Traffic Management Centers
IN A CONNECTED VEHICLE ENVIRONMENT

Task 3. Future of TMCs in a Connected Vehicle Environment

Final Report

Prepared for:

CTS Pooled Fund Study, University of Virginia

Prepared By:

Kimley-Horn
and Associates, Inc.

noblis.

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1 Introduction

The members of the Connected Vehicle Pooled Fund Study (PFS) recognize that the role of the TMC and TMC operations will be impacted or influenced by a future connected vehicle environment. To better prepare for the potential impacts, and to identify operational activities, resource and system needs, the PFS initiated this project to identify how a connected vehicle environment will shape the role and function of TMCs. The project examines operational, technical, and policy impacts of a new TMC environment, and informs the Connected Vehicle PFS members about priority needs and gaps that would need to be addressed relative to TMCs in a future connected vehicle environment.

Task 1, Review of Connected Vehicle Program Activities in Relation to Traffic Management Center Operations, aggregated and summarized key operational functions performed by TMCs and began to assess the readiness of TMCs to integrate new processes, functions, and data in a connected vehicle environment. Task 2 builds on information received from an electronic survey distributed during the first task, and included more in-depth interviews with early adopters of connected vehicles. The deliverable for Task 2 summarized the feedback, considerations and potential impacts of connected vehicles on the TMC operating environment. This task focuses on concepts for future operating environments for TMCs and the functions and capabilities that will be enabled by a connected vehicle environment.

2 Context for Connected Vehicle Data-Enabled TMC Operating Concepts

There is a significant range of TMC operating environments for agencies in the United States. While the focus of this study has primarily been on state department of transportation or large urban/regional operating entity, this study recognizes the challenges in developing a set of operating concepts that can apply to each and every TMC operating model. TMC functions, capabilities and responsibilities vary with such factors as:

- Geographic area served (regional, mega-region, statewide, multi-state);
- Transportation systems managed (highways, urban freeways, arterial signal systems, etc.);
- Types of devices connected, monitored and controlled;
- Staffing, staffing models (in-house, contracted or hybrid);
- Presence of collocated partners within a TMC facility;
- Hours of operation;
- Services provided, such as coordination or dispatch of service patrols, public information, traveler information systems, special event management, work zone monitoring, etc. ;
- Data sharing agreements and data sharing links with other agencies or with the private sector;

- Presence of dedicated IT staff and data management environment;
- Performance reporting functions or requirements; and
- Relationship to and coordination with other agency divisions or groups (such as maintenance, construction, district/region or headquarters).

Other factors influencing a TMC operating environment, as well as future concepts and considerations in a connected vehicle-enabled view, include the trend toward more proactive and integrated operations of the transportation network, as well as innovative approaches to addressing staffing technical skill set needs. There are a growing number of examples of agencies making fundamental programmatic shifts toward better utilizing technology tools to affect and influence transportation system operations, as well as recognition that a higher expectation of operational efficiency requires new strategies, new operations skills sets, and increased integration of system capabilities. These operating environment influences are dependent on agency priorities, allocating the appropriate funding and staff resources, and a willingness to modify "business as usual" to better respond to a growing customer service-driven operations culture.

The operating concepts in this document do not present a "one size fits all" recommendation, nor do they attempt to prescribe a preferred path or end state for TMCs. A key premise framing these concepts is that with the current unknowns and evolution of connected vehicle capabilities, there is an assumption that TMCs also will continue to evolve. Integrating new capabilities in a connected vehicle environment will be an incremental process, dependent on several factors, including:

- Density and availability of real-time dynamic data
- Agency appetite and ability to embrace new approaches
- Business and partnership models
- Perceived benefit to agency operations and the benefit to the transportation network

3 Operating Concepts in a Connected Vehicle Environment

To create a potential future vision for how a TMC would operate in a connected vehicle environment, as well as the evolution toward more active traffic management and operations in several TMCs, the following list identifies the 'TMC of the future' that is proactive, responsive, adaptable, and appropriately supported. Not all TMCs will want to or need to fit this model, although many will need to have some component of this list to stay relevant within their agency structure, demonstrate benefit for the past and ongoing investment, and be responsive to a more dynamic transportation network and operating environment.

From a functional perspective, TMCs are envisioned to have the following characteristics:

- TMC functions will continue to rely on people and engineering judgment; not all functions will or should be replaced by new data or new technologies, but many functions and capabilities can be greatly enhanced with a more robust and dynamic data pool. The roles people serve within those functions will need to be redefined and realigned to be more responsive to a dynamic transportation network. Functions such as data modeling and specialists in data interaction across operating systems will become integral.
- Systems will be more efficient, through integration and automation, and will include logic that supports processing of many pieces of data to translate that into usable, actionable information. Workstations will be designed to accommodate more robust functionality.
- Overall situational awareness of the transportation network will be increased, including the broader "network" outside of the TMC agency responsibility. A majority of today's TMCs are able to monitor their systems and networks, but not those networks of adjacent or nearby jurisdictions. This multi-network view will provide a broader, real-time context for traffic management and response strategies. Agreements and partnerships will help to facilitate this broader role and redefinition of boundaries.
- TMCs role and functions are expanded with new data and information sources. An example of this is an expanded responsibility for functions that may have been more typical for maintenance groups, such as real-time weather device and road conditions monitoring, and device troubleshooting and maintenance. Some TMCs co-locate these functions, others mirror those functions, and in some cases functions have migrated to the TMC.
- When not focused on situational awareness, TMC functions will be focused on performance analysis and identifying opportunities to improve the transportation network operations. Analytics will become a real-time function, rather than focused primarily on historic analysis. Quality assurance and quality control measures will be heightened both in terms of the effort required for activities as well as the standard set for quality based on new data to support decision making and engineering judgment. These opportunities may extend to beneficial information to support other departmental responsibilities (such as roadway infrastructure maintenance, planning, work zones, etc.).
- TMCs will have a heightened awareness of the impact of strategies on traffic movements and user response to traffic management strategies.
- TMC functions for alerts and notifications may be much more automated and targeted toward users on specific corridors approaching specific hazards or conditions. While wide area alerts will remain a core function, a connected vehicle environment enables segmenting users to be able to receive specific alerts or warnings.
- TMCs will be able to better inform regional Transportation Demand Management strategies by having more precise information on user travel patterns and characteristics. This can inform other modes such as transit operations, parking management, and even longer-range planning activities, which are not typically functions within today's TMCs.
- There will be a robust field network capable of supporting these new capabilities, and a closer synergy between those responsible for the field network and the supporting system and data

networks. A broad-based focus on reliability and capacity of networks (field and control room) will ensure capabilities are maximized.

