A Life Cycle Cost Analysis Approach for Emerging Intelligent Transportation Systems with Connected and Autonomous Vehicles

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This is the author's version of a work that has been accepted for presentation at the Transportation Research Board's 97th Annual Meeting, Washington D.C., 2018. The final version is available here: http://amonline.trb.org/2017trb-1.3983622/t007-1.3999867/378-1.4000048/18-03895-1.3992195/18-03895-1.4000055

A LIFE CYCLE COST ANALYSIS APPROACH FOR EMERGING INTELLIGENT TRANSPORTATION SYSTEMS WITH CONNECTED AND AUTONOMOUS VEHICLES

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Word count: 5735 Texts + 3 Table + 4 Figures = 7485
Abstract: 214
Submission Date: November 15th, 2017

Paper resubmitted for Presentation and Publication in the
Transportation Research Board's 97th Annual Meeting, Washington, D.C., 2018

Abstract

The objective of this paper is to describe five fundamental differences arising from the application of Life Cycle Cost Analysis (LCCA) to a technology-oriented Intelligent Transportation System (ITS) project rather than a conventional transportation project such as pavement or bridge projects. These five differences are related to the temporal behavior of inflation, consideration of uncertainty, out-of-pocket costs, risks in terms of technical obsolescence, and need for a pro-active inventory management strategy. A novel conceptual ITS LCCA framework which is introduced to capture these differences has the potential to be more efficient in a connected and autonomous vehicle (CAV) environment. The findings from an in-depth discussion of the inflation rate indicate that the trend of the inflation rate for ITS components does not need to follow the general trend of consumer and producer price index. In addition, a viable alternative to quantify user cost is introduced by utilizing outputs from traffic simulations based on traffic delay, vehicle operation and crash risk cost models. Hypothetical failure rate scenarios were developed through the use of an open-source micro-simulation traffic software namely, SUMO, in a connected vehicle environment. This approach is shown to be useful in quantifying user costs. Moreover, this tool can be readily implemented within the ITS LCCA framework when actual failure rate information becomes available.

Keywords: Life cycle cost analysis, Intelligence transportation system, Connected and autonomous vehicle, SUMO, Inflation rate

INTRODUCTION AND MOTIVATION

In recent years, various emerging concepts of connected and autonomous vehicle that fall under the umbrella of Intelligent Transportation Systems (ITS) are being incorporated into long-term plans and policies of Federal, State, and local transportation agencies. In September 2015, Connected Vehicle (CVs) Pilot Deployment Program awards were made by the U.S. Department of Transportation (USDOT) to three sites: Wyoming, New York City (NYC), and Tampa *(1)*. This pilot program is "a national effort to test, deploy, and evaluate innovative mobile and roadside technologies and enable multiple CVs applications" *(1)*. The 2014 Update Report of "ITS Benefits, Costs, and Lessons Learned" *(2)* highlighted the ITS evaluation trends towards connected and autonomous vehicle environment in various aspect including arterial management, crash prevention and safety, traveler information, and driver assistant. Several State and local Departments of Transportation (DOTs) also emphasized that future ITS investments should be "in conjunction with the coming wake of Connected Vehicle technology" *(3-6)*. The potential for immediate beneficial impacts of CVs has been acknowledged in many aspects such as safety and mobility improvements and system efficiency *(7)*. However, for transportation agencies, it is important to evaluate the cost-effectiveness of these emerging ITS technologies, especially on transportation infrastructures. Life cycle costs should be considered, including not only the initial purchase and installation costs, but also costs associated with maintenance and repair, and externalities such as delays and socio-economic impacts. This type of time-dependent comprehensive economic analysis is known as the Life Cycle Cost Analysis (LCCA).

LCCA is one of the most renowned economic evaluation tools for transportation infrastructure management, planning, and decision-making support in the development of optimum investment strategies by accurately assessing estimated costs while satisfying budget constraints *(8)*. LCCA has been widely used for planning economic feasibility of infrastructure components focusing on pavements or bridges. However, technology-oriented Intelligent Transportation Systems (ITS), especially its applications in connected and autonomous vehicle environments, have different characteristics than the traditional transportation systems. Applying long-established conventional LCCA practice to such systems may not always be appropriate.

