A Technology Framework for Smart City Infrastructure Maintenance

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Introduction

America's economic health depends on a surface transportation system that provides for the safe, reliable, and timely movement of people and goods. The U.S. transportation network is multimodal, intermodal, massive, and complex. It contains more than four million miles of road, more than 600,000 bridges, nearly 140,000 miles of rail, approximately two million miles of pipelines, more than 25,000 miles of navigable waterways, more than 25 international container ports, and almost 20,000 airports (USDOT 2017). This article focuses on road and rail infrastructure condition and performance because of their level of importance to safety and U.S. economic competitiveness.

The condition and capacity of the rail and highway networks has not been keeping up with growing demands. Trucks haul more than 70 percent of U.S. freight by tonnage (ATA 2017). Railroads lead all modes in moving the heaviest loads across the greatest distances. They account for approximately 40 percent of intercity freight in ton-miles (AAR 2017) (FRA 2017). Gross Domestic Product (GDP) is a key measure of U.S. economic competitiveness. Freight transportation is directly proportional to GDP, which has been growing at an average rate of approximately 3 percent annually (BEA 2017). With increasing demands and deteriorating conditions, congestion levels continue to expand throughout the multi-modal roadway and railway network.

A deteriorating infrastructure will deplete capacity, diminish performance, and create hazards. Figure 1 illustrates the author's viewpoint of how infrastructure supply and condition affect key aspects of the transportation system, and the impacts as they relate to national objectives. Congestion ultimately hampers business efficiencies, curtails productivity, waste fuel, increase emissions and environmental pollutants, and lead to unsafe situations. Load densities will increase with economic expansion. Heavy traffic will further stress the infrastructure and promote a cycle of accelerating deterioration.

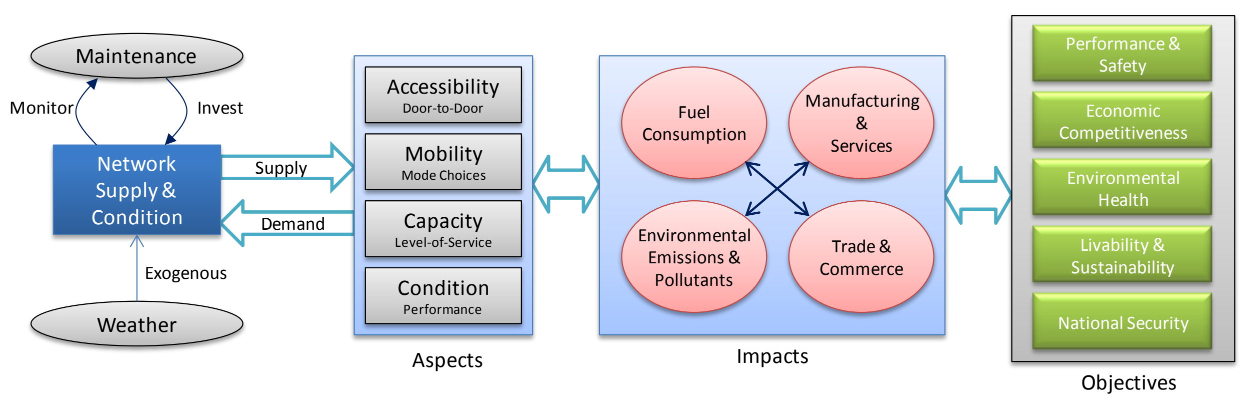


Figure 1: Key interactive elements of a transportation system.

Without additional investments in capacity and maintenance, the gap between supply and demand will likely widen. High traffic demands to move heavy loads will lead to widespread infrastructure deterioration. As shown in Figure 2, vehicle miles traveled continues to outpace the highway miles available. Without additional network capacity, studies forecast that areas of peak-period congestion will expand significantly (FHWA 2010) (FHWA 2017). The American Society of Civil Engineers has consistently rated the nation's infrastructure at a low grade of D or D+ since 1998 (ASCE 2017). Poor pavement conditions deplete capacity even in uncongested situations because vehicles cannot travel the speed limit safely. Rough roads can cause loss of control, which can lead to crashes (Hu, et al. 2017). In addition to lives, other potential losses include freight damage from excessive vibration, lost revenue from late deliveries to just-in-time manufacturing facilities, and vehicle damage. Studies estimate that driving on roads in need of repair costs U.S. motorists an average of $400 extra in vehicle repairs and operating costs each year (TRIP 2017).