- With a robust and dynamic data engine informing traffic operations and management strategies, TMCs (and by extension, transportation management agencies) will be held more accountable for activities, use of resources, coordination with others, and system and network reliability.

The following were identified as common or typical data and information types to many TMCs today. Information from the Task 1 survey about TMC core functions and focus areas also provided input to this selection of typical data types:

- **Incident data** – this may include specific location information, visual confirmation (via CCTV), automated data feed from law enforcement/public safety, manual notification or alert, or system alert (such as alarms indicating traffic flow has stopped). Specific incident details may vary, such as severity, extent of congestion impacts or incident clearance.
- **Weather** – nearly all TMCs have access to some type of weather information. It is common to have some level of information from local National Weather Service operations, although this is typically forecast information. Some TMCs have access to real-time information from environmental sensing stations (either agency owned or from others). This information is more typical for state DOT TMCs (that serve a region or a state) rather than municipal TMCs.
- **Speed and volume data (from detectors)** – TMCs that operate urban freeway management systems typically have some level of detector instrumentation to provide real-time speed and volume information. This information is more typical for agencies operating these freeway systems, and real-time detector based speed information are likely limited for arterials.
- **Speed data (probe)** – Many areas around the country are acquiring speed data from third party providers. This anonymous probe data can provide speed information for corridors outside of instrumented areas, but they do not provide other contextual information (such as volume or occupancy). Accurate arterial speed data from probes is more challenging than limited access facilities, although third party data providers continue to focus on improving this capability.
- **Field device data** – TMCs can be connected to a wide range of field devices, ranging from traffic signals to detectors, ramp meters, and dynamic message signs, among others. Data available to the TMC today could consist of device operating condition (or failure), operating status (active, idle, traffic signal cycle, preemption activation, message displayed, etc.) or communications connectivity status.
- **Work zones** – Many TMCs have access to at least some level of information on planned work zone activity on corridors (typically limited to their agency corridors). This could range from a weekly bulletin or report of planned activities, or more up-to-date information if the TMC has an active role in monitoring work zone traffic conditions.
- **Planned special events** – Similar to work zones, many TMCs have access to at least some level of information on planned special events that might impact the transportation network. This could range from notification of event routes to more detailed information if the TMC has an active role in managing special event traffic on those routes.

Table 1 below defines the data/information categories that are typical today on some scale by most TMCs in the country, regardless of size, breadth of responsibility, or location. Some TMCs already acquire a lot of data in each data category, but still are generally limited to the current data types available in a pre-connected vehicle environment. For many data types, the limitation stems from the geographic coverage of infrastructure (such as detection), or connectivity to support real-time conditions monitoring. For other data or information types, the limitation may be in the form of institutional silos and inability to integrate data from other sources or partners. Furthermore, bringing additional data in does not always result in improved efficiency; having to monitor multiple sources of information inherently creates some latency and may even result in conflicting information.

Within a connected vehicle environment, it is envisioned that new data types and new processes will provide each TMC with unique opportunities to elevate their operations, and influence the traveling public. Not all TMCs will be capable or interested in managing the influx of available data, although most should consider at least minimal changes based on the new information because of the expected benefits of being able to accurately measure performance and therefore spend dollars more wisely in the future.

Table 1 – Typical Data Types across TMCs and Potential Changes

Data/Information Category	Typical Data/Information Currently Available	Data Environment enabled by Connected Vehicles	Potential Changes to TMC Operations and Processes
Incident	• Location • Start time/end time • Duration • Severity	• Geo-locating capability for precise incident location • Real-time and specific impacts to network • Lanes restricted • Types of vehicles involved • Response status • Condition of potential detour routes	• Respond better to scene with the right resources and the right equipment • Network management to support incident impact mitigation • Real-time information on incident clearance • Improved traveler notifications on nearby corridors • Before-and-after analysis to determine cause/improvements • Improved predictive modeling
Weather	• Road and pavement conditions • Atmospheric conditions • Forecasts • Alerts • Precipitation	• More precise pavement conditions • More precise information about road conditions • Network impacts • Safety impacts • Numbers of vehicles impacted • Extent of impacts • Vehicle metrics • Prediction of impacts	• Immediate warnings of incidents • Immediate warnings of unsafe conditions • Advanced warnings of impacts based on forecasting customized based on proximity to weather event • Preparation of resources and response strategies anticipated weather impacts • Improved multi-state corridor condition information • Better notifications to long-haul freight of travel conditions • Enhanced decision support to provide to road weather response teams

Data/Information Category	Typical Data/Information Currently Available	Data Environment enabled by Connected Vehicles	Potential Changes to TMC Operations and Processes
Speed (Detection and Probe)	• Volume/occupancy/speed • Spot locations • Lane by lane • Directional • Freeway congestion • Historical volumes • Moving/tracking data • Robust historical data • Freeway and arterial congestion	• Density context • Broad coverage • Continuous movement/tracking • Arterial congestion • Back of queue and flush rate • Lane by lane • Vehicle metrics • Prediction	• Monitoring of real-time state of the transportation network • Congestion warnings to notify of issues on network • Performance reporting on state of network • Support for multi-agency integrated corridor strategies • Real-time information on impact of transportation management strategies implemented (user response) • Potentially larger road network to monitor and manage (ubiquitous probe coverage will enable information on a much larger network than traditionally instrumented roads)
Field Device	• Status • Control • Spot deployments • Non-essential communications network	• Integration status • Required system uptime • New technology systems with new types of data • Performance metrics • Essential communications network	• Maintain uptime and integration of devices • Performance reporting and management on state of field devices • Automated alerts and troubleshooting • Asset and issue tracking based on performance; improved equipment lifecycle management
Construction / Work Zone	• Surveillance • Lane restriction updates	• Speed adherence • Vehicle maneuvering • Real-time lane restrictions • Traffic control verification and violations	• Advisory warnings in advance of work zone and to surrounding travelers as warranted • Improved safety warnings approaching and within work zone • Dynamic speed and lane restriction warnings • Inform work zone implementation strategies based on traffic response to configuration • Dynamic lane restriction changes • Traffic control violation notifications
Event	• Day, time, and length • Lane restrictions • Localized network impacts • Some monitoring of images and signal timing changes during events	• Situational awareness surrounding event location • Broader network impacts • Multi-modal traffic information	• Improved advanced traveler information to support event ingress and egress of traffic • Partner department / agency response and active management of event • Advanced network response to ingress and egress of traffic • Real time management of multiple modes and mode shifting support • Potential reduction in field resources needed to support event traffic management