The main differences between ITS and traditional transportation systems regarding LCCA considerations can be summarized as follows:

- Different inflation behavior. Assuming the project-specific inflation rates to be the same as the general inflation rate may not be appropriate as various ITS components have different inflation behavior compared to the general inflation behavior.
- Higher uncertainty. When new ITS technologies are first used, they have insufficient records or historical data on their unit costs and how they perform under different conditions over the mid- or long-term.
- More emphasis on out-of-pocket costs. The life cycle of ITS systems is shorter than that of a traditional transportation project. They usually are subject to more frequent failures as well which may result in traffic congestions or crash risks. Therefore, out-of-pocket costs such as user cost and social cost play a more critical role in ITS LCCA.
- Higher risks in technical obsolescence. Rapid innovations in ITS technology have forced a continuous reduction in the time that it takes to bring a new product to market. On the other hand, take CAV as an example, it usually takes longer for car manufactories to develop a new car model than the connected technology with which they need to work.
- Need to consider inventory management. Spare parts inventory management of essential components of ITS equipment and its associated costs due to unavailability of spare parts should be considered.

In the light of all these complications, ITS technologies with dynamics of connected and autonomous vehicles present a new challenge and opportunity for LCCA in terms of selecting best alternatives. A novel life cycle conceptual framework that takes into account all these complications is critical for achieving sustainable transportation system.

This study proposed a conceptual ITS LCCA framework, mainly on transportation infrastructures to support the decision-making process for transportation agencies, followed by discussions of each component in the framework. Next, the inflation rate is investigated in detail, and several simulation-based hypothetical scenarios are examined in terms of user cost. This paper ends with conclusions and future research suggestions.

LITERATURE REVIEW

In transportation engineering, the first official LCCA technical bulletin developed by Federal Highway Administration (FHWA), "Life-Cycle Cost Analysis in Pavement Design"*(9)*, can be chased back to 1998. This report recommends step-by-step procedures for conducting LCCA at the project level and has become the agency’s guidance document. Since then, various state departments of transportation (DOTs) incorporated life cycle cost consideration in their decision-making process and transportation asset management under the guidance of FHWA, State Highway Agencies (SHAs) along with MAP-21 *(10)*.

In general, the traditional way of calculating life-cycle cost of a transportation asset is by summing up the monetary equivalency of all costs (i.e. construction and maintenance cost) throughout the analysis period *(11)*. FIGURE 1 shows a traditional LCCA flowchart for bridge and pavement applications.

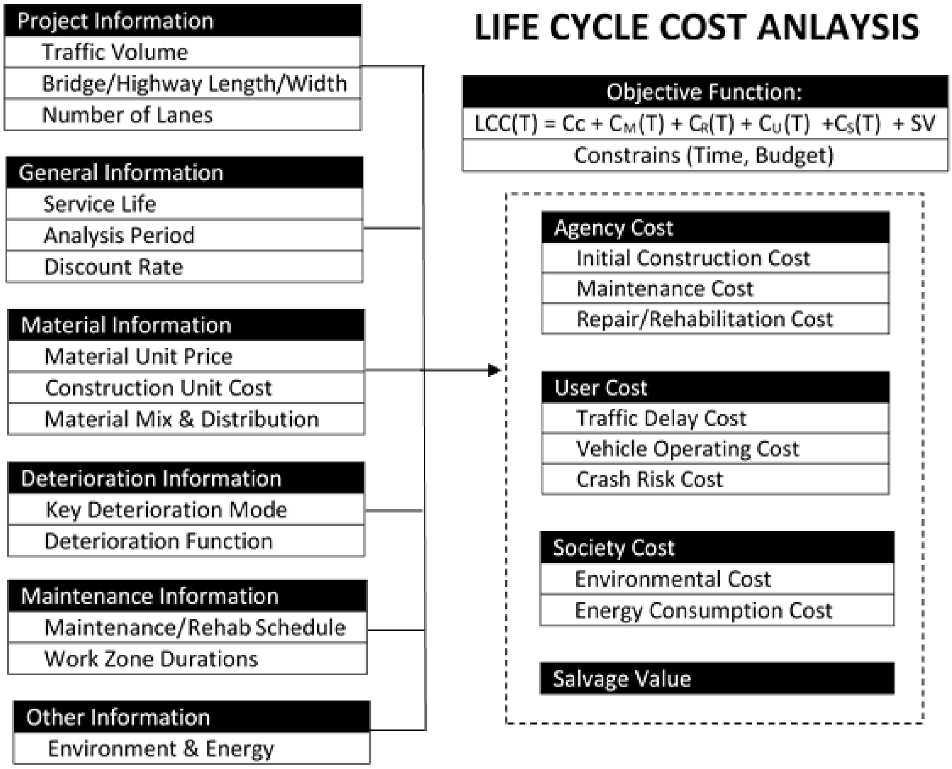


FIGURE 1 Traditional LCCA flowchart for bridge and pavement applications *(12)*.