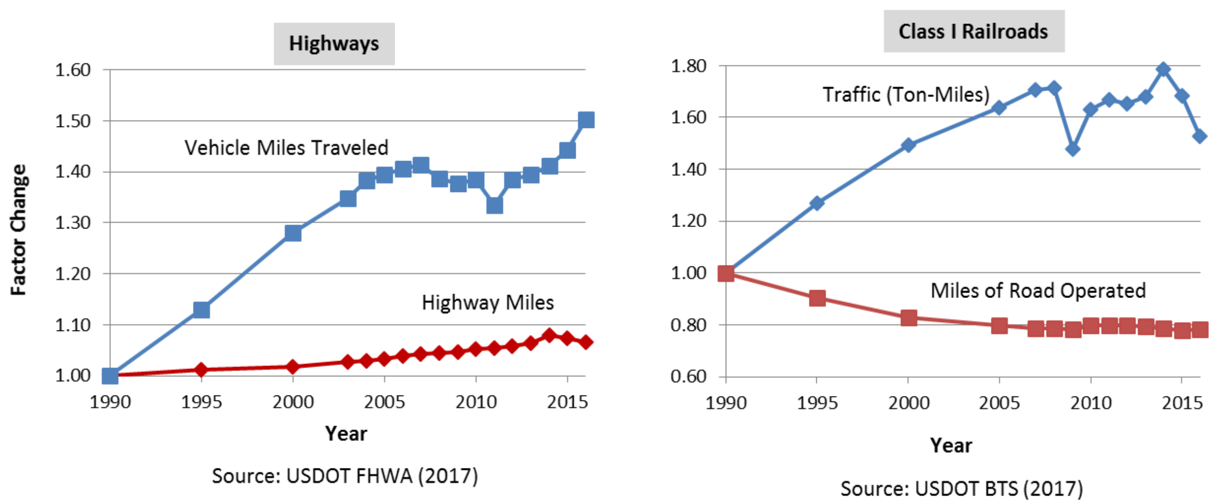


Figure 2: Supply and demand gap in transportation system.

Policies to move truck traffic to rail may not necessarily alleviate the situation because the gap in supply and demand also persists for railroads. Figure 2 also illustrates how rail traffic grows relative to the miles of railroad operated. Class I railroads own and maintain their rights-of-way. According to the Association of American Railroads (AAR), Class I railroads collectively spent 40 percent of their revenue on infrastructure maintenance (AAR 2017). At this level of expense, it is doubtful that railroad companies can afford to further increase spending on maintenance to keep up with increasing traffic density. Similarly for roadways, federal highway spending regularly exceeds the gas tax revenue needed to fund maintenance (Langer, Maheshri and Winston 2017).

Demand for infrastructure capacity and performance in an environment of escalating fiscal deficits has motivated research for innovative approaches to reduce maintenance costs. This article summarizes existing and emerging technological approaches to road and rail condition monitoring. The technology developments presented aim to reduce maintenance cost and maximize the amount of infrastructure that is in a state-of-good-repair at any given moment.

Current Approach to Infrastructure Condition Monitoring

Transportation agencies worldwide spend trillions of dollars maintaining infrastructure based on a *fix-worst-first* approach. Studies show that an alternative *preserve-first* approach will reduce asset preservation cost by at least a factor of three, saving hundreds of billions of dollars. However, a preserve-first approach requires more frequent monitoring to forecast optimum maintenance triggers. Transportation agencies and railroads do not regularly monitor all network segments because existing manual and automated inspection methods are relatively expensive.

Rail

Railroads must visually inspect most tracks in service as often as twice weekly to comply with the Federal Track Safety Standards (FTSS). However, the defect formation rate increases with traffic load-density, and railroads are hiring fewer employees per track-mile (AAR 2017). These trends result in a widening gap between the rate of defect formation and the resources available to find them before they result in accidents, delays, and lost revenue.

Railroads augment visual inspections with automated non-destructive evaluation (NDE) inspection cars to locate developing and mature defects. However, the overall inspection rate is practically limited because a trailing repair gang must still be able to schedule track time, weather permitting, and keep up with the rate of defect discovery. A Federal Railroad Administration (FRA) survey found that railroads conduct 94 percent of their visual inspections with the aid of a Hi-Rail vehicle (Al-Nazer, et al. 2011). These vehicles are hybrids that can legally operate on both road and rail. They contain hydraulic pumps to lower track wheels onto the rail when entering the line and raise them when returning to the pavement. Since many defects are not observable from a Hi-Rail vehicle, inspectors must still patrol the tracks by foot. Automated NDE cars can conduct several different types of inspections simultaneously while Hi-Rail vehicles typically specialize in only a few types at a time.