As each of the typical types of data that TMCs use today expands exponentially with the introduction of connected vehicle data, the systems and management to be able to utilize that data also will need to grow. **Figure 1** below depicts this growing responsibility.
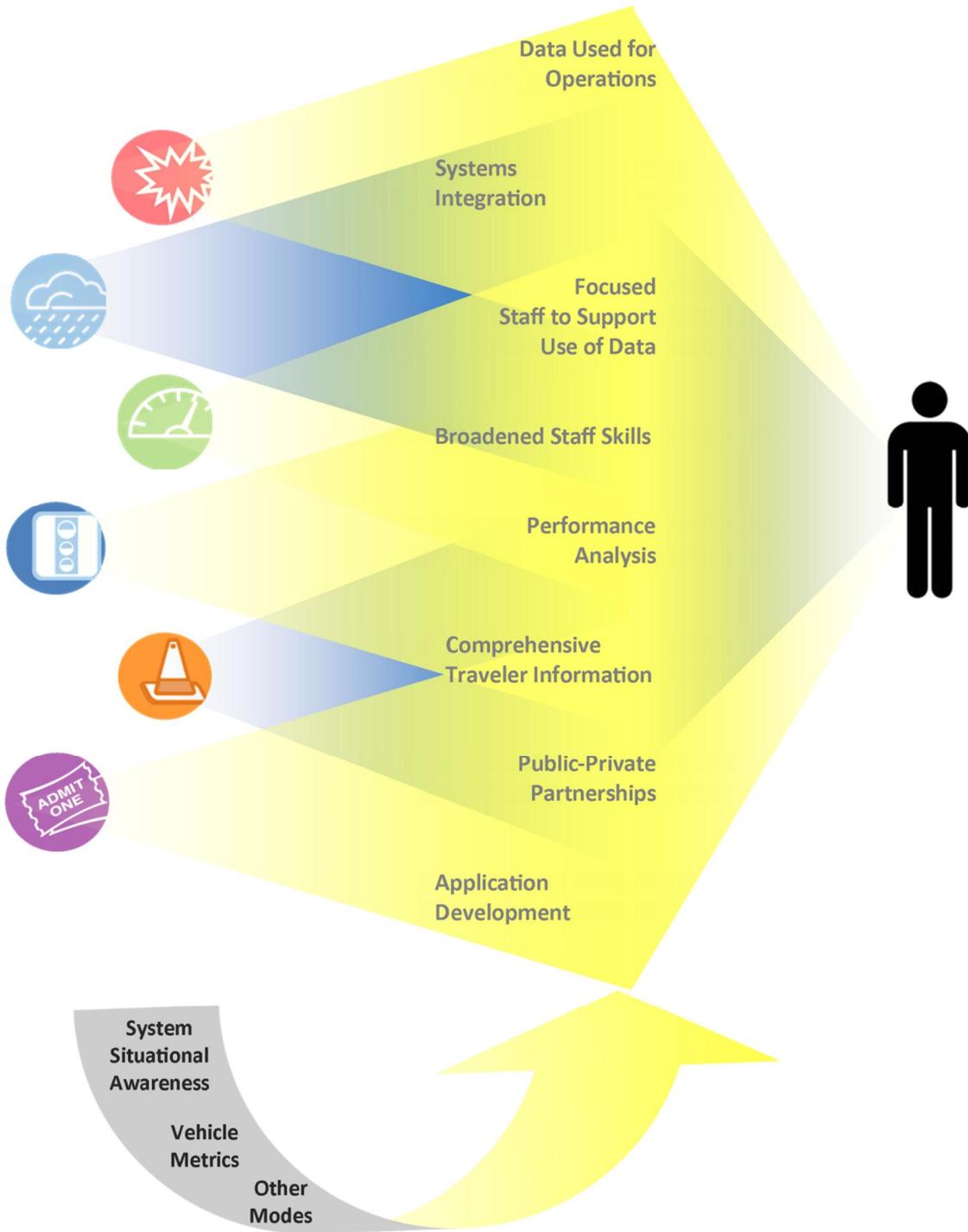

Figure 1 – Relationship of TMC System Enhancements from Connected Vehicles

Typical data types on the left are collected and used today on a different size scale for each unique TMC. For large urban areas where a TMC operates with many functions, the data used today will be larger in the sense of network conditions, weather, and device management. For small rural areas where a local public works office functions as the local TMC, there may not be much existing detection or device management occurring, but if in a high-risk weather zone, may focus most efforts on collecting and using weather data.

The scale of data is different for each TMC, but it is consistent across the board that with the introduction of connected vehicle data that all data types will expand in scale beyond their current levels. As each of the data types grow in scale and usefulness, so do the relationships between data types. For example, certain weather data combined with certain detection data can be used to determine what resources need to be allocated to an area in preparation for a winter storms impacts on the traveling public. Data relationships become very important as the data is collected into systems because it is the responsibility of the systems and the people who use the systems to turn data into information. The center of the graphic outlines the various responsibilities TMCs will have in managing all of the data that could potentially be utilized. Other data types that are not currently common to TMCs (such as system and network situational awareness, vehicle metrics, and other mode information) will be added to this influx of growing data sets. The purpose of all of the data in a connected vehicle environment is for the underline person to be able to make smarter decisions quicker on all levels – whether it is the traveler that needs to know a better route to work or a better mode to work, an agency staff person that needs to know what device is next on the list to maintain or replace, or the operator of a bus or commercial vehicle who should know they cannot take a certain route because of updated lane restriction information.

Table 2 below identifies the current functions of most all TMCs in the country, regardless of size, breadth of responsibility, or location. Connected vehicle data from the previous table as the data types apply to specific functions are provided in this table to link how current processes will be affected by new data causing potential changes to occur within the TMC operational environment. Staffing and resource allocation are directly impacted by the addition of operational processes that TMCs may not be performing today.

