Network Performance Measures for Arterials—A Systematic Level Perspective

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Introduction

This report introduces a framework for arterial network performance measures and management. Rather than investigating new performance measures, this report focuses on how to effectively use existing performance measures to track network performance as a whole across time and to communicate that performance effectively with many audiences. This report is being generated at a time when the US Department of Transportation (US DOT) is promulgating rules for congestion reporting as a result of the Moving Ahead for Progress in the 21st Century Act (MAP-21) legislation. As part of this activity, US DOT has developed rules to standardize reporting of congestion on the freeway and principal arterial system of the United States. The method of network performance assessment presented in this report is not intended to supplant, challenge, or provide recommended alternatives to the current US DOT MAP-21 measures. Rather, this report presents a framework for a municipality or roadway jurisdiction to track the performance of their arterial network system, which spans various functional classes, in such a way as to effectively assess, communicate, and track progress towards goals over a long period of time and communicate that progress to a large constituency that, for the most part, does not have in depth knowledge of arterial or traffic engineering. The MAP-21 measures are directly analogous to other data reported in the federal Highway Performance Monitoring System (HPMS) which is intended primarily to create a consistent reporting mechanism from states to the federal government. Although the goal of MAP-21 is consistency of nationwide performance tracking, the audience is typically other engineers educated in the field and the data is used to support federal initiatives or federal perspectives of the state of the US travel network. As will be introduced later, this report uses a management construct, effectively first applied to pavement management systems (PMS), which characterizes performance at three levels: good, intermediate and poor. Similar to congestion, states are required to report pavement condition, as part of HPMS data submittals, based on common engineering measures such as the international roughness index (IRI). The construct presented in this report is based on standard engineering measures but uses a framework for creating an effective management system that incorporates a language which is much easier to communicate to a broad local constituency, including non-technical audiences.

This report broaches the subject of how to rate the health of an entire arterial roadway network, rather than individual intersections and corridors. Whereas performance measures and associated visualizations, such as the *Purdue Coordination Diagrams*, *Travel Time Cumulative Frequency Diagrams*, and capacity assessment based on red-occupancy-ratio (ROR) and green-occupancy-ratio (GOR), provide effective metrics to diagnose issues at the intersection and corridor level, such metrics fail to inform a larger audience (without specialized knowledge in traffic engineering) on the health of the entire network. An effective network performance measure answers the question of whether the network of urban arterials in aggregate are performing well, performing poorly, or performing somewhere in between. Similar inquiries include: ‘*Has the arterial network declined or improved over the past five years?... and to what extent?*’, or ‘*What improvement in performance has been experienced from major capital investments in the upgrade of signal controllers and detectors?*’. Such questions are the focus of this report. This report proposes a framework for assessing system wide performance, based on an approach used in other infrastructure management programs.

It is true that some individual metrics can be aggregated across an entire network to provide measures that reflect some type of average for all the roadways and intersections in the network. An example is the probability of stopping at a signalized intersection. This probability can be calculated from high-

resolution controller data, which is the basic data needed to produce the Purdue Coordination Diagram. The probability of stopping can be aggregated for a corridor, region, or even a city, metro area, or a state. For example, a statewide analysis by Utah Department of Transportation using high-resolution data resulted in the headline shown below.

Odds of hitting a red light in Utah? Just 1-in-4

Salt Lake City Tribune, Dec 23, 2013

This same approach of aggregating a single engineering metric to the entire network can be used with various measures. Even travel time can be normalized, using minutes per mile or miles per hour, and averaged in various methods such that a single measure can be produced at various levels of aggregation. Though feasible, such metrics provide insufficient information on the health of the system to understand the network's ability to meet the expectations of the traveling public. Ranges within such a metric indicating desired or good operation from an engineering perspective could be introduced (similar to "Level of Service" measures from the Highway Capacity Manual [1] (HCM) for intersections or corridors) but will still fall short of concisely communicating the health of the signalized arterial roadway system in a meaningful way to the voting public, elected officials, or executive management in a manner to support funding or influence decisions involving other competing programs.

Network level performance criteria are typically used to communicate how the system is performing to an audience beyond the technical community responsible for the care and maintenance of the system itself. A functioning Network Performance Framework should include the following characteristics:

- Top level measures provide intuitive qualitative feedback to a broad audience that would not typically possess specialized technical knowledge, yet can still be presented in a quantifiable scale.
- Network measures take into account numerous technical aspects, but abstract the complexity – in much the same way that an academic grading system of A,B,C,D & F takes into account numerous scores on exams, homework assignments, and other criteria to reflect the overall quality of a student's performance.
- The performance of an individual signalized intersection or a corridor contributes to overall network measures, such that the improvement in a single intersection or corridor will impact the overall health index, but not be unduly weighted.
- Though presented as a qualitative scale, the composition of the metric is fully based on objective, measurable, and traceable attributes of the system, and the network measures can be replicated by any appropriately trained personnel, and they do not rely unduly on engineering or professional judgment.
- The network measures can be used to track performance over time, as well as compare performance from one region to another.

The National Transportation Operations Coalition asked its members to rate their traffic signal operations on an A through F grading scale, giving the general public insight into the state of the industry even

without any engineering knowledge of traffic signal operations. Indeed, in 2011, the industry rated itself a D, indicating to the public the need for additional funding to keep the system in good condition. In a similar manner, arterial network performance should carry a relative quality scale to the general public without the need of specialized engineering knowledge.

Specific to arterial performance, network measures additionally have to account for varying expectations of how the roadway should operate based on the type and function of the facility. For example:

- High level arterials whose primary purpose is to provide through movement of traffic are expected to have greater speed and capacity, and highly coordinated signals to improve throughput efficiency. Such roadways interconnect freeways to mid-level arterials which in turn distribute traffic to commercial properties and local streets.
- Mid-level arterials provide access to commercial properties, and intersect with collector streets. Frequently such roadways have pedestrian facilities and a higher proportion of turning movements than through traffic, especially at intersections providing access to traffic generating land uses. A mid-level arterial is expected to operate at a moderate speed, have signal coordination between major intersections (across minor side streets intersections), and have adequate split times to service all the turning movements, particularly at peak periods.
- Low-level arterials connect residential and local streets to mid-level arterials, typically have pedestrian facilities, and may have entrances to businesses and residences apart from roadway intersections. Such roadways will also have un-signalized intersections with side streets. Accessibility takes precedence over speed and progression on such facilities. Consequently, speeds are lower and signal coordination is a lower priority concern.

In reality, the classification of arterial roadways from high to mid to low occupies a continuous spectrum of tradeoff between throughput and land access for vehicles as well as varying levels of pedestrian facilities. An appropriate network framework will accommodate varying expectations and appropriately weight various performance attributes to create a meaningful overall qualitative scale.

The approach taken in this report is adopted from another infrastructure management domain that faces many of the same challenges as arterial management. That domain is pavement management. Although the overall objective in pavement management is to provide a safe and smooth ride to the traveling public, the appropriate metrics vary significantly by roadway type, composition, and function. The authors use the pavement management system that has been used at the Kansas Department of Transportation (KDOT) for over three decades to illustrate and draw parallels to a proposed framework for the management of arterial roadways. The fundamental aspects of the KDOT pavement management approach are summarized as follows:

- Performance is judged as belonging to Level 1, Level 2, or Level 3, in much the same approach as academic evaluations use grades A, B, C, D and F. Level 1 is the most desirable state of roadway pavement, reflecting a range of attributes that when taken as a whole are considered to be good or adequate performance for pavement. Level 3 is the non-desirable state reflecting roadway surface conditions that are in need of attention or some type of remediation to be considered minimally adequate. Level 2 is any roadway pavement condition in between. These

are roadways that do not perform to full expectation, but also are not performing so poorly that some type of immediate remediation may be called for.

