm{AQL} = {} & (\mathrm{Link\_len} - \mathrm{Qe\_len}) \times (\mathrm{Link\_len} + \mathrm{Qe\_len})/(2 \times \mathrm{Qo\_len}) \\ & + \mathrm{Link\_len} \times (1 - (\mathrm{Link\_len} - \mathrm{Qe\_len})/\mathrm{Qo\_len})\end{aligned}$$

3.3.2 Unqueued Delay

The unqueued delay is determined by the unqueued delay per vehicle and traffic volume. Methods used to estimate the unqueued delay per vehicle vary by facility type.

For signal-controlled facilities, it is estimated with the following equation:

$$UQDEL = 1/FFS + ((1 - Exp(-0.29 \times NSIG)) \times (0.027 + 0.033 \times V/C^{1.23})))$$

where:

FFS = free-flow speed (or FFSUP)
NSIG = number of signals per mile
V/C = ratio of volume to capacity with an upper bound of 1.

For stop sign-controlled facilities, the following equations are used to calculate delay:

$$D_{ss} = NSTP \times (1.9 + (0.067 \times FFS))$$
$$UQDEL = (1/FFS) + (D_{ss}/1000)$$

where:

NSTP = number of stop signs per mile
D_{ss} = delay due to stop signs in hours per 1,000 vehicles

For multilane roadways, the following equation is used to estimate unqueued delay:

$$UQDEL = (1 + (0.2 \times V/C^{10}))/FFS$$

where:

V/C = the ratio of volume to capacity. If greater 1, it is 1.

For the remaining facilities, delay due to grade can be calculated first (using the HERS-ST speed model). The following equation is used to estimate unqueued delay:

$$UQDEL = (1 + (0.2 \times V/C^{10}))/FFS + DGRADE / Link\_len$$

where:

V/C = ratio of volume to capacity with an upper bound of 1
DGRADE = delay due to grades in hours

QSPACE is assumed to be 43.9 ft. CAP is determined by peak capacity and peak lanes, which are provided in HPMS.

The research team used the procedure outlined above to estimate hourly speed for a segment when the available speed data were not adequate for the segment.

3.4 Ramp Performance Measures

Probe speed data are available and adequate for almost all ramps in Kentucky. Therefore, delay can be estimated when ramp volume data are available. In rare cases where a ramp speed needs to be estimated due to insufficient data, the methodology presented in the HCM 6th Edition was used.

Since the HCM method does not explicitly provide output for hourly speed, researchers applied the hourly speed estimation method as presented in Section 3.3 for ramps. VHDPM and AHD were used, as mentioned in Section 3.2.2.

3.5 Project Ranking Formula

In consultation with KYTC, the research team selected VHD as the recommended measure of congestion for the project identification and selection process. VHD was estimated for each project for a typical weekday daytime period of 6 am – 8 pm using speed data from 2015 to 2017.

To determine where each project ranked among all projects during the scoring process, VHD was first scaled by calculating the percentile VHD value of each project. To reflect the strategic significance of highway types, a functional classification (FC) adjustment factor (f) was applied to scaled VHD values. The factors are shown in Table 8. The Appendix includes a summary of the methodology.

Table 8 Functional Classification Adjustment Factor

FC	1	2	3	4	5	6	7
Adj. Factor (f)	1	0.95	0.90	0.85	0.80	0.75	0.70

Congestion Measure (CM) = VHD-Scaled * f

Statewide Score = 20% * CM

Regional Score = 10% *CM

4. Conclusions

This study developed a framework that can be used to integrate speed data into traditional congestion performance measures. Implementation of the framework requires the following steps: data quality assessment, network conflation, setting reference speed, and calculating congestion measures for each year. A white paper outlining these steps is included in the Appendix.

Speed data from 2015 to 2017 were acquired from a private sector vendor that aggregated GPS-based vehicle location data into speed data at various temporal and spatial resolutions. The quality of these speed data required verification since low-volume roads may lack full coverage. Minimum availability rate values were introduced based on the facility type to determine whether available data were adequate or not. Then, speed data and HIS attributes were integrated using network conflation. Before calculating the congestion measures, reference speed was set as the benchmark for congestion utilizing the speed data. If the speed data did not meet the minimum availability rate, the adapted HERS-ST model was used to obtain hourly speeds for each segment. This model was adjusted for lane width and traffic control devices and calibrated using measured data. Finally, performance measures were calculated at the segment level for a typical weekday and aggregated into annual statistics. All measures were aggregated to daytime hours (6 am-8 pm).