Table 2 – Typical TMC Functions and Potential Changes

Functions	Current Processes	Connected Vehicle Data Introduced	Potential Changes to TMC Operational Processes
Incident Management	• Initial notification of incident location and lane restrictions • Sometimes 'all clear' notification • Disseminate information to emergency responders.	• Impact to network • Lanes restricted • Types of vehicles • Response status • Preferred detour • Incident clearance status	• Disseminate incident information (planned and unplanned) to vehicles • System-wide vehicle preemption • Real-time detour assigning / verification

Functions	Current Processes	Connected Vehicle Data Introduced	Potential Changes to TMC Operational Processes
Work Zone Management	• Deploy and monitor mobile surveillance • Provide information to motorists on-site and advanced through websites	• Speed adherence • Vehicle maneuvering • Contraflow lane management • Real-time lane restrictions • Traffic control verification and violations • Broadcasts of restriction information based on vehicle type	• Advisory and safety warnings • Dynamic lane restriction changes • More accurate assessment of lane restrictions
Traffic Management	• Updating signal timing periodically or as-warranted • Monitor / use camera images • Provide notification (in some form)	• Traffic violations • Hazard alerts • Continuous lane by lane detection of volumes and congestion • Density context • Back of queue and flush rate • Pavement conditions • Network impacts • Vehicle metrics • Forecasting • Prediction of impacts	• Greater accuracy in signal control analysis • Signal timing updates responsive to traffic patterns • System-wide vehicle priority • Responsive traffic metering • Lane management • Lighting control systems • Parking availability information • Safe speed warnings • Intersection control and warnings • Continuous dynamic roadway warnings
Data Processing	• Archive data for period of time • Some historical analysis on network performance • Some automated applications to provide operational support or decision support	• All data that will be determined on a TMC-to-TMC basis that will influence operations and management	• Incident impact studies • Traffic law / speed limit analysis • Environmental impacts • Performance metrics on infrastructure, use of network, TMC operations, staffing effectiveness, and response / support • Automation to support all processes • Electronic payment / fee collection • Real-time emissions and air quality analysis
Distribution of Information	• Travel times along specified corridors • Construction permitting locations / restrictions • Incident location / restrictions • Camera images	• All data that will be determined on a TMC-to-TMC basis that will influence operations and management	• Travel times as desired • Prioritized and customized traveler information • Broad methods of information distribution • Real-time detour and safety warning distribution • Travel conditions • Performance reporting to public and officials

Potential new roles/functions for TMCs to consider with an influx of reliable transportation network data that could be processed to support these roles/functions include (some may be traditional maintenance or IT department functions but could be collocated within the TMC or integrated into TMC functionality):

- **Asset Tracking Management** – accurate and reliable asset and performance tracking to inform for maintenance, upgrades, or replacements needed which extends from field devices to static signs to pavement
- **IT Network Management** – close collaboration or integration of IT departments due to overlap in functional responsibility, essential-service performance, and threat or other security provisions of the communications and Enterprise networks based on device type and use of the network infrastructure and data
- **Non-Typical Infrastructure Monitoring** –bridges/tunnels, railroad or port network, and other types of assets within the agency jurisdiction as well as potentially assets in other jurisdictions
- **Real-time performance analysis/reporting** – on-the-spot data analysis to support decision making and investments in times and resources

4   Implications of Connected Vehicle Data on TMC Systems and Data Management

TMCs are not only transportation management centers but technology management centers. Hardwire and wireless connections to field devices are managed through a variety of wiring, equipment racks, networking switches, and server computers. Communications software is used to poll field devices for health and status, view remote images, and send commands to field devices to implement strategies. Depending on the size and jurisdiction type of the agency, the number of field devices managed by a TMC can range from the tens to the tens of thousands. This means the implications of connected vehicle data and devices on TMCs can only be expressed as a range of potential scenarios.

For many agencies, Big Data is already here with a wide variety of real-time streaming information coming in from the field. Some of it is stored in relational databases and other data is transitory and thrown away. For most agencies, database management is expressed by two standard practices: daily backups and size truncation. Daily backups preserve configuration data and allow the system to be restored in the event of hardware failure or software. Truncation keeps database tables a manageable size for speed of reporting. The new era of Big Data database management technologies and the relative low cost of system storage are obsoleting the need to throw much data away and enabling analytics applications that few could have imagined just a few years ago.

Connected vehicle data stands to overwhelm currently collected information by an order, if not orders of magnitude, from what is collected, processed, and stored today. Today, a typical agency with a regional population of 200,000 might have less than 500 field devices to manage and control. Such a system might amass 100GB of status and conditions data over a year. Storage of video en masse might

launch that storage towards terabytes per year. With connected vehicles penetration of just 10% in the example 200,000 jurisdiction, the information explosion could be 40-fold with 20,000 vehicles reporting status and conditions data on a daily basis. 40TB of data per year requires the Big Data technologies and tools to provide rapid reporting, display, and analysis. As the penetration level of connected vehicles increases, the data storage and processing challenges grow substantially.   Of course, just like with traditional data on field device telemetry, status, and diagnostics, it is not clear that storage of all raw connected vehicle data is necessary, or even valuable.

Urban areas across the U.S. have a wide variety of operating structures, politics, and procedures. Some areas are well organized and share information readily. Large agencies struggle with large agency issues such as coordination across districts, and small agencies struggle to staff TMCs altogether with limited budgets and managers that wear multiple hats. The long 100+ year political history of "who is responsible for what" with respect to transportation management across the country is so varied that no one-size-fits all approach is possible when it comes to managing the impacts of connected vehicles on regional mobility.

It is clear, however, that travelers do not currently perceive differences in jurisdictional responsibility, other than the fact that they might perceive that "signals work better on Main Street than at the freeway interchange".   The promise of connected vehicles technology may further exacerbate this challenge since explicit feedback will now be available to the traveler at certain locations, but not at others. Hopefully these positive experiences will spur investment and support for tax-dollar spending, but it is possible that the experiences could highlight the differences in management by one agency versus another. Interoperability across jurisdictional boundaries becomes a key issue to mitigate these challenges. Furthermore, an open-source architecture will be critical for data to enable interoperability, and one that incorporates appropriate security and access requirements.

All of these issues point towards regional cooperation on connected vehicle data storage and applications coordination for TMCs in a region. While a monolithic approach for Day 1 applications may not be possible, or even desirable, an evolution will be necessary; and each region will likely evolve independently as regions across the U.S. similar to the way that regions have evolved with traditional technologies to date.

The following subsections identify some of the specific TMC data and data management scenarios in a future connected vehicle environment

4.1   Big Data Software Tools and Systems

Reporting, organizing, and analyzing connected vehicle data will require modern technologies focused on Big Data management. While the landscape of Big Data is changing rapidly, there are a variety of mature technologies that are used to handle extremely large databases. By the time that CV data is being collected en masse, new tools will likely be available and others will be retired, so specific trade names used here are not intended to be recommendations.   In general, the connected vehicle data being managed by TMCs will need the following tools and components:

- Acquisition and storage
- Marshaling
- Analysis
- Action tools

While many Big Data solutions include all of these components, it is possible to mix and match some components by use of open standards. Acquisition and storage tools, commonly referred to as NoSQL, allow massively parallelized and rapidly retrievable datasets. Traditional SQL relational databases cannot appropriately handle the volume of inserts nor provide reasonable response to queries when the tables have hundreds of millions of rows. NoSQL technologies were invented for this purpose and underlie the most popular web applications such as Google and Amazon which have hundreds of millions of users daily. While connected vehicle data from a region will not come close to the volume and database size of the Google repository, NoSQL tools are likely necessary.