- The network is divided into classes or sub-networks in which the roadways serve similar functions and have similar expectation of performance. For pavements, the classes are determined by the pavement composition (concrete versus asphalt), Interstate versus non-Interstate, and average daily load. Within the bins established by these attributes, appropriate base level engineering metrics, as well as appropriate thresholds are identified that reflect the overall quality of the roadway pavement. The earlier discussion classifying roadways as high, mid, and low level arterials is one such classification appropriate for arterials network performance. Within each class of roadway, the expectation of performance should be consistent.
- Primary engineering metrics, also called condition metrics (to differentiate from the overall network performance measures) are identified within each class. Multiple condition metrics combine to form a condition index (also called a condition state index) that reflects the overall health or quality of a specific roadway. For pavement management, such metrics include ride quality, as measured by the International Roughness Index (IRI), various pavement cracking measures, specific to either concrete or asphalt, degree of rutting on asphalt pavements, and degree of faulting on concrete pavements. Condition metrics for arterials could encompass the measures introduced in previous research such as travel time and travel time reliability as evidenced by re-identification data, quality of progression measured by the probability of stopping along a corridor (using the same data needed for the Purdue Coordination Diagram), and capacity restriction as provided by capacity analysis in the ROR/GOR metrics at intersections. Mid and lower level facilities may have additional condition metrics that reflect access and safety of pedestrians and vehicles. For each condition performance criteria identified, condition levels 1, 2, and 3 are defined, with 1 being highest level or desirable range, 3 being lowest or undesirable, and 2 falling in between. The reasoning behind condition metric levels is consistent with the network performance level philosophy.
- Lastly, the network performance levels of 1, 2 and 3 are mapped to the condition metrics for each arterial class. A condition state for a specific roadway is a combination of the condition levels (1, 2 or 3) of its primary conditional performance measures. For example, on Interstate concrete pavements the three condition measures at KDOT are the IRI, joint distress, and degree of faulting. If the IRI measure falls into the range for a condition level 1, the cracking measure falls into the range of condition level 2, and the faulting measure falls into the range for a condition level 1, the overall condition state for the segment of concrete Interstate pavement would be a 121. A network level 1 performance is then defined by the allowable condition states of the performance condition indicators. A network level 1 performance may encompass condition states of 111, 211, 121, 121, and 122. Level 3 network performance may include condition states of 333, 223, 232, 322, 133, 313, or 331. Level 2 would then include all remaining condition states. In the same way, the conditional states for arterials would be mapped to overall network performance levels.

This report outlines a framework for defining network performance using top level network categories of 1, 2, and 3, analogous to a good, intermediate and poor rating scale. Overall health can be communicated

by the proportion of the system in good condition, which is level 1, and the proportion in a poor condition, or performance level 3. Sample roadway class definitions and condition metrics are identified for arterial networks.

The baseline data needed to develop network performance measures could potentially be chosen from a variety of sources. The Highway Capacity Manual, for example, provides a series of analysis techniques for evaluating the Level of Service (LOS) on a variety of facilities. The LOS is defined by various measurable roadway attributes and estimated performance based on limited traffic counts. The LOS is an A to F grade system based on a particular performance measure for a given facility. Though well established, HCM measures are based on measurement philosophies that are neither continuous nor real-time. The data for HCM measures is periodically sampled using a minimal number of floating car runs. The network framework illustrated herein is founded on measures supported by modern arterial performance data which includes travel times from re-identification technology and signal performance from high-resolution controller data, both of which continuously log performance. Using these new methods, service on a minor movement at a signalized intersection may be measured directly across a number of cycles for which the green time was not adequate and the quality of progression along an arterial corridor can be jointly measured by the probability of stopping and by the measured travel time through the corridor. The results from these modern methods are similar in spirit to aspects of the LOS for signalized intersections and urban streets but these methods are intended for use in an environment where continuous monitoring is possible, rather than periodic estimation based on travel time runs and traffic counts. The authors acknowledge that the network performance measures framework could equally be applied using older HCM methods, though with less granularity.

The report is organized to familiarize the reader with the framework without undue complexity. The goal of the framework is to facilitate top level assessment of the health of an arterial network for use in budgeting, prioritizing programs, and communication with elected officials, executive staff, and voter constituency. This framework enables discourse on the overall health but also, extensions to this methodology can be used as management tools to model, predict and optimize performance within a constrained resource environment.

The report is organized into five chapters as described below.

Organization of Report

Chapter 1. A Performance Level Framework from a Pavement Management Perspective

The performance measure framework adapted for arterial roadways is modeled from one used for pavement management at the Kansas DOT. The Kansas system masks the complexity of engineering metrics in order to yield an effective means to communicate overall pavement performance to a wide range of non-technical constituencies. This chapter summarizes the technical framework and provides graphical examples of how the system effectively captures and communicates network level performance. The goal is for the reader to recognize the potential in the approach and begin to draw analogies of how it can be employed for arterial network management.

Chapter 2. Classification and Segmentation of Arterial Networks

In order to employ the proposed framework, the arterial network system within a metropolitan area must be divided into classes in which the operating states within each sub-network are similar enough so as to have consistent expectations of performance. For illustration purposes, the report defines sample road categories of arterials based on expectations of throughput versus access as discussed earlier in the introduction, and enumerated in the 2000 Highway Capacity Manual.

Chapter 3. Selection of Performance Condition Metrics

Objective and measurable performance criteria are identified as condition indicators for arterial roadways. For each condition indicator, thresholds appropriate for each arterial class, as identified in Chapter 2, are established.

Chapter 4. Map Segment Condition States to Network Performance Levels

The condition metrics are aggregated to condition states and then mapped to network performance levels 1, 2 and 3. This step relies on engineering expertise and judgment to set policy on which states of the roadway correlate to customer expectations for well performing arterial segments and poor performing arterial segments. This is the final step in transforming highly technical engineering data into measures that can be communicated effectively to a non-technical audience.

Chapter 5. Implementation and Extension of the Network Level Measurement Framework

Implementation of such a framework is not a minimal task. It requires institutional commitment, dedicated resources, and a well laid out plan. This chapter also describes extensions to the framework such as network level performance objectives, projections of performance, and optimization schemes as also used in pavement management.

Chapter 1: A Performance Level Framework from a Pavement Management Perspective

Pavement Management Systems are typically employed at state wide levels to assist in the allocation of funding, selection of projects, and the selection of project scopes in order to effectively manage limited public funds to the maximum public benefit. At the heart of a pavement management system is a performance analysis framework that allows an ‘apples to apples’ comparison of the condition and relative need of remediation of varying roadway surfaces despite inherent differences in pavement materials, roadway function, and distress mechanisms. The ability to quantify how well the roadway running surface performs with respect to driver expectations, and to do so across all roadway types within a state, provides the key information to fairly and equitably allocate limited financial resources statewide. Furthermore, such information, when properly communicated, provides a method to report to elected officials and the voting public the return on investment of public resources.

Assessing statewide pavement performance presents many challenges analogous to arterial performance. Varying roadway functions, types of construction, and varying distress metrics and deterioration mechanisms create a complex and challenging environment from which to compare and contrast needs and performance. The Kansas Pavement Management System (PMS) is showcased to show how these challenges were addressed in a robust framework to create appropriate network performance measures. This framework, which has been successfully employed for over three decades, abstracts the complexity of various technical and engineering metrics to yield an effective means to communicate overall pavement performance to a wide range of non-technical constituencies. This chapter summarizes the technical framework, and provides graphical examples of how the resulting framework effectively captures and communicates network level pavement performance. The goal of this chapter is to illustrate the potential in the proposed approach so that the reader can begin to draw parallels of how a similar methodology can be employed for arterial network performance.

1.1 Defining Network Performance Levels

At the very top level the Kansas DOT defined three performance levels of a roadway, denoted as performance level 1, 2, and 3, to reflect the degrees to which the running surface meets the expectation of the user.

- Performance Level 1 – Good pavements not in need of attention or remediation. They adequately meet the user’s expectations in terms of ride quality and condition. Level 1 condition is the desirable state of the roadway.
- Performance Level 2 – Level 2 pavements are not in top repair or condition, but still yield a ride quality that is adequate. It may be considered rough, or in need of some maintenance, but not degraded to undesirable ride quality.
- Performance Level 3 – Poor pavements that fail to meet user’s expectations in terms of ride quality and condition. When traveled upon, Level 3 pavements ‘draw attention to themselves’, and create an undesirable experience for the driver.