Track inspections are a necessary expense for preventative maintenance and safety compliance practices, but they also deplete the track capacity available for revenue service. Hi-Rail vehicles are practically limited to speeds between five and thirty miles-per-hour (mph) because inspectors must often stop to verify possible defects. Automated inspection vehicles are three to five times more expensive than freight train locomotives, and the inherent complexities of NDE technologies they carry limit their speeds. Even though the capabilities of these technologies have improved over the years, they still move slower than average train speeds, and they cannot locate all defects with perfect recognition rates.

Roads

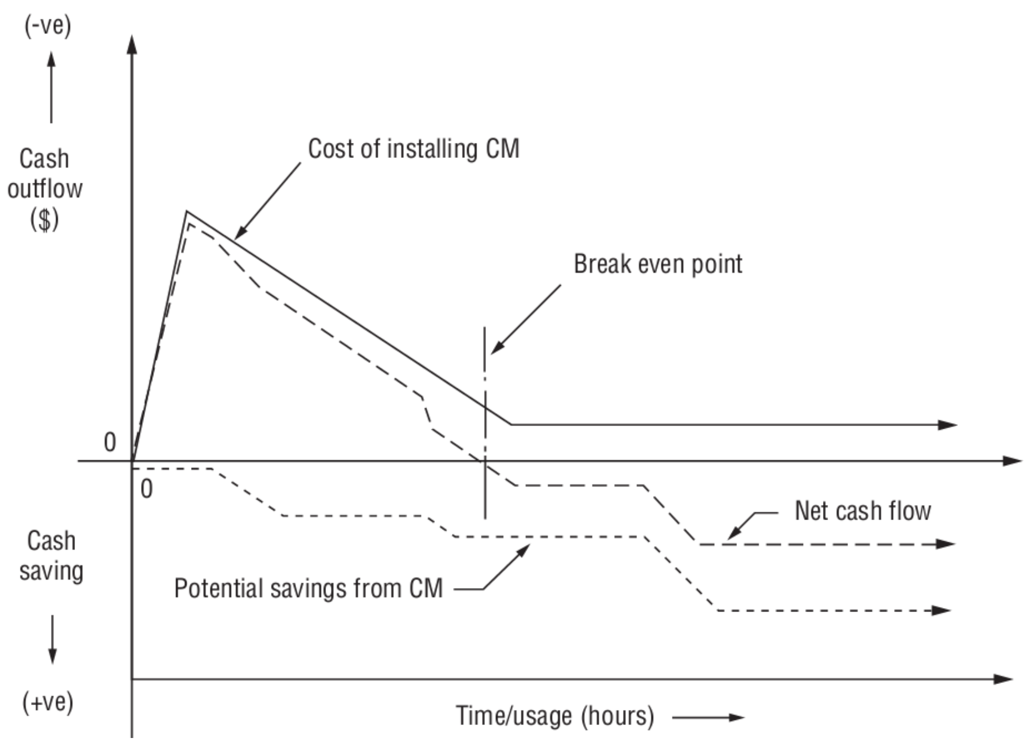
To achieve a state-of-good-repair using the preserve-first approach, Department of Transportation agencies must regularly update pavement life-cycle models as conditions change due to varying traffic load and weather patterns. However, agencies cannot afford frequent pavement condition monitoring with existing approaches that rely on special Profilometer vehicles and extensive visual inspections. Profilometers equipped with expensive imaging, Ground Penetrating Radio Detection and Ranging (GP-RADAR), and Light Detection and Ranging (LIDAR) equipment inspect interstate roads once every few years. Agencies inspect local and collector roads less frequently and tend to use human visual inspections for those.

Automated pavement profiling requires highly trained professionals riding in vehicles specially equipped with cameras, lasers, and/or radio frequency based sensors to capture images for post processing. Vehicle speed, lighting conditions, and available computing resources limit the effectiveness and accuracy of these approaches. Alternatively, manual visual inspections are labor intensive, time-consuming, irregular, and inconsistent.

Data Driven Predictive Approach

Studies show that preventative maintenance done at the optimum time will extend the lifecycle of a pavement. An effective preservation program that doubles the life of a pavement can save states over three times the cost of reconstruction (NCHRP 2004). Similarly, an optimized track maintenance program can substantially reduce the risk of train derailments (Osman, et al. 2017). However, those programs are only as effective as the quantity and quality of conditioning monitoring inputs. Surveys of American production industries indicate that one-third of maintenance cost was unnecessary. Conversely, repairs performed in the "run-to-failure" mode averaged about three times higher than the same repair made within a preventative maintenance mode (Mobley 2002).