Marshaling tools turn the NoSQL storage of raw data into structured software objects that can be analyzed quickly and efficiently. In the connected vehicles context, marshaling tools will also describe software services that will process the raw connected vehicle data and store derived metrics that are then the subject of analysis. For example, a trajectory of an equipped connected vehicle would include time-stamped geo-location and speed, among other data elements. A marshaling process would compute the travel time between two points and store that derived metric, or collect the necessary trajectories from the NoSQL storage and organize them for analysis.

"Analytics" is a popular buzzword right now, with hundreds of competing applications in the marketplace for mining those nuggets of information from the vast sea of a Big Data dataset. Each TMC will need analytics tools to generate findings from real-time and archived connected vehicle data that can then be used for decision making and taking actions.

Action tools do not necessary describe brand new systems that need to be procured, but most existing TMC systems will need to be enhanced and augmented to leverage the connected vehicle data. Further in this section, we will discuss each of the Service Packages described in Task 2 and the implications of each for existing and new Action Tools.

4.2 Communications and Computing Infrastructure

Most TMCs currently utilize dedicated hardware for communications and data processing that reside inside of the TMC itself. In the last few years, however, it is becoming more and more common that TMC databases and hardware are becoming more integrated with Enterprise IT systems and managed by Enterprise IT staff. Systems are also increasingly becoming virtualized in massive virtualization servers that can emulate 100s of physical computers and rack servers. Cloud storage and cloud computing is becoming more and more popular as IT departments continue to transition to less and less physical equipment. With the emergence of connected vehicle data, TMCs will need more of everything - communications bandwidth (both field to center and internal networking capabilities), hardware, and storage. The amount of "more" needed by individual TMCs and partnerships across regions will vary

widely based on what is available today; but based on the anticipation of 40-fold increases in the volume of data, similarly-sized capacity increases would be warranted. However, current Gigabit and 10Gigabit switching systems are vastly over-specified for most current-day data processing needs, except when considering real-time video streams. Strategies for expansion will be dependent upon the IT landscape of each agency, and how the agency relates to regional partners and organizations.

4.3 Regional Organization and Partnerships

It is not enough to simply say that each TMC needs to be upgraded for software and systems functionality to support the influx of connected vehicle data. Since many regional organizations and partnerships already exist, it may make both technical and organizational sense that CV data is retrieved, stored, and processed by a regional agency or coalition at a regional TMC rather than each individual agency procuring Big Data systems and tools, deploying equipment and software, and maintaining staff and capabilities for analysis and operations. Perhaps the best current example of such a regional operation is the I-95 Corridor Coalition. Partner states have access to a central clearinghouse of corridor-wide probe data, and the clearinghouse is managed by the University of Maryland, which also has developed tools for partners to access and analyze corridor data. In most of the major metropolitan regions of the U.S., there is only a small percentage of travel that starts and ends in the same jurisdiction. The intersection of freeway and arterial networks naturally brings State and local systems together at interchanges. Connected vehicle data may be the catalyst to bring together agencies and TMC staff in a region that may not already be strongly coordinated, since the nature of travel naturally spreads across agency boundaries. The trend toward increased integrated corridor management strategies, often involving freeway, arterial, and transit, helps to support this concept. Some connected vehicle applications are well suited for this consolidated approach; particularly those that do not necessarily require DSRC RSEs at a specific location. Joint operations and interoperability across multiple states and local jurisdictions might be best served by procuring services and systems from a third-party provider. While there are some good examples of this regionally, multi-state partnerships are emerging, with the I-95 Coalition providing a successful model. The recent federal grant selections for Multi-State Corridor Operations and Management selected several coalitions, and among those, several intend to pursue some mechanism and partnership for corridor-wide data.

4.4 Agency Categorizations

The implications of data management of CV information in TMCs are varied primarily by the size and structure of the agency or agencies that are involved. Common agency TMC organizations include the following:

- • State DOT, focused on freeways only (e.g. Tennessee DOT)
- • State DOT, freeway and arterial responsibilities (e.g. Virginia DOT, Michigan DOT, Caltrans, Utah DOT)
- • Combined State DOT and City/County   (e.g. Tallahassee JOC, Austin CTECC)
- • Multi-state coalition (e.g. I-95 corridor)

- Local city/county or other municipal (isolated or "rural", e.g. Lubbock, TX)
- Local city/county or other municipal (urban/suburban, e.g. Seattle, Miami/Dade County)

Table 3 discusses the implications of the systems and data management issues identified above on different kinds of TMC environments. The applicability of the application area to the type of TMC is denoted as "high", "medium", or "low" with comments as appropriate for clarification. **Table 4** then presents the three primary systems and data management issues (Big Data, Communications and Computing, and Regional Organization) for each of the application areas. This table provides high-level guidance for impacts, but does not specify level of investment, specific costs or specific data sizes or footprints.

Table 3 - Applicability of CV Service Packages to different types of TMCs

	Incident mgmt.	Rwy Hazard Warning	Speed warning	CICAS	Signal Control	Probe data coll.	Metering	Lane mgmt	Elec. pymt	Traffic info	Emissions mon.	Weather mon.	Asset mgmt.	Parking mgmt.	Perf. Meas.
State DOT, focused on freeways only	High	High	High	N/A	N/A	Regional coordination suggested	High	High	Toll authorities	Regional coordination	Medium	Important in rural areas	High	Low, except for state-managed freight facilities	Regional coordination suggested
State DOT, freeway and arterial responsibilities	High	High	High	High, many state roads are high-speed	High	Regional coordination suggested	High	High	Toll authorities	Regional coordination	Medium	Important in rural areas	High	Low, except for state-managed truck/freight facilities	Regional coordination suggested
Combined State DOT and City/County	High	High	High	High	High	High	High	High	Toll authorities	Regional coordination	Medium	Important in rural areas	High	Low, except for state-managed truck/freight facilities	Regional coordination suggested
Multi-state coalition	At state borders	Low	Low	N/A	N/A	High	Low	Low	Low	High	High	Medium	N/A	Low	Medium
Local city/county or other municipal (rural)	Low	High, esp. on high-speed roads	High, esp. on high-speed roads	High	High	Regional coordination suggested	N/A	Low	Low	High	Low	High	Medium	Medium	High
Local city or other municipality (urban	Low	Medium	Medium	High	High	Regional coordination suggested	N/A	Medium, Arterial ATM emerging	Low	Regional coordination	Medium	High	Medium	High	High