These basic definitions of performance are mapped to measurable technical attributes. These top level definitions are communicated and shared with the widest possible audience. Even though elected

officials, executives, and the public are welcome to drill down to the technical attributes from which the network level performance is derived, it is these top level descriptions of pavement performance that form the basis of interacting with state legislature, competing with other programs for funding, and setting policy on long term objectives, as well as reporting back to the legislature and the public on progress towards those objectives. Figure 1.1 illustrates a common visualization of pavement performance on the Kansas highway system over a multi-year time period. This graph is updated yearly based on a thorough survey of state roadways conducted in late spring. The graph tracks the percentage of the state highway system in performance level one (PL1), and performance level three (PL3) from 1983 through 2014.

Figure 1.1 Performance of Pavements on the Kansas State Highway System

The graph in Figure 1.1 succinctly characterizes several attributes concerning the system.

- The figure tracks the proportion of the state system, >10,000 miles, in network performance levels 1 and 3 from 1983 to 2014, providing a historical perspective of over 31 years.
- Performance is called out separately for Interstate vs Non-Interstate. This differentiation is due both to differing performance objectives as well as differing funding mechanisms that support their maintenance.

- Only PL1 and PL3 are graphed, while PL2 is inferred. This also corresponds to the method used to set performance goals by the Kansas DOT. Performance goals target the minimum proportion in PL1 (such as >85%) and the maximum proportion in PL3 (such as < 5%) that is acceptable. The goals may change depending on public feedback, available funding, and needs of other programs competing for limited state funding.
- This framework of network performance measurement was instituted in 1983 concurrent with major investments in the improvement of the Kansas Highway System (KHS) by the state legislature. The state funding bill also required a systematic statewide method for assessing and reporting the quality of the roadway network which lead to the formation of the Kansas PMS, and which tracked the consistent improvement of the KHS as a result of the infrastructure investment.
- Note the dip in performance of Non-Interstate PL1 starting around 2004. This coincides with a downturn in economy resulting in less funding for roadway maintenance. The decision was made in 2003/2004 to keep the interstate performance targets at existing levels, while relaxing the non-interstate performance targets (and thus reduce funding to the non-interstate system).
- The graph encompasses the whole roadway system, including portions added and taken away over the course of three decades.

This fundamental graph provides the vision of what is possible with arterial networks. Rather than speaking in technical terms of progression, capacity, travel time or reliability, this approach aggregates all base performance metrics into three categories, a state of roadway that is considered good or desirable (PL1), a state of roadway that is considered deficient and not acceptable (PL3), and everything else in between (PL2). Just as the Kansas PMS assessed and tracked the health of the PMS and garnered consistent funding support in the process, an effective framework for arterial network performance assessment may have similar results.

In order to create this view of the system, the state highway network was appropriately divided into subclasses, and individual metrics applied to each subclass to assess performance.

1.2 Roadway Classification for Pavement Management

Although Figure 1.1 depicts only two roadway categories (Interstate and Non-Interstate), the performance levels for each were aggregated from 23 road categories as illustrated in Table 1.1 below. Five road categories describe various Interstate facilities and the remaining 18 road categories sub-divide Non-Interstate roadways.

Table 1.1 Kansas DOT Pavement Management Road Categories

Road Category Number	Functional Classification	Pavement Type	Roadway Width	Design Lane ADL
1	Interstate	PCC	ALL	0-749
2		"	"	750-9999
3		Composite	"	0-749
4		"	"	750-9999
5		Full Design Bituminous	"	0-9999
6	Other	PCC	"	0-87
7		"	"	88-162
8		"	"	163-9999
9		Composite	"	0-87
10		"	"	88-162
11		"	"	163-9999
12		Full Design Bituminous	<32'	0-22
13		"	"	23-50
14		"	"	51-9999
15		"	>32'	0-22
16		"	"	23-50
17		"	"	51-9999
18		Partial Design Bituminous	<32'	0-22
19		"	"	23-50
20		"	"	51-9999
21		"	>32'	0-22
22		"	"	23-50
23		"	"	51-9999

The roadway categories were chosen such that the expectations of performance were consistent within each category, and the base level conditions metrics that determine performance were also consistent within the road category. Note that *roadway width* within the Kansas PMS system was primarily a cost consideration needed as part of the optimization program that selects candidate projects to meet management goals. Performance expectations for roadway widths >32' and <32' are consistent in the Kansas PMS system, however, the road categorization scheme would allow for differentiation in expected performance if deemed necessary in the future.

1.3 Condition Level Performance Measures

The performance within each road type is based on engineering measures. Condition performance measures for the Kansas DOT pavement management system are summarized in Table 1.2 below. Common to both asphalt and concrete pavements is the level of roughness as measured by the International Roughness Index, or IRI, the primary condition measure. The condition levels for roughness were set by a user survey in which participants rode in a standard vehicle across varying roadway conditions. The user survey assisted in setting IRI thresholds for good, acceptable, and rough pavement. The IRI that correlated to the user surveys were chosen as boundaries between condition levels of 1, 2 and 3.

Table 1.2 Condition Performance Metrics for Kansas Pavements

Asphalt

- **Roughness Level**
  - 1 IRI from 0 – 105 in/mile
  - 2 105-165
  - 3 >165
- **Transverse Cracking**
  - 1 “a few small and not depressed”
  - 2 “some, wider, few depressed”
  - 3 “many/wide/depressed”
- **Rutting**
  - 1 <0.25 inches
  - 2 0.25 – 0.5
  - 3 >0.5

Concrete

- **Roughness Level**
  - 1 IRI from 0 – 105 in/mile
  - 2 105-165
  - 3 >165
- **Joint Distress**
  - 1 “none to little”
  - 2 “some not severe”
  - 3 “send a tow truck”
- **Faulting**
  - 1 “none to little”
  - 2 “starting to feel it”
  - 3 “will this ever end”

The second and third condition metrics are specific to the type of pavement. Transverse cracking and rutting are used for asphalt pavement and joint distress and faulting for concrete pavements. The levels for these are determined by engineering experts with respect to the condition and expected life of pavements. Even though the definitions in Table 1.2 may appear seemingly subjective, such as ‘a few small and not depressed’ for transverse cracking, these subjective descriptions are further defined by the number and extent of observed cracking patterns in yearly surveys. Note the somewhat whimsical descriptions of condition levels for joint distress and faulting. Actual threshold definitions are quite detailed based on consistent methodology and industry standard practices. An example of the precise definition of joint distress is shown below as an example.

Joint Distress Levels:

1. Most joints show no distress or only staining
2. At least 10% of joints have cracking along ¼th of the joint and no joints have 3 or more inch spalls over ¼ of the joint length
3. More than 50% of joints have cracking along ¼th of the joint or are spalled more than 3 inches over ¼th the joint length

1.4 Mapping Condition State to Performance Level

Each mile of roadway segment on the Kansas Highway System is rated for three condition performance measures. For each of the three measures, the pavement segment is assigned a condition level of 1, 2 or 3 according the definitions in Table 1.2. After the yearly pavement condition survey is complete, the performance of each mile on the system can be characterized by a three number condition state reflecting its condition level for each condition performance measure. For example, a condition state of 111 indicates that the segment of highway performed in the top tier in all three condition performance measures. A condition state of 333 indicates quite the opposite. The Kansas DOT system employs three condition measures, each with three levels, bringing the total number of possible condition states to 27 for each segment. Each of the 27 possible condition states is assigned to a network performance level of 1, 2, or 3. This mapping is performed for each type of road category.

An illustration of this mapping for the Kansas PMS is shown in Figure 1.2. Each condition state is mapped to a corresponding network performance level (1, 2, or 3). Note that Figure 1.2 has four columns labeled *PCCP*, *Composite*, *F.D. Bit* and *P.D. Bit*. These four columns correspond to subsets of the road categories defined in Table 1.1 based on pavement type. *PCCP* encompasses road categories 1,2,6,7, & 8. *Composite* encompasses road categories 3, 4, 9, 10, &11. *F.D. Bit* encompasses road categories 5 &12-17. *P.D. Bit* encompasses road categories 18-23. The mapping from condition state code (DS Code) to performance level is consistent within pavement types, allowing the table in Figure 1.2 to be condensed to four columns.