After testing a number of performance measures, the study identified congestion measures potentially appropriate for Kentucky: VHD, VHDPM, and AHD. Based on analysis, the research team recommends using VHD for project rankings. VHDPM and AHD can be considered alongside VHD for systemwide screening to identify bottlenecks.

With the methodology developed for this study and the data used, KYTC can further advance its data-driven decision-making practices. Applications such as travel model calibration and validation, quantifying user delay and travel time savings, and integrating travel time reliability into decision making have been identified.

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Appendix A SHIFT2020 Measures of Congestion White Paper

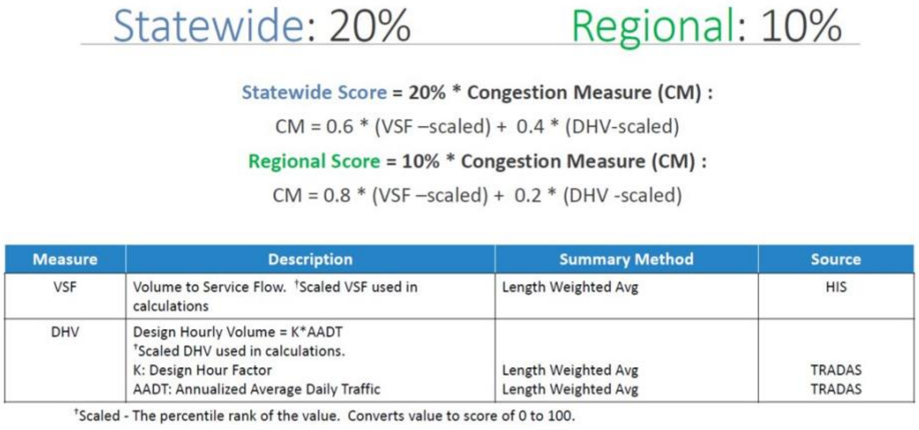
Measures of Congestion

October 25, 2018

Introduction

This document summarizes research on development of the data and methodology to quantify congestion for project selection and systemic network evaluation. The goal is to update the measure of congestion for SHIFT2020.

The SHIFT2018 considers VSF and AADT as two components of the congestion measure. Their relative importance varies for statewide and regional projects. The formula used in SHIFT2018 is shown in
Figure A.



Statewide: 20% Regional: 10%

Statewide Score = 20% * Congestion Measure (CM) :

CM = 0.6 * (VSF –scaled) + 0.4 * (DHV-scaled)

Regional Score = 10% * Congestion Measure (CM) :

CM = 0.8 * (VSF –scaled) + 0.2 * (DHV -scaled)

Measure	Description	Summary Method	Source
VSF	Volume to Service Flow. [†]Scaled VSF used in calculations	Length Weighted Avg	HIS
DHV	Design Hourly Volume = K*AADT [†]Scaled DHV used in calculations.		
	K: Design Hour Factor	Length Weighted Avg	TRADAS
	AADT: Annualized Average Daily Traffic	Length Weighted Avg	TRADAS

[†]Scaled - The percentile rank of the value. Converts value to score of 0 to 100.

Figure A1 SHIFT 2018 Formula

VSF is a traditional measure of service quality and has been widely used by agencies. It has several limitations when used to measure congestion. VSF reflects condition during peak hour but does not account for congestion beyond that. The value of VSF is not a consistent representation of the level of service across all facility types. For example, on two-lane highways, service quality deteriorates well before volume approaches capacity. Further, VSF relies on the knowledge of peak capacity, which requires a number of data items that may not be available for all facilities, especially for ramps.

Basic Approach

Previous studies have established the value of third-party probe speed data in generating performance measures at corridor, regional, and statewide levels. The basic approach of the SHIFT2020 update is to use these speed data wherever they are available and deemed adequate.

After the speed data are integrated with KYTC's HIS data set, various travel time-based performance measures can be developed.

For roadways lacking adequate speed data, the speed model in the HERS-ST is adapted to estimate hourly speed. HERS-ST is a benefit-cost analysis tool for highway investment programs and policies. It uses highway inventory data in the standard HPMS format. The detailed methodology can be found in HERS-ST Technical Documentation. Major adaptions to the HERS-ST speed model include:

- Calibrated free-flow speed model using measured speed data;
- Incorporated zero-volume delay for signal- and stop sign-controlled facilities;
- Incorporated lane width adjustment factor for rural one/two-lane roads to account for the impact of narrow lanes; and
- Expanded the methodology to estimate hourly speed.

Data Sources

Major data sources include (1) historical speed data acquired from a third-party data provider, HERE Technologies, Inc., and (2) roadway geometric condition and usage data extracted from KYTC's HIS.