Table 4 - Systems and Data Management Issues for Connected Vehicle Service Package Applications

Service Package	Big Data Tools	Communications and Computing	Regional Organization and Partnerships
Incident management	- Acquisition and storage – leverages basic probe data streams, no additional impact - Marshaling – limited additional structures needed - Analysis – methods for fusing connected vehicle data with traditional detection reporting - Action tools – methods for dissemination to connected vehicles	- Communications - leverages basic probe data streams, no additional impact; requires adequate output capacity - Computing – limited additional capacity needed	Incident management has long been practiced by State DOTs and rarely by Local municipalities. Active management in more local TMCs would improve arterial conditions in the U.S. Diversions from incidents inevitably involve coordination among jurisdictions.
Roadway hazard warnings	- Acquisition & storage – extends basic probe data to include transient conditions data, low impact; - Marshaling – geo-collections of conditions reports - Analysis – methods for fusing conditions reports from CV for geo-location - Action tools – methods for dissemination to CV; methods for configuration of fixed and transient hazards	- Communications - leverages basic probe data streams, no additional impact; requires adequate output capacity to push alerts - Computing – limited additional capacity needed	Minor compelling reasons that this functionality should be regionally coordinated.
Speed warning	- Acquisition and storage – leverages basic probe data streams, no additional impact - Marshaling – limited additional structures needed - Analysis – methods for fusing connected vehicle data with traditional detection reporting - Action tools – methods for dissemination to CV; methods for configuration of fixed and transient speed limits and recommendations (VSL)	- Communications - leverages basic probe data streams, no additional impact; requires adequate output capacity to push alerts - Computing – limited additional capacity needed	Minor compelling reasons that this functionality should be regionally coordinated.

CICAS	• Acquisition and storage – storage of traffic signal status data has medium impact; post-analysis of CICAS events requires very high resolution trajectories • Marshaling – signal status; high resolution trajectories • Analysis – methods for fusing connected vehicle data with signal status • Action tools – post-mortem summaries; signal system features to update key settings to improve safety	• Communications - leverages basic probe data streams, no additional impact • Computing – post mortem analysis of CICAS events could require additional resources given the high-resolution nature of the data.	Minor compelling reasons that this functionality should be regionally coordinated. Applies only to arterial facilities.
Traffic signal control	• Acquisition and storage – storage of traffic signal status data has medium impact; • Marshaling – signal status • Analysis – methods for fusing CV data with signal status • Action tools – signal system features for visualizing, analyzing, and changing key settings based on CV information	• Communications - leverages basic probe data streams, no additional impact • Computing – additional resources may be necessary in large deployment areas	Significant improvements can be gained by coordinating regionally with signal control. Partnerships suggested to amplify impacts.
Probe data collection	• Acquisition and storage – significant assets necessary • Marshaling – significant assets necessary • Analysis – significant assets necessary • Action tools – Primarily represented by the other applications in this Table	• Communications – significant resources needed • Computing – significant resources needed	Underlying basis for almost all other applications. Regional coordination is suggested where appropriate to minimize duplication of expenditures and capabilities.
Traffic metering	• Acquisition and storage – leverages basic probe data streams, no additional impact • Marshaling – limited additional structures needed • Analysis – methods for fusing CV data with traditional detection reporting • Action tools – methods for dissemination to CV (warnings); enhancements to FMS to change metering parameters	• Communications - leverages basic probe data streams, no additional impact • Computing – limited additional capacity needed	Minor compelling reasons that this functionality should be regionally coordinated. Applies only to freeway facilities.

Lane management	• Acquisition & storage – leverages basic probe data streams, no additional impact • Marshaling – limited additional structures needed • Analysis – methods for fusing CV data with traditional detection reporting • Action tools – methods for dissemination to connected vehicles; enhancements to FMS for "virtual" ATM	• Communications - leverages basic probe data streams, no additional impact • Computing – limited additional capacity needed	Minor compelling reasons that this functionality should be regionally coordinated. Applies mostly to freeway facilities. Arterial ATM is emerging.
Electronic payments	• Acquisition and storage – significant additional data may need to be collected and stored for financial processing • Marshaling – significant additional structures will be needed • Analysis – methods for computing fees; methods for analyzing trends & patterns • Action tools – payment processing, reporting. Confirmation dissemination to connected vehicles	• Communications – significant security implications; may require higher speed / more responsive systems for timely payment processing • Computing – significant additional capacity needed for processing financial data	Mileage based user fee is an emerging concept that should be coordinated regionally. Other tolling capabilities may not need regional operations.
Traffic information	• Acquisition and storage – leverages basic probe data streams, no additional impact • Marshaling – fusing alerts and status conditions with CV data • Analysis – post-incident or event responses, diversions • Action tools – methods for dissemination to connected vehicles; customization apps for travelers	• Communications - leverages basic probe data streams, no additional impact • Computing – limited additional capacity needed	Primary "golden app". Regional coordination is suggested where appropriate to minimize duplication of expenditures and capabilities.

Emissions monitoring	• Acquisition and storage – vehicle performance data for emissions requires significant additional storage above basic probe records • Marshaling – additional structures for emissions modeling • Analysis – methods for synthesis of emissions estimates • Action tools – visualization, estimation, and reporting tools	• Communications – additional bandwidth may be required for higher resolution data needed for emissions monitoring • Computing – major additional capacity for modeling and simulation	Emissions models and reporting are inherently regional in nature. Regional coordination is encouraged. The "emissions management center" is best co-located with the TMC to maximize resource investments.
Road weather monitoring	• Acquisition and storage – may require additional resources to archive vehicle equipment statuses • Marshaling – additional structures for vehicle statuses needed • Analysis – methods for fusing connected vehicle data with traditional RWIS or other radar/traditional weather data collection • Action tools – methods for dissemination to connected vehicles, methods for weather modeling and simulation	• Communications – possible additional bandwidth needed for higher-resolution vehicle status records • Computing – major additional capacity for modeling and simulation needed in the maintenance center, with data to be provided to the TMC • Alternative might be to leverage TMC capabilities and migrate this function to the TMC in some instances	Weather models and reporting are inherently regional in nature. Regional coordination is encouraged. Strong potential to co-locate this capability with the TMC in the future.
Infrastructure asset management	• Acquisition and storage – additional resources for storage of infrastructure conditions • Marshaling – significant additional structures for infrastructure objects • Analysis – methods for detecting issues and trends in infrastructure systems • Action tools – significantly new management tools for infrastructure heath monitoring, control, and real-time status	• Communications - leverages basic connections • Computing – limited additional capacity needed	Some argument for regional cooperation where other applications require it. Infrastructure asset management (i.e. maintenance) is a necessary component of any other application whether regional or local/isolated.