Performance Levels Assigned to each Distress State

DS Code	PCCP	Composite	F.D. Bit	P.D. Bit
111, 112	1	1	1	1
113	1	1	1	2
121, 122	1	1	1	1
123	1	2	2	2
131, 133	2	2	2	2
211	1	1	1	1
212	1	1	1	2
213	1	1	2	2
221	1	2	2	2
222	1	2	2	2
223	2	2	2	2
231-233	2	2	2	2
311	2	2	3	3
312, 313	3	3	3	3
321 - 323	3	3	3	3
331 - 333	3	3	3	3

Good!

Poor!

Figure 1.2 Condition States Mapped to Performance Levels

In the KDOT PMS, these assignments were based primarily on customer expectation, but also on the ability to change the condition to a more desirable state. As an example, early in the development of PMS there were very few options to cost effectively improve the condition of rough concrete pavements. A concrete pavement that was structurally sound but was rough was assigned a better performance level than a comparable asphalt pavement because the only ways to fix such concrete pavements were very expensive, but the asphalt pavements could be fixed at a reasonable cost. Later, more cost effective methods for fixing concrete roughness (such as diamond grinding) became available. As a result, KDOT was faced with a choice to keep the assignments the same to maintain historical consistency, or to change the condition state to performance level assignments to reflect the change in options.

The mapping of conditions states to performance levels allows for performance reporting as illustrated in Figure 1.1. The ranking or performance levels (such as a 111 being better than a 212 even though both are mapped to a performance level 1) can still be preserved and used in management tools. The definition of a *benefit* term is a further refinement of the condition state that is more suited for optimization tools. Indeed, within the Kansas PMS, a benefit is also assigned for each segment based on its condition level. This benefit metric is a value from 0 to 1 based on the pavement type and the condition state. A condition state of 111 for any pavement types gets a benefit of 1. A 211 for most pavement types is assigned a benefit of 0.85, and so on. Defining a benefit term is not necessary for reporting network performance, but is useful for extensions in which optimization criteria are introduced to select projects to maximize anticipated utility or minimize cost.

1.5 Extensions of the Kansas PMS Performance Measure Framework

This method for creating a top level metric (Performance Level 1, 2, and 3) based on technical data collected yearly forms the basis of a network performance management system. The base condition performance metrics combined with the engineering expertise and judgment of Kansas DOT pavement engineering staff to appropriately set thresholds for condition levels produce a system which can objectively track performance. When the condition metrics are mapped to network performance levels, the percent of pavement falling in each level can be used to easily communicate and track the state of the system. Conversely, goals that indicate the percentage of pavement in PL1 and PL3 are set by Kansas DOT management to comply with available funding and balance needs in other infrastructure programs.

The Kansas PMS has several extensions to help manage the system. Pavement performance models have a useful property in that they can facilitate predictions of system conditions under different investments. For example, a Markov state probability model can be used to project likely future pavement conditions based on current state and different maintenance levels. A pavement with a condition state of 122, and for which routine maintenance is applied, has a measurable probability to transition to a group of other condition states when measured the following year. It is not likely to improve its state with just routine maintenance. Rather, it is likely to remain in its current state (122), or slightly degrade (such as 222, 123, or 132). A probability is assigned to each of these outcomes, for all possible initial states and applied actions. Initially these probabilities were assigned using a modified Delphi approach using a panel of experts. The experts were asked to predict the future conditions given the current conditions and possible improvements (or routine maintenance). Once several years of actual data were available, the models were refined.

This model is combined with the anticipated impact of various pavement maintenance and rehabilitation strategies, and with the cost of each strategy. Combined, the models and framework can be used in an optimization engine. If a performance goal is requested by management or the legislature (such as raising the minimum proportion of pavements in PL1 from 85% to 90%, while maintaining a maximum of 5% in PL3), the system can calculate the minimum cost for achieving the stated objective, the portfolio of maintenance and rehabilitation strategies required, and the length of time needed to move from current conditions to the desired performance. Similarly, in leaner economic times, the system can predict the long term impact on pavement performance if maintenance and rehabilitation funds are channeled to other programs. The system will predict the proportion of pavement falling into PL1 and PL3 based on the level of funding. Indeed the system has been utilized to estimate and appropriately set expectations whenever funding for ongoing pavement management activities was significantly changed.

Chapter 2: Classification and Segmentation of Arterial Networks

2.1 Choosing Roadway Categories

The remaining chapters introduce a network performance measure framework for signalized arterials similar in structure to that used for Kansas pavement management, but customized to the unique challenges and demands of a metropolitan signalized roadway system. The first challenge is to segregate the network into appropriate roadway classes such that the expectation of performance within the classes is consistent and the base level condition performance measures and thresholds are also consistent. If at some point the system may also be used for optimization and other management tools in addition to performance monitoring, additional factors for developing roadway classes may be warranted in consideration of remediation or corrective actions. The set of remediation or corrective actions also need to be consistent within a roadway classification.

Several classification systems already exist for roadway types, such as the Highway Performance Monitoring System (HPMS), A Policy on the Geometric Design of Highways and Streets [2] produced by the American Association of State Highway and Transportation Officials (AASHTO) (frequently referred to as the AASHTO Green Book), and the Highway Capacity Manual (HCM), to name just a few. The definitions found in established classification systems are consistent with the needs of a network management framework and can serve as a starting point to appropriately sub-divide the network.

The attributes that impact arterial classification are varied. A recent study by the University of Maryland for assessing probe traffic data accuracy cataloged the geometric and operational attributes of several corridors sampled from a multi-state region. The metrics that were cataloged form a basis from which to consider appropriate attributes for classification for network performance levels. Table 2.1 provides a sample of the attributes cataloged in the study.

Table 2.1 from study that correlated traffic data accuracy to geometric road attributes

Segment NJ-00##	GEOMETRIC DESCRIPTION						TMC CODES		BTM Data		General Description and Notes (All lengths in miles and speeds in MPH)	
	Crossroads		Lanes	AADT	Signals				Sensor			
	Starting at	Min	Min	#	Access Points	Med	Begin	Len	Beg	Length		
	Ending at	Max	Max	#/Len	Speed Limit	Maj Junct	End	#	End	% Diff		
US-1 Northbound in New Jersey, commonly known as Trenton Fwy or Brunswick Pike NJ11-0001 to -0007												
03	US-1 Bus/Brunswick Pike		2	33352	1	9	Yes	103P04923	0.75	C	0.74	1/3 in Trenton Fwy, 2/3 in Brunswick Pike, Ends with signalized intersection with Bakers Basin Rd.
	Bakers Basin Rd/Franklin Corner Rd		3	47987	1.3	55	0	103P04924	3	D	-1.2%	
05	I-295/I-95		3	87729	0	11	Yes	103+04926	1.16	Q	1.12	Brunswick Pike, Grade separated intersection with Quakerbridge Rd/US-533
	Quakerbridge Rd		4	89635	0.0	55	0	103P04926	2	I	-3.5%	

Measureable attributes of an arterial corridor shown in Table 2.1 include:

- **Number of Lanes** - the minimum and maximum number of through lanes observed on the corridor obtained from aerial photography.
- **AADT** - the minimum and maximum AADT reported as obtained from the publicly released Highway Performance Monitoring System (HPMS) shapefiles.
- **Signals: Number and Density** -the total number of signalized intersections on the segment. If the segment begins at a signalized intersection, that intersection is not included in the count (it will be included in the preceding segment). Density is calculated by number of signals divided by segment length.
- **Number of Access Points** –includes intersections with other roads (other than signalized intersections), and entrances to business centers and malls. Data is obtained from aerial photography.
- **Speed Limit** – posted speed limit as obtained by street view photography.
- **Median Barrier** – the existence of a median barrier on the segment that prevents left hand turning movements except at designated access areas as obtained by aerial photography.
- **Number of Major Junctions** - the number of junctions with another roadway of significantly higher class such that the segment acts as a feeder/distributor to another roadway at that junction. Criteria for a major junction:
  - If crossroad is a freeway
  - If crossroad intersection is a grade separated interchange and the number of through lanes is the same or greater than the segment
  - If crossroad intersection is signalized, the number of through lanes of the cross road is greater than the segment
- **Length of roadway segment**- the combined length of the segment in miles.