Speed Data

Archived speed data for 2015-2017 on all Kentucky roadways were acquired from HERE Technologies, Inc. The speeds are referenced to HERE 2017Q3 map links, and available in 5-min and 60-min epochs for each day of the year. Further, speeds are available for all vehicles, cars only, and trucks only. In SHIFT2020, speed data from the 3-year period of 2015-2017 are used to generate performance measures.

Due to limited probe vehicle data on some roads in Kentucky, especially rural low-volume roads, speed data were not available for all segments in all time periods. Data adequacy analysis was performed using a bootstrap sampling method. Results indicate that if speed data are available for at least 10% of the time epochs in the analysis period, they are representative of the true operating condition.

HIS Data

KYTC's HIS extract provides key data items required for estimating speed using the adapted HERS-ST speed model. The traditional methodologies require a number of data items on roadway geometric condition and usage.

Measures of Congestion

Various performance measures have been developed through studies at the national and state levels. This section lists several commonly used measures that can be developed for Kentucky highways.

Delay is frequently used as a measure of congestion. It is defined as the excess time a traveler experiences on a trip over the time that would be required in uncongested conditions. A threshold value of speed that separates the congested and uncongested conditions must be determined before delay can be estimated. This threshold value is referred to as "reference speed" in this document.

Setting Reference Speeds

When speed falls below the reference speed, the roadway is deemed congested. Several methods of setting reference speeds are tested using 2015-2017 data. Based on data adequacy evaluation and the feedback from the SHIFT2020 workgroup and KYTC's congestion focus group, the recommended reference speeds for Kentucky roadways are set below and capped at the speed limit.

Freeways:	The 85th percentile speed of all speed data
Non-freeways:	The average speed during weekday daytime (6am-8pm)

Performance Measures

After setting the reference speed, a number of performance measures can be calculated. Several variations of delay that can be used as the primary measures of congestion are defined below. Other measures, such as travel time index, travel time reliability index, cost of congestion, and unreliable travel time, can also be estimated.

VHD: Delay is the extra time spent traversing a segment beyond the reference travel time. Individual vehicular delay for the i_{th} hour (D_i) is defined as:

$$D_i = \frac{L}{S_i} - \frac{L}{RS}$$

in which, L = Segment Length, S_i = Average Speed for the i_{th} hour, RS = Reference Speed. Vehicle hours of delay for the i_{th} hour (VHD_i) can be estimated as:

$$VHD_i = V_i \times D_i$$

in which V_i = Volume for the i_{th} hour.

Total vehicle hours of delay (VHD) for a typical weekday during 6am-8pm (i.e., the 14-hour daytime period) can be estimated as:

$$VHD = \sum_i VHD_i$$

VHD reflects the total delay experienced by all vehicles traversing a segment of highway.

VHDPM: VHDPM reflects vehicle hours of delay per unit length (e.g., 1 mile) of a segment. It can be calculated as:

$$VHDPM = \frac{VHD}{L}$$

AHD: AHD measures the delay experienced by a vehicle traveling one mile on a segment. It is the ratio of total VHD to VMT over the same time frame, as defined below:

$$AHD = \frac{VHD}{VMT}$$

and

$$VMT = \sum_i V_i \times L$$

It is recommended that VHD be used in ranking projects, of which project lengths have been pre-determined. VHDPM and AHD are more suitable for system-wide screening to identify bottleneck.

Ramp Performance Measures

Probe speed data are available and adequate for almost all ramps in Kentucky. Therefore, delay can be estimated when ramp volume data are available. In rare cases where ramp speed needs to be estimated, the methodology presented in the HCM 6th Edition was experimented primarily for assessing the operational conditions on ramps. However, the method was for this study. Later, it was decided that HERS-ST for freeways would be applied for ramps. As for the performance measures, VHDPM and AHD are used as mentioned in the previous section.

For projects involving interchanges or ramps, it is recommended that project mapping be expanded to include the portion of the connecting roadway that may be subject to the impact of queue spillover.

Project Ranking Formula

To prioritize projects, VHD is chosen as the recommended measure of congestion. VHD is estimated for each project for a typical weekday daytime period of 6am-8pm using speed data for the years of 2015-2017.

To reflect the strategic significance of highway types, a FC adjustment factor (f) is applied to the scaled VHD. The factors are shown in **Error! Reference source not found.**.

Table A1 Functional Classification Adjustment Factor

FC	1	2	3	4	5	6	7
Adj. Factor (f)	1	0.95	0.90	0.85	0.80	0.75	0.70

Congestion Measure (CM) = VHD-Scaled * f

Statewide Score = 20% * CM　　Regional Score = 10% *CM