Parking management	• Acquisition and storage – additional storage for parking facility status • Marshaling – parking facility status structures • Analysis – methods for parking analysis • Action tools – methods for dissemination to connected vehicles, methods for synthesizing parking availability visualization, reports, real-time status	• Communications - no additional impact • Computing – limited additional capacity needed	Minor compelling reasons that this functionality should be regionally coordinated. Except for limited state- and local-municipality managed facilities, most parking facilities are private and compete for business. Management of on-street parking, which is 100% municipal, has been successful in recent pilot projects in California. The TMCs' limited role in parking management will not likely change in the foreseeable future with CV data
Performance measures	• Acquisition and storage – depends on the measure(s), but in general storage of the measures is necessary and will have significant storage impact • Marshaling – significant additional structures required for each measure and aggregation • Analysis – methods for fusing connected vehicle data with traditional detection reporting, methods for computing each measure and aggregation level • Action tools – visualization, analysis, reporting, display, and real-time status displays	• Communications - leverages basic probe data streams, no additional impact • Computing – significant additional capacity for measures that require continuous, real-time calculations.	Some argument for regional cooperation where other applications require it. Performance measurement is a necessary component of any other application whether regional or local/isolated, in particular in light of the focus on performance-driven investment and decision making in MAP-21.

4.5 Summary of Recommended Data Management Strategies for TMCs

TMCs are not only transportation management centers but technology management centers. Connected Vehicle data will require TMC operators and systems to move into the world of Big Data. In this section, we have identified some of the issues related to storage, computing, processing, and regional operations across the principal CV applications that TMCs for arterial and freeway management will likely be involved with.

1. Big Data technologies will need to be procured, configured, and operated to manage, process and analyze the connected vehicle data sets. Even if all of the connected vehicle data is not stored and archived, the sheer size of the data sets that will be amassed over a month or a year will require sophisticated and modern Big Data management software to enable reasonable report and functionality response. Existing SQL-based server applications will likely not be enough. Funding for implementing Big Data technologies, as well as sustaining and expanding them over time, will be an important issue for many agency budgeting and programming processes. Funding sources will need to be identified, whether federal, state/local, and will perhaps include a multi-partner funding strategy.

2. How these Big Data technologies and capabilities (and associated hardware and communications equipment) are procured and deployed is a strong function of (a) the applications that are envisioned, and (b) how regional partnerships are structured. Some thoughts about factors involved in making these decisions were provided across the six basic categories of TMC types, and for each application area.

3. A wide variety of add-on functionality to existing management applications will be needed for augmenting connected vehicles information with traditional sensors and field control devices, sending messages to new RSE field devices as well as to CV themselves. Sending messages to CV directly implies a relationship between the CV and the TMC, which would be initiated by the CV (privacy constraints indicate that most likely, CV will not have long lasting addresses). This means the TMC has to be prepared to handle many requests for information, and then provide responses. This is a different pattern of information distribution than is typical for TMCs, and may require some additional computing and communications capacity.

4. A cellular/mobile connected vehicle environment will raise even more issues in terms of TMCs ability to acquire data as well as the relationship between the TMC and CV to disseminate data directly to vehicles. Security, privacy and autonomy will be important policy decisions that need to be addressed, as well as system analytics and logic capable of developing response and message scenarios tailored to specific vehicles and circumstances. Research within the OEM arena and V2V is looking at this kind of communications using the cellular network, but additional research to identify role and impacts to the TMC is needed.

5. New third-party applications and vendor-supplier applications are also likely to emerge. TMC operators and partners will need to make smart decisions about whether or not to integrate new features in existing systems from existing suppliers, or to add new systems in parallel with existing components. RSEs have certain mission critical functions, CICAS in particular, but may not be the best possible delivery mechanism for many other applications that are not highly

time-critical. In addition, line-of-sight limitations of RSEs based on DSRC technology will need to be considered when deploying field devices.

6. As standards for CV communications emerge, TMC operators will need to be mindful to use them as much as possible to ensure interoperability of new software and legacy applications with the new data. This also applies to field equipment and the field/technical staff that implements and supports it.

7. Security issues regarding which entities can be "trusted" as a CV field element are extremely important. The digital certification process which has been explored in the Safety Pilot will need to be continued to be refined and modified as technologies mature.

5   TMC Staffing for a Connected Vehicle Environment

The need for the human element as part of the TMC functionality is not envisioned to be diminished in a future connected vehicle environment. Exponentially increasing the amount of data available to support transportation operations decision making creates a need for new skill sets beyond what exist in many TMCs today. Staffing levels, skill set requirements, and staffing models vary widely among TMCs throughout the U.S. For smaller TMCs with primarily signal management responsibility, it is not unusual to have no dedicated TMC staff, but rather staff might be present if event or incident conditions warrant. Larger TMCs with responsibility for managing urban freeway systems or with regional or statewide responsibility may have shifts of operators that provide around-the-clock monitoring and response. There are myriad models in between ranging from peak hour coverage to fully integrated, multi-agency operating models. Variations are dependent on geographic size covered by the TMC, agency responsibility for traffic management and operations, funding, and a host of other factors.

What the research and prior sections of this document point to is a need for identifying the technical skill sets that will be required for agencies to successfully migrate to and integrate connected vehicle data into their operating environments. Most notably, information management and analytics will require staff capable of managing the requirements of a Big Data environment, and effectively supporting the integration of that data into TMC functions and processes. This was identified as a high priority item during the interviews, as there are many unknowns about the level of data that will be generated and how it needs to be managed to support TMC and other agency functions. Operators also will be enabled with much more information to develop and implement corridor and network strategies, and this may necessitate operations staff with specific education and training in quickly assessing situations and implementing engineering-based strategies.