Other attributes of an arterial corridor not shown in Table 2.1 include:

- **Presence of sidewalks** – presence of sidewalks within the segment as obtained by street view photography.
- **Left turn and right turn lanes** – presence of turning lanes
- **Lane Width**
- **Type of curb / shoulder**
- **Presence of steep grades**
- **Presence of bike lanes**
- **Presence of bus stops / transit stops**

Many, if not most, of these attributes are considered in published road classifications systems. For the purposes of illustration, the authors chose the HCM published in 2000 as the basis for which arterial roadways are classified into four categories based on function and design. A broad overview of the four classes is provided below. Detailed characteristic, geometric, and operational parameters are provided in Chapter 10 of the HCM 2000, specifically Exhibits 10-3 and 10-4. Note, the authors provide this classification for illustration purposes. This or other arterial road classification systems can serve as a basis and can be further customized to suit the local jurisdictions expectations for consistent performance.

The 2000 HCM uses a combination of the AASHTO Green Book functional categories combined with design criteria to define four classes of arterials. The design category depends on the posted speed limit, signal density, driveway/access-point density, and other design features to classify the segment as either a high-speed, suburban, intermediate, or urban roadway. The combination of the AASHTO functional category of either principal arterial or minor arterial combined with the four design categories determines which of the four classes (I, II, III, or IV) into which a roadway falls. The AASHTO functional categories and the four HCM design classes are summarized in the following inset (next page).

The AASHTO functional categories are divided into principal arterial and minor arterials:

- A principal arterial serves major through movements between important centers of activity in a metropolitan area and a substantial portion of trips entering and leaving the area. It also connects freeways with major traffic generators. In smaller cities, principal arterials also service traffic passing through the urban area. Service to abutting land is subordinate to maintaining efficient through traffic.
- A minor arterial connects and augments the principal arterial system. Although its main function is traffic mobility, it performs this function at a lower level and places more emphasis on land access than does a principal arterial. Minor arterials service trips of moderate length, and frequently serve as collectors and distributors for principle arterials and activity centers.

Within the 2000 HCM, roadways are further classified by their design criteria as specified below:

- High-speed design has very low driveway/access-point density, separate left-turn lanes and no parking. It may be multi-lane divided or undivided or a two-lane facility with shoulders. Signals are infrequent (0.5 to 2 signals per mile), roadway development is low density, and speed limit is typically 45 to 55 mph.
- Suburban design has low driveway/access-point density, and, similar to high-speed design, separate left-turn lanes, no parking, and may be multi-lane divided or undivided, or a two-lane facility with shoulders. Signal density is 1 to 5 per mile, and timed for good progression. Roadside development is low to medium density and speed limits are usually 40 to 45 mph.
- Intermediate design reflects roadways with moderate driveway/access-point density. It may be multi-lane divided, an undivided one-way, or a two-lane facility. Left turn lanes may be present, as well as some portions where parking is permitted. Signal density is 4 to 10 signals per mile, servicing higher density roadside development than suburban design, with speed limits typically 30 to 40 mph.
- Urban design represents roadways with a high driveway/access-point density, with roadway geometries that frequently include undivided one-way or two-way facilities with two or more lanes. Parking is usually permitted, separate left-turn lanes are sparse, if they exist at all, and pedestrian activity is present at intersections. Signal density is commonly 6 to 12 signals per mile. Roadside development is dense with commercial uses and speed limits range from 25 to 35 mph.

The urban street classification (I, II, III, or IV) is established in consideration of both the functional classification (principal versus minor arterial) and the four design categories as shown in Table 2.2 (recreation of Exhibit 10-3 of the 2000 HCM).

Table 2.2 Urban street classification (from 2000 HCM)

Design Category	AASHTO Functional Category	
	Principal Arterial	Minor Arterial
High-Speed	I	N/A
Suburban	II	II
Intermediate	II	III or IV
Urban	III or IV	IV

The urban street classifications (I through IV) as given in Table 2.2 and supported by the 2000 HCM is the basis for the arterial classification used in the sample framework. As with any classification system, there are sometimes ambiguities in determining classification, which then require engineering judgment. The reader is referred to HCM 2000 for additional reading on this classification system.

An important characteristic of roadway classification is the anticipated speed of traffic. The HCM uses the concept of a *free flow speed*, which is the speed that traffic is likely to exist in absence of congestion or control delay (that is, when traffic is flowing freely and avoids red signals). A summary of the free-flow speed and signal density for the arterial class I through IV are provided in Table 2.3.

Table 2.3 An example classification based on free-flow speed and signal density

Road Classification	Free-Flow Speed MPH	Signal Density Signals per Mile
I	50	0.8
II	40	3
III	35	6
IV	30	10

Any effort to apply a network performance level framework as described herein would require an initial effort by traffic engineers and transportation personnel, perhaps augmented by user surveys, to appropriately assess user expectations for various roadways. The end result will be a categorization system analogous to the 23 road categories for pavement management (similar to Table 1.1), wherein each road category is defined by objective and measureable attributes, and the expectations of performance in terms of the quality of traffic flow and methods to measure that performance would be consistent within each road category. The 2000 HCM road classification system is used to illustrate a possible arterial road classification system amenable to the network metric framework. It could also be used as a point of departure from which the jurisdiction either sub-divides or augments the 2000 HCM for further granularity. This four class system will be used for the road categorization basis for the remainder of the paper.

Note that the road classifications for arterial roadway categorization (i, ii, iii, and iv) shown in Table 2.3 are for illustrative purposes only. The categorization of roadways for any implementation of such a framework should be based on a network inventory of existing roadways in sufficient detail to support the classification.

To facilitate comparison across a diverse inventory of roadways, it would be desirable for classification criteria to be consistent in its application. However, at the same time, the system should be flexible enough to accommodate local roadway contexts. For example, a principal arterial in a dense urban area may have a lower speed than a minor arterial in a suburban area. The AASHTO Green Book uses different design controls for rural and urban areas, as well as flat and mountainous terrain. Ultimately, multiple criteria are needed to classify a roadway for evaluation purposes, and a balance struck between consistency and flexibility.

Once a roadway classification system is established, each roadway segment (the beginning and ending point of road segments are discussed in the next section) is assigned a road category.

2.2 Segmenting Arterial Roadways

‘Segmentation’ refers to the method of defining individual portions of a contiguous roadway for evaluation purposes. In the Kansas PMS, the 10,000 mile state highway system is divided into one mile segments. The one mile limits were originally an optimization requirement. Since the segments were nominally the same length, the network level performance could be aggregated directly from the proportions of segments without applying a weighting factor. Segments begin or end at political boundaries and roadway intersections (in addition to the one mile limits).

Similarly, the roadways within an urban area require segmentation into units for analysis and management. Segmenting by arterial type may be a considerably more challenging process than segmenting by pavement type, requiring judgment by the practitioner to segment roadways into homogeneous corridors. As with pavement management, the goal is to segment the system into manageable pieces, where each segment of roadway has consistent characteristics and performance expectations. General suggested guidelines are given below.

- **High Level Facilities:** Segment high-level facilities into longer corridors (several miles or longer) consistent with expectation of signal coordination.
- **Mid Level Facilities:** Segment mid-level facilities into one to three mile corridors, consistent with localized expectations of consistent flow. Segments should break if mid-level facilities intersect with a higher level facility or at an intersection with another mid-level facility with significant turning movements. If segments extend longer than 3 miles, they should be broken into shorter segments as necessary. Target two mile segments if possible.
- **Low Level Facilities:** Lower level segments should break at intersections with high level segments. Target one mile segment length if possible.

When complete, the network should consist of manageable segment sizes, with each segment having consistent expectations for operations and performance.