However, the difference between traditional projects and technology-oriented ITS projects regarding LCCA should be considered very carefully. Jawad and Ozbay *(13)* pointed out that inflation rate of ITS will not follow the general positive inflation rate as does when considering the conventional transportation projects. A micro-level analysis of the ITS unit cost, a macro-level analysis of the Consumer Price Index (CPI) of ITS components, and an analogous comparison to historical inflation performance of a comparable sector with the ITS sector were conducted. This study also summarized other unusual characteristics of ITS projects such as higher risks because of technology's novelty, obsolescence, and perpetuity. Hadi *et. al (14)* estimated ITS deployment impacts and costs using default ITS deployment analysis system (IDAS) values and customized Florida costs. They introduced ITS "impact factors" that were based on previous deployments (i.e. a negative impact factor due to an increase crash rates on electronic toll collection (ETC) deployment). Although lifetimes of ITS components were adjusted in this study, authors followed a traditional approach of "constant dollar" without consideration of inflation.

Chiu *et al. (15)* conducted an LCCA for selecting cost-effective wireless communication technologies for ITS. Their study expressed the concerns about technology obsolescence such as Microsoft Windows system update cycles and discontinued support for 2G network. They took these considerations into account when determining upgrade activity timing. Although authors admitted a probabilistic approach would be more robust, due to budget and time constraints, a deterministic approach was applied in their study.

Moreover, Ozbay *et. al (16, 17)* stated that long-term downtime of ITS equipment due to the unavailability of spare parts would increase personnel and repair times and may also lead to increased traffic delays, poor air quality, and fuel consumption. They proposed a spare parts inventory control model that can identify the optimum safety stock levels to improve the efficiency of related maintenance and repair activities. Both probabilistic failures and various level of demand uncertainty are also considered.

The differences stated above demand a new framework to refine ITS LCCA process. This includes accounting for unique needs of such a technology-oriented system, new performance measures for the evaluation system effectiveness, and enhanced methodologies for identifying sub-system or system times to failure. For system effectiveness evaluation and identification of time to failure, ITS deployments are found to have many similarities with power plants or transmission systems. Besides the traditional LCCA considerations (i.e. initial installation cost), cost components for maintenance, replacement, and user or social costs rely more on their system effectiveness. In other words, system's reliability, availability, maintainability and capability (RAMC) should be taken into account. Few of the most relevant recent works *(18-20)* in power plants or transmission systems suggested using effectiveness equation *(21)* to address the trade-off between life cycle costs and system performance considering RAMC. Adoption of the LCCA methodology for such systems with stochastic treatments of high uncertainty cost components such as the cost of failure or repair is vital to establish a practical LCCA framework for ITS deployments.

Regarding ITS cost and benefit data sources, one of most popular and useful ITS cost and benefit database is ITS Knowledge Resources *(22)* developed and maintained to support ITS investment decisions by tracking the cost-effectiveness of deployed ITS from multiple sources. As of July 2017, the ITS Knowledge Resources databases contain a total of 1,628 summaries of ITS benefits, costs, and lessons learned in the United States. However, due to the relatively new deployment of CAV applications, a limited number of resources are presented in these databases (77 benefit and 19 cost summaries). As CAV programs continue to be deployed across the U.S., the number of summaries is expected to continue to increase in the future.

PROPOSED CONCEPTUAL FRAMEWORK

The ITS LCCA framework that will be discussed includes the conventional LCCA cost components such as agency, user, and social cost, as well as comprehensive considerations to account for different characteristics of a conventional transportation system and an ITS. A conceptual framework is demonstrated in FIGURE 2.