TMCs, like many DOT and agency departments, have been operating in a fiscally-constrained environment. Additional human resources can be a challenging justification, particularly when many of the benefits of new sophisticated systems and automated processes would seem to point to streamlining the number of staff required to support them. An important consideration in a future connected vehicle data environment is the potential "expansion" of the geographic network covered. Traditional boundaries for TMCs often conform to the extent of agency-owned infrastructure or defined geographic borders. A more ubiquitous data environment could broaden the current boundaries, which may necessitate additional staff resources to provide adequate coverage over this expanded footprint. For some regions and states, contracted or outsourced models are used to be able to bring the required operator and other technical resources to support the TMC. It is difficult to predict the precise impact

that connected vehicles will have on overall staffing numbers, but rather may require a realignment or redistribution of the resource pool currently available within TMCs today. TMCs should consider shifting to a staffing approach based on needed skill sets versus number of Full Time Equivalent (FTE), as this could support redefining positions and potentially acquiring the needed skill sets to support system operations in a connected vehicle environment. As an example, a TMC with a shift supervisor and two operators may not need to add additional numbers of staff, but require that the shift supervisor have the engineering training to interpret analytics information and implement engineering-based strategies.

Depending on the TMC operating environment, device maintenance may or may not be under the TMC staffing model. In many areas of the country, there are distinct business organizations within transportation agencies for operations and for maintenance. Staff that had focused primarily on electrical and signal repairs often had roles expanded to include new field devices (such as highway advisory radio, new types of telecommunications, dynamic message signs, detection, etc.) as those were installed and came on line. A broad generalization, but one that applies to most transportation agencies, is that maintenance resources for current ITS field equipment are not adequate. Maintenance is challenged with keeping up with the pace of deployment, and with maintaining legacy equipment that has reached or exceeded its useful life. With connected vehicle roadside equipment, new skill sets will need to be added to current maintenance staff, and there may be additional responsibility for communications network maintenance to support an additional layer (or more) of infrastructure.

Table 5 presents recommended new positions and/or technical discipline areas that may be necessitated for this new environment.

Table 5 – TMC Skill Set Needs in a Connected Vehicle Environment

Technical Discipline	Skill Sets and Credentials
Information Technology and Data Management	• Hardware and software support for Big Data environment, and integrating data/information into TMC processes • Data warehousing, queries and support for data access and redistribution • Support data management and sharing policy development • Integrate new software and updates • Coordinate with system developers and integrators for new TMC systems and software
System Analytics and Processing	• Identify how to update TMC processes with new capabilities • Identify what types of analysis can lead to improved operations and decision support • Support process enhancements to TMC functions • Coordinate with other TMCs or other agency divisions to identify how new data can support their functions (i.e., safety, planning, programming, project development, etc.) • Aggregate and process data (if this function will be completed in-house) to create useful information for system and operational performance metrics • Analyze system performance and recommend modifications based on outcomes • Support development of performance metrics and performance management strategies
Network and Device Maintenance	• Specialized training for maintaining new field devices to support connected vehicles

	• Testing and implementation of new devices • Coordinate with device vendors for technical specifications and requirements • Coordinate with IT and Operations to integrate new devices into TMC processes
Operations Engineering Decision Making	• Specialized training and registration or certification for traffic engineering • Skill sets to develop traffic signal timing plans and strategies, and to implement modifications to signal operations to optimize traffic flow and safety • Technical inputs to metering strategies for safe and optimum operations • Authorize and/or implement changes in strategies based on real-time connected vehicle data inputs, such as weather response strategies, balancing network demand, or multi-agency corridor operations • Support development and active monitoring of system performance metrics, and identify where strategies need to be implemented to achieve performance goals

Transportation management agencies are likely going to be faced with some challenges in terms of staffing for a connected vehicle environment. Historically, many agencies have been challenged attracting and retaining highly skilled technical staff, because this is one area that has some significant overlap with the private sector, which may be able to offer more competitive salary incentives. Furthermore, several agencies have expressed frustration in adequately defining specific technical needs within their requirements for job descriptions, and as a result, these descriptions reflect what staff currently does rather than what specific new or expanded skill sets might be needed. Institutionally, it may be difficult to reclassify positions to better reflect specific skill sets if there is not a precedent within the respective agency to do so.

One option might be to explore contracting for specific skill sets to supplement agency FTE staff within the TMC operating environment. There are several models in use today in TMCs throughout the country where a hybrid of agency and contractor staff are able to meet the technical and staffing needs. Two agencies interviewed for this project expressed minimal concern for skill set needs; within their contracted operations model, these technical skill requirements would be incorporated into their contractor requirements and performance expectations.

Another option might be to explore regional resources to support a multi-agency environment. It might not be practical for smaller cities within regions to individually acquire specific resources, but there may be economies of scale for a regional agency (or one agency in a region) to take that responsibility. Funding for those regional positions could utilize some form of a fair-share strategy (funding from partners based on number of devices in their jurisdiction). Similarly, some elements of data management might be more feasible and effective if handled regionally. Table 4 in the previous section identified some of these regional vs. localized considerations for data storage and management.

6 TMC Operations Readiness Considerations

With new data brings new responsibilities and there will need to be systems and processes in place to collect, aggregate, and analyze the Connected Vehicle data to become an effective operational tool. That effort precedes any potential changes in operational processes that could be realized across TMCs nationwide. The following are recommended activities for TMCs to undertake based on the operational tools that connected vehicle data could support:

- Identify operational capabilities agency / region / corridor would like to realize in the future through using Connected Vehicle or other enhanced data environment;
- Begin to define the different data types that could potentially be added to the TMC data environment, as well as document specific issues associated with acquiring and storing that data. Data could include information from agency-owned RSEs, third party cellular data, on-board data from vehicles (public and private, which will have different requirements), and a host of other data types. Some agencies already have experience with unique requirements or restrictions on third party probe data, but additional consideration needs to be given to acquisition, ownership, storage and dissemination of a much broader connected vehicle data environment.
- Put a performance measurement system in place to be able to measure the 'before' state and identify areas for improvement prior to accepting new data types;
- Evaluate capacity of current technologies / systems to support adaptation and integration with evolving Connected Vehicle technologies / systems;
- Develop requirements for adaptable technologies / systems (if needed);
- Establish ongoing maintenance and support access to existing systems that can be utilized during a transition period to added or changed TMC operations;
- Partner with internal departments to determine overlaps in data, processing, staff, skill sets or roles to streamline;
- Adjust or fill personnel roles to match future vision and skill sets, including agency staff, contracted operations, or public-private partnership agreements;
- Determine data archiving and processing capabilities in-house and if an external department or third party entity would be better suited for the resource requirements involved;
- Institutionalize processes for adaptation through flexible and evolving job responsibilities and skill set placement within organizational structure.