Note that it is important to break segments at the intersection with higher level facilities. For example, a minor arterial is expected to have coordinated signals at intersections with collectors and local streets. However, when a minor arterial intersects with a principal arterial, a common expectation is that the minor arterial will have a lower expectation of coordinated movement, because the principal arterial has higher priority.

When segment breaks occur at an intersection (as opposed to a midblock location), ambiguity arises as to what segment to attribute the performance of the intersection where the break occurs. Guidelines to resolve the ambiguity include:

- Attempt to break segments at “midblock” locations away from intersections with other arterials as opposed to breaking the segment at an intersection.
- When two arterials cross, break the lower priority road where it meets a higher priority arterial. The performance of the breakpoint intersection should be attributed into the higher level arterial segment, rather than affecting two segments of the lower level arterial.

Chapter 3: Selection of Condition Performance Measures

3.1 Candidate Condition Performance Measures

Condition performance measures, as identified in *Performance Measures of Interrupted-Flow Roadways using Re-identification and Signal Controller Data* [3], are proposed for use in the Network Performance Framework. These performance measures are based on re-identification data and high-resolution controller data and can quantify the quality of progression and the adequacy of green time for signalized movements. Re-identification data directly samples the travel time of vehicles along an urban corridor, providing not only average travel time, but also the distribution of travel time from which reliability metrics can be calculated. Travel time and travel time reliability are analogous to the International Roughness Index, in that they directly reflect the user experience. High-resolution controller data provides more detailed information on specific signal operations related to the scheduling and duration of green times. Examples include the successful (or unsuccessful) progression of arriving traffic, and whether standing queues are cleared by green during a signal cycle. As with pavement performance metrics such as cracking and rutting, such measures directly reflect the operations of the signal control as well as reflect failure mechanisms that directly impact the end user.

This report proposes the following condition performance measures as the basis for developing network performance measures based on re-identification and high-resolution controller data:

- ***Median Travel Time – measured in minutes per mile, or miles per hour***

Travel time, or equivalent space mean speed, directly measures the user experience on the roadway. Poor signal timing, inadequate green time, or other issues on the roadway ultimately increase travel time. Although travel time typically cannot be used to assess the cause of poor performance, it is a direct indicator of the arterial health from a user's perspective. In many respects it is similar to the International Roughness Index with respect to pavement management, providing a direct measure of user experience. Travel time based on re-identification data is directly measured, rather than inferred from spot speed measurements taken at discrete points along a roadway. Travel time, when normalized to the length of the roadway, is often expressed in units of minutes per mile. However, the inverse measurement, speed, may be easier for non-technical audiences to understand when converted to miles per hour.

The 50th percentile normalized travel time is recommended over a mean travel time, because of the prevalence of outliers in directly sampled re-identification data that tend to inflate the mean. On mid to low level facilities, vehicles may stop for gas, coffee, or other momentary stops, yielding greater than normal travel times which are difficult to filter. The median (50th percentile) is less sensitive to outliers than the mean.

Many public agencies use slightly different variations of travel time or speed-based measures to quantify congestion on urban arterial streets. In most of these measures, the travel time or space mean speed is compared to an expected or desired norm, such that a score of 1.0 or 100% is the best possible measure value. For example, the travel time index is a ratio that compares peak period travel times to those travel times during light traffic flow (best possible index value is 1.0). The Highway Capacity Manual recommends the percent of base free-flow speed for determining Level of Service on urban streets (best possible measure value is 100%). FHWA has proposed the Peak Hour Travel Time Ratio as a MAP-21 national system performance measure (applied on all

National Highway System roads, including 60,000 miles of principal arterial streets), which is calculated as the ratio of the peak hour travel time to the desired peak hour travel time. Despite these different variations of travel time-based measures, the central tendency of the measured travel time is in the numerator and it is compared to (or divided by) an expectation of the ideal or normal travel time. Although there is no consensus on the expected or desired norm to which the peak hour or peak period travel time is compared, the results are none the less correlated. Many have argued that this is a state or local policy decision that could even vary within a city (say, different expectations in an activity center then suburbs or exurbs). Within the management framework proposed, the expectation of travel time performance simply needs to be consistent with the roadway classification.

Delay (vehicular or person) is another travel time-based measure that has been used by several public agencies – and is closely correlated to travel time measures. Its primary advantage is that it accounts for the greater number of people and/or vehicles involved in congestion. As with travel time, delay would also need to be normalized by the length of the arterial corridors, resulting in delay per mile. The authors present travel time as the primary condition performance measure, but recognize that delay (which is directly calculated from travel time measurements) may also be used. Delay is the form of travel time measures most frequently used in Level of Service (LOS) calculation from the Highway Capacity Manual.

- ***Travel Time Reliability – difference in the 15th and 85th percentile normalized travel times***
Similar to travel time, reliability measures the variability of travel time experienced by travelers throughout the day, or during non-recurring congestion events. Travel time reliability is measured with respect to median travel time, similar to the coefficient of variation. The ratio is the difference between the 85th and 15th percentile travel time divided by the median travel time. Again, percentiles are used to avoid instabilities associated with the prevalence of outliers in continuously sampled re-identification data, particularly on mid and lower level facilities.

As with travel time, travel time reliability has been expressed in many different ways in the recent performance measure literature. Examples include the Planning Time Index, Buffer Time Index, coefficient of variation, and many others. Each of these is intended to measure the variability of travel time experience by the user as a ratio of the magnitude of variation divided by a central tendency or design travel time. The ratio of the difference between the 15th and 85th percentile travel time to the median travel time could be substituted for any of these reliability metrics without any substantial loss of meaning.

- ***Signal Coordination – minimum percent of traffic that progresses along a corridor on green***
This metric is based on the arrival and green time data, used to generate the Purdue Coordination Diagram, which is contained in a high-resolution controller from an intersection which has the ability to measure arriving traffic with appropriately located vehicle detectors. This metric, called “percent on green” (POG) measures the minimum percentage of traffic that is able to successfully progress along a corridor on the green phase. A simple implementation could assess this percentage in the direction of the dominant movement for the peak period. However, not all facilities will have a dominant direction at all times of day. An alternative, though a more complex methodology, would be to use a weighted score considering bi-directional traffic, with the weighting factors based on volume.

- ***Capacity Evaluation – percentage of cycle with a split failure***

A measure of the number of cycles during which the queues are not fully discharged by the green interval within an individual cycle. This is measured by analysis of the occupancy of vehicle detectors located near the stop bar, relative to the signal state, using high-resolution controller data. Split failures are defined by an occurrence when the Green Occupancy Ratio (GOR) and the Red Occupancy Ratio (ROR) are both greater than 80%. This indicates that the green interval was fully utilized (high GOR), and that there was a standing queue after the end of green (high ROR). Note that no weighting factor is given (such as weighting by volume of movement), as this would hide lower volume movements with poor service. Weighting factors that normalize this metric across all intersections movements within a corridor, giving higher priority to major movements, but without neglecting minor movements may be justified.

The above four condition metrics are products of previous research in this initiative [3]. Other condition level metrics may also be identified, particularly for low level facilities in which vehicle and pedestrian access are critical indicators of arterial health.

The above measures are recommended in lieu of the traditional Highway Capacity Manual measures based on Level of Service (LOS). The LOS is a grade of A–F given to any element of a roadway (movement; intersection; urban street). For intersections, the LOS requires knowledge of the signal timing plan and turning movement counts from a representative day. The LOS for an urban street is measured using the floating car method, collected on a representative day, to estimate delay associated with signalized intersections the segments connecting the intersection. The Highway Capacity Manual expresses the basic concepts that determine the elements of arterial performance (good progression and good allocation of green times), but is oriented toward planning analyses under alternative scenarios rather than real-time measurements. LOS measures are typically assessed periodically, while the measures collected from re-identification data and high-resolution controller data can be assessed continuously – and thus are more adaptable to the continuous network performance assessment advocated herein.