Figure 3 illustrates the net benefits of continuous condition monitoring (CM) over time. CM technology can provide regular and consistent inputs to a preventative maintenance program and enable a predictive maintenance approach by forecasting optimum maintenance triggers. The inputs from CM sensors embedded in roadways (Zhiming, et al. 2015), and the use of regular vehicles to monitor ride quality (Bridgelall 2014) will provide a more consistent, long-term indication of the infrastructure deterioration rate.



Source: Mobley, R., K., "An Introduction to Predictive Maintenance", 2002

Figure 3: Typical cash flow from an investment in predictive maintenance.

Smart Cities

Smart cities integrate diverse sets of information and communication technologies to monitor asset condition, security, safety, service quality, and operational efficiencies, often in real time. Emerging CM technology that use ubiquitously connected sensors and networks will provide regular and consistent condition assessment to trigger maintenance decisions at the optimum times. Components include low-cost, autonomous wireless sensor networks that operate in one of two modes:

- stationary sensors embedded into the physical infrastructure report defects due to stress, strain, and corrosion (Zhiming, et al. 2015)
- mobile sensors on-board moving vehicles report data to assess ride quality (Bridgelall 2014)

Cloud based computing systems analyze signals from a fusion of stationary and mobile sensors to generate a complete picture of the infrastructure condition and performance. Railroads can use sensors aboard revenue service trains to isolate both track and vehicle locations that exhibit symptoms of a defect for follow-up remediation (Bridgelall 2013). For pavements, sensors on-board vehicles can report roughness and navigation data. Deterioration models will utilize the CM data to forecast optimum maintenance triggers so that railroads and highway agencies can prioritize repair and program funding allocations. This continuous monitoring approach using regular vehicles will cost significantly less than present approaches and will scale more easily with infrastructure expansion.

Cloud based sensor interface and big data analysis can utilize the connected vehicle network to monitor road and rail condition as vehicles traverse pavement and track segments. The United States Department of Transportation (USDOT) expects that nearly all new vehicles will be equipped with vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications technology by 2030 (NHTSA 2016). Manufacturers are developing sensor architectures that leverage rapid advancements in low-cost, battery-free, miniaturized Global Position System (GPS) receivers, wireless communications, and micro-electro-mechanical systems (MEMS).

Short-Term and Long-Term Effects

In the short-term, sensor deployment can be in the form of participatory sensing using smart phones. These devices can log and report GPS coordinates and inertial sensor characteristics. Such devices will allow road and rail users to obtain useful information about the network condition and real-time travel advisory relevant to their current location. Planners will have access to high quality GPS data to improve travel demand models and forecasting. Short-term effects of sensor deployment will result in greater visibility and insights into the state of infrastructure condition and produce accurate travel demand projections. With improved forecasting models and data quality, stakeholders will gain the confidence needed to propose policies that improve the efficiency and effectiveness of asset management practices.

Long-term effects will be standardization of sensor deployment for infrastructure preservation and asset management. These programs will produce more accurate maintenance triggers for optimized pavement and rail line preservation. Agencies will begin to realize the projected savings that result from using new sensor-based preservation and asset management systems. Consequently, a greater portion of the infrastructure will transition to a state-of-good repair.

Conclusions

Roads and rail are critical to the economic competitiveness of any nation. In the U.S., they move more freight and people than any other mode of transportation. U.S. economic and population growth will double the demand for freight transportation within 25 years. However, both highway and rail transportation networks are running out of capacity. Without additional infrastructure investment, a significant portion of both the road and rail network will be operating above capacity by 2035. As the widening gap between supply and demand places greater stress on the infrastructure, the deterioration rate will increase. Organizations are seeking cost-reduced asset preservation approaches to maximize the amount of infrastructure that they can maintain in a state-of-good-repair.

Effective asset preservation programs require regular and continuous condition monitoring. Existing methods are expensive and lacks network coverage. Emerging solutions can leverage recent technological advancements in wireless micro-electro-mechanical systems (MEMS) and the USDOT Connected Vehicle program to implement a lower cost, participatory sensing system for network-wide, real-time condition monitoring. In the short-term, agencies will gain improved visibility of the infrastructure condition and stakeholders will gain the confidence to enact policies for improving asset management programs. Long-term effects will result in standardization of participatory sensing deployment for optimized asset preservation programs that accurately forecast deterioration rates to produce optimum maintenance triggers.

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