3.2 Establishing Condition Level Thresholds

For each condition measure, appropriate levels reflecting good, intermediate, and poor performance are established as condition levels 1, 2, and 3 respectively. Threshold boundaries are defined for each condition performance measure and for each applicable road category. Suggested thresholds are provided in Table 3.1. This table is analogous to Table 1.2 Condition Performance Metrics for Kansas Pavements.

Table 3.1 Candidate Condition Level Thresholds

Travel Time - 50th Percentile						
Road Category	Level 1		Level 2		Level3	
	Minutes/Mile (maximum)	MPH (minimum)	Minutes/Mile (maximum)	MPH (minimum)	Minutes/Mile (maximum)	MPH (minimum)
I	1.20	50	1.50	40	> 1.71	<40
II	1.50	40	2.00	30	> 2.4	<30
III	1.71	35	2.40	25	> 4.0	<25
IV	2.00	30	3.00	20	> 4.0	<20

Travel Time Reliability - 100 * (85th - 15th)/50th Percentile			
	Level 1	Level 2	Level3
Road Category	maximum	maximum	maximum
All Road Categories	20%	40%	> 50%

Coordination - Minimum Throughout on Green			
Road Category	Level 1	Level 2	Level3
	minimum	minimum	minimum
I	65%	50%	< 50%
II	55%	40%	<40%

Capacity - Percent Any Cycle Failure at Peak			
Road Category	Level 1	Level 2	Level3
	maximum	maximum	maximum
I	10%	20%	> 20%
II	15%	25%	> 25%
III	20%	25%	> 25%
IV	20%	30%	> 30%

Note that in the above table, road categories can be grouped. Threshold definitions may be different for each individual road category or for appropriate groupings of road categories. Engineering judgment and user expectation, as well as the need to minimize complexity, should guide the selection of performance level thresholds. [Note: Travel time rate (minutes/mile) and conversely minimum speed (MPH) are cited as absolute thresholds in Table 3.1. Alternatively thresholds could be indexed to the posted speed limit. A local study of travel time rates that correlate to user expectation will inform the boundaries of condition performance measures.]

3.3 Mapping Conditional Performance Levels to Road Categories

A candidate selection of the primary, secondary, and tertiary condition performance measure for each road category type is shown in Table 3.2. Travel time, coordination, and capacity are chosen as the three condition metrics for road categories I and II. For road categories III and IV, the second condition measure is based on travel time reliability rather than coordination, because expectation of signal coordination diminishes with lower roadway classes.

Table 3.2 Designation of Condition Performance Measures for Each Road Category

Condition Performance Measures			
Road Category	CP1	CP2	CP3
I	Travel Time	Coordination	Capacity
II	Travel Time	Coordination	Capacity
III	Travel Time	Travel Time Reliability	Capacity
IV	Travel Time	Travel Time Reliability	Capacity

Note that the number of condition metrics is not limited to three, nor does the number of metrics need to be the same for each road category. For example, categories I and II may also include a fourth (CP4) condition measure for travel time reliability. Likewise, categories III and IV may have only two condition metrics (CP1 and CP2) if data to support capacity utilization is not available. Three metrics are used in developing the examples, both to maintain the parallel with the Kansas PMS template, as well as to minimize the complexity. As the number of condition metrics chosen grows, the number of condition states likewise increases. For three condition performance measures, each with three levels, there are 27 (3^3) condition states.

Chapter 4: Mapping of Condition States to Performance Levels

4.1 Mapping Condition State to Performance Levels

The condition state of the arterial is determined by the condition levels of its condition performance measures. For example, for a segment in road category I (a high-speed principal arterial), the travel time performance may be level 2, the coordination may be level 1, and capacity may be level 3, creating an overall condition state of 213. These condition states are mapped to overall network performance levels in Table 4.1. This mapping is a direct analogy to the mapping demonstrated for the Kansas PMS in section 1.4, and, as with pavements, the assignment of a condition state to a performance level should be based primarily on customer expectation. Additional factors, such as available remediation actions and the cost of actions, may also influence this mapping. Even so, the primary factor is customer expectation.

Table 4.1 Sample Mapping from Condition State to Network Performance Level

Condition Level Index	Network Performance Level Mapping			
	Road Category			
	I	II	III	III
1 1 1	1	1	1	1
1 1 2	1	1	1	1
1 1 3	2	2	2	2
1 2 1	1	1	1	1
1 2 2	1	1	1	1
1 2 3	2	2	2	2
1 3 1	2	2	2	2
1 3 2	2	2	2	2
1 3 3	3	3	3	3
2 1 1	1	1	1	1
2 1 2	2	2	2	2
2 1 3	2	2	2	2
2 2 1	2	2	2	2
2 2 2	2	2	2	2
2 2 3	2	2	2	2
2 3 1	2	2	2	2
2 3 2	3	3	3	3
2 3 3	3	3	3	3
3 1 1	2	2	2	2
3 1 2	2	2	2	2
3 1 3	3	3	3	3
3 2 1	2	2	2	2
3 2 2	3	3	2	2
3 2 3	3	3	3	3
3 3 1	3	3	2	2
3 3 2	3	3	3	3
3 3 3	3	3	3	3

Chapter 5: Implementation and Extensions

Figure 5.1 Network Performance Framework

5.1 Implementation

Chapters 2, 3, and 4 go into detail concerning the definition of a logistical framework for arterial performance measures that includes several steps:

- Logical road category classifications
- Dividing the system into manageable segments for reporting
- Determining the appropriate condition performance measures for each road category, and their thresholds for condition levels 1, 2, and 3
- Mapping the condition levels (ex. 213) to an overall network performance levels of 1, 2, & 3

These steps form the groundwork from which to initialize a network performance system. A yearly data collection exercise, similar to the Kansas PMS yearly condition survey, could collect representative performance on the network, compute condition levels, and calculate the corresponding network performance levels. If logged over time, the result would be network perspective for arterials, similar to Figure 1.1, that provides the proportion of the network in top condition (Performance Level 1) and the proportion in poor condition (Performance Level 3).

However, arterial conditions measures differ in nature from pavement metrics. Pavements tend to degrade in a predictable manner proportionately to traffic loads, while traffic performance varies considerably from minute to minute, on top of daily, weekly, and seasonal variations—bearing some similarity to weather, which must also be sampled at a relatively high rate to develop meaningful aggregate values. Ideally, arterial condition data would be logged continuously, whereas pavement management is sampled yearly. As a result, the arterial network system can provide higher time granularity. Whereas the Kansas PMS network performance level chart in Figure 1.1 provides a yearly snapshot, arterial performance data can be aggregated daily, weekly, monthly, yearly – or by time of day, day of week, season, etc., or in response to capital improvement programs, weather events, or other external influences. Samples of possible graphical realizations are provided in Figure 5.2 through Figure 5.4. Figure 5.2 shows variation by time of day, with rush hour performance degraded. Figure 5.3 shows network performance over the last 30 days, with periodic spikes (every 7 days) suggesting weekend performance needs attention. Figure 5.4 is a representative plot of the impact of signal retiming on a network (implemented day 15), showing overall network improvement.

Figure 5.2 Performance by Time of Day

Figure 5.3 Performance over Last 30 Days

Figure 5.4 Impact of Signal Retiming

These are only the authors' visualization of what is possible. Although re-identification and high-resolution are quickly maturing in the market, they have not been co-deployed on a full network making such data available at this time. However, continued market penetration will make such network wide arterial performance possible in the future.

5.2 Goal Setting

Once a performance measures framework is established to communicate the health of the system to a non-technical audience, a natural extension of the discussion is to set goals to keep the network within desired parameters. As with pavement management, in which the legislature and Kansas DOT management used minimum and maximum proportions for performance levels PL1 and PL3, similar approaches could be taken with arterial networks to define the desired performance. Goals can be set differently on different classes of roadways (similar to Interstate and Non-Interstates) and may be reported separately if desired.

5.3 Modeling and Predicting Future Conditions

The performance level framework is purposely structured so that performance models can be constructed that predict future condition states based on existing condition states and the treatment (if any) applied to the system. For arterial roadways, a factor for growth or economic activity would also be critical. For example, if a high-class arterial corridor is currently in a state of 112, indicating good travel time, good coordination, and adequate capacity – the future state of the arterial, in a probabilistic sense, can be estimated. If no signal retiming is applied to the corridor, and the corridor is in a high-growth development zone, in future years the health of the system is likely to degrade faster than if the same arterial was in a low-growth zone. For example, the probability of a 112 condition state remaining in a 112 (and not degrading to a worse condition state) the following year in a high growth zone may only be 20%, while the probability of it remaining in 112 in a low growth zone may be 40%. The system of predicting future states based on current states, actions taken, and other influence variables is well established using a process called Markov state modeling. This tool then allows the exploration of probable outcomes based on actions taken on the system and various external influences.

5.4 Optimization and Tradeoffs

Combining goal setting with modeling capabilities allows for optimization techniques and tradeoff analysis. With a modeling tool to predict future arterial network conditions based on action (or inaction) and various outside influences, as well as goal setting based on desired proportions within performance levels PL1 or PL3, an optimization approach can determine the cost of goals, the appropriate strategy to attain the goals (that is what actions to take and when), and the time frame to expect improvement. Likewise in resource constrained environments, the same tool can be used to optimally allocate limited resources, or inform stakeholders about the consequences if funds are diverted to competing infrastructure programs. The specific details of establishing an optimization program are beyond the scope of this report but, as with the performance level framework, parallels exist within other infrastructure programs to serve as a guide.

Glossary

Condition Performance Threshold (Condition Level Threshold)

For each Condition Metric combined with each applicable road category, threshold boundaries must be defined for condition performance levels 1, 2, and 3. For example, for the road category of Principal Arterials, Level 1 for the condition metric of Travel Time might be defined as a maximum of 1.33 minutes per mile (corresponding to a minimum speed of 45 miles per hour).

Condition Performance Metrics

Engineering measures used to rate or qualify the condition of a roadway segment. Possible condition metrics for arterials include Median Travel Time, Travel Time Reliability, Signal Coordination, and Capacity Evaluation.

Condition Performance Level

A performance indicator (such as 1, 2, or 3) defined for each condition performance metric and its associated condition performance threshold, which may be specific to each road classification. The Condition Performance Level is used when assigning performance levels to roadway segments for the selected primary, secondary, and tertiary condition performance metrics in order to create the segment's condition state.

Condition State

A condition state is a combination of the condition levels (1, 2 or 3) of the primary, secondary, and tertiary condition metrics. For example, on an arterial, three condition metrics might be travel time, travel time reliability, and signal coordination. If the travel time condition measure falls into the range defined for a condition level 1, the travel time reliability condition measure falls into the range defined for condition level 2, and the signal coordination condition measure falls into the range defined for a condition level 1, the overall condition state for the arterial segment would be a 121. Condition States are then mapped to overall Performance Levels.

Green Occupancy Ratio (GOR)

Green Occupancy Ratio is the proportion of the green time in which a stop bar detector is occupied at a particular movement and/or lane at an intersection. A high GOR indicates high utilization. A low GOR reflects low utilization.

High-Resolution Controller Data

Data logged at a traffic signal controller that consists of time-stamped events as they are observed by the controller. The “high-resolution” term serves to contrast this type of data with legacy measures of volume and occupancy that are usually aggregated in bins ranging from 1 to 15 minutes. The high-resolution data captures three basic types of events:

- Vehicle detections, which describe when each detector becomes occupied or unoccupied. This measures the behavior of traffic at the intersection or on approach to the intersection.
- Signal output changes (e.g., when a signal head changes to green, yellow, or red). This measures the allocation of capacity and the schedule of green times.
- Other events internal to the controller that are relevant to traffic control decision making, such as pattern changes or preemption inputs.

Highway Capacity Manual

The Highway Capacity Manual (HCM) is published by the Transportation Research Board. It contains concepts, guidelines, and computational procedures for computing the capacity and quality of service of various highway facilities, including freeways, highways, arterial roads, and various other types of facilities.

Highway Performance Monitoring System (HPMS)

As defined by the Federal Highway Administration, Office of Highway Policy Information (<https://www.fhwa.dot.gov/policyinformation/hpms.cfm>), “The HPMS is a national level highway information system that includes data on the extent, condition, performance, use and operating characteristics of the nation's highways. The HPMS contains administrative and extent of system information on all public roads, while information on other characteristics is represented in HPMS as a mix of universe and sample data for arterial and collector functional systems. Limited information on travel and paved miles is included in summary form for the lowest functional systems.”

Level of Service (LOS)

As per the Highway Capacity Manual, a Level of Service (LOS) is a qualitative measure used to relate the quality of traffic service or traffic flow. LOS categorizes traffic flow and assigns quality levels using a scale of A, B, C, D, and F based on measureable attributes such as speed, density, etc.

Markov State Modeling

A Markov model is a probabilistic model used to model randomly changing systems where it is assumed that future states depend only on the present state and not on the sequence of events that preceded (i.e. the Markov property). This allows complex sequences to be rationally modeled.

Network Performance Framework (Performance Measures Framework)

A Network Performance Framework is rating system which takes numerous technical aspects into account but abstracts the complexity in order to communicate the level of performance of the system to a non-technical audience. Though presented as a qualitative scale, the composition of the metric is fully based on objective, measurable, and traceable attributes. Also, the network measures can be replicated by any appropriate trained personnel while not relying unduly on engineering or professional judgment.

Network Performance Levels

Network Performance Levels are the top level ratings in the Network Performance Framework. They are used to communicate how the arterial system is performing to an audience beyond the technical community. Top level measures provide intuitive, qualitative feedback to a broad audience without the need for specialized technical knowledge, and yet still present on a quantifiable scale. These ratings are an aggregation of condition metrics of individual segments based on their condition state.

Pavement Management System (PMS)

Pavement Management Systems are methodologies employed by road jurisdictions to consistently assess the quality of roadway surfaces, and select appropriate maintenance and rehabilitation actions to maintain the roadway network at acceptable levels.

Purdue Coordination Diagram (PCD)

A standard chart constructed from high-resolution controller data which provides an effective visualization reflecting the quality of progression for a particular movement through an intersection or series of intersections.

Red Occupancy Ratio (ROR)

Red Occupancy Ratio is the proportion of the first five seconds of red in which a stop bar detector is occupied at a particular movement and/or lane at an intersection. A high ROR indicates that vehicles were present at the end of green. A low ROR indicates that vehicles were not present. When a high ROR is combined with a high GOR for the preceding green interval, it is likely that a split failure occurred.

Roadway Types

Categorization of arterial roadways based on measureable attributes. The categorization of roadways for implementation of a Network Performance Framework should be based on a network inventory of existing roadways in sufficient detail to support the classification. Performance exceptions (from a user perspective) should be consistent within each roadway type.

Segmentation

Segmentation refers to the method of defining individual portions of a contiguous roadway for evaluation purposes. Performance is evaluated on a segment by segment basis, and then aggregated to corridor and network performance indicators.

Travel Time Cumulative Frequency Diagram

A Cumulative Frequency Diagram (CFD), also known as a cumulative distribution function, reflects the percentage of traffic that progressed through the corridor at a travel time less than or equal to the 'x' coordinate. A CFD is constructed from calculated percentiles of travel time. The graph always increases to the right. It provides a compact representation of the distribution of travel time along a corridor and is an efficient way to compare travel time performance from two or more time periods (such as before and after signal re-timing) on a corridor.

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Open Access and Collaboration with Purdue University

The Indiana legislature established the Joint Highway Research Project in 1937. In 1997, this collaborative venture between the Indiana Department of Transportation and Purdue University was renamed as the Joint Transportation Research Program (JTRP) to reflect state and national efforts to integrate the management and operation of various transportation modes. Since 1937, the JTRP program has published over 1,600 technical reports. In 2010, the JTRP partnered with the Purdue University Libraries to incorporate these technical reports in the University’s open access digital repository and to develop production processes for rapidly disseminating new research reports via this repository. Affiliated publications have also recently been added to the collection. As of 2017, the JTRP collection had over 1.5 million downloads, with some particularly popular reports having over 20,000 downloads.