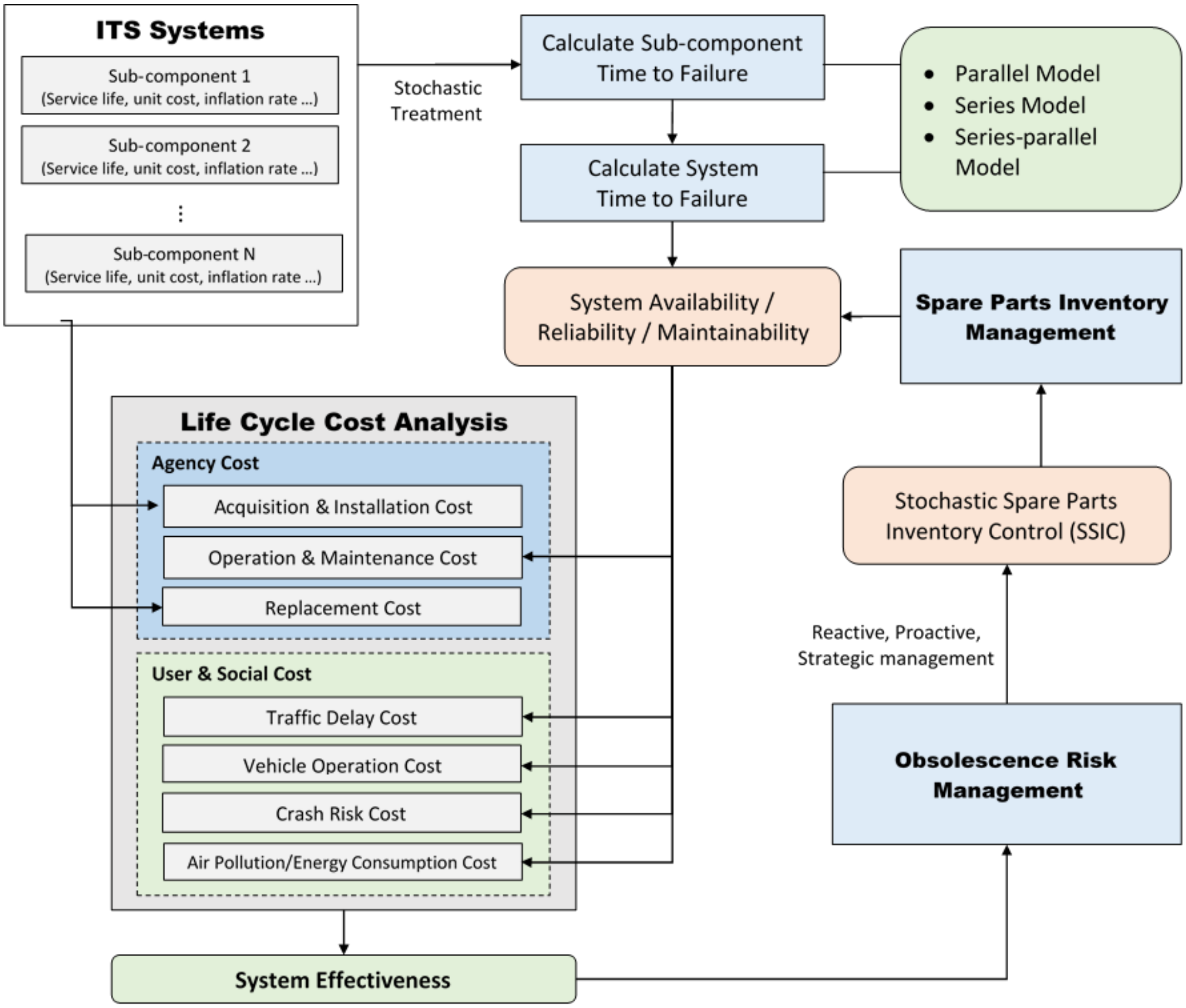
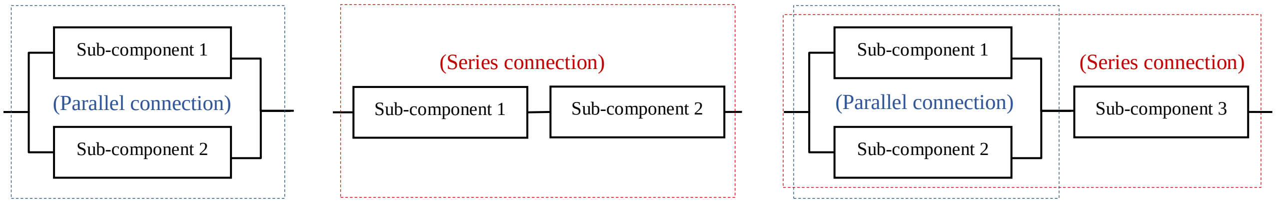


FIGURE 2 Proposed conceptual ITS LCCA framework.

The first step is to identify characteristics for each sub-component of ITS such as service life, unit cost, and inflation rate. Although it is a common practice to use a single general inflation rate in transportation projects, this approach might not be appropriate when it comes to ITS. An in-depth discussion of the ITS inflation rate is given in the next section.

The second step is to calculate the time to failure for ITS sub-components as well as the whole system. Ranking the importance of sub-components *(23)* and identifying their dependency relations are crucial in this step. Next, three dependency relations from electronic circuit theory are adopted in this framework for ITS LCCA: 1) parallel connection, 2) series connection and 3) series-parallel connection (FIGURE 3). A parallel connection indicates that if one or more sub-components of the ITS are down, the remaining sub-components will still function. For example, if the onboard-unit (OBU) on one of the connected vehicles fails, it will not affect the Vehicle-to-vehicle (V2V) communication for all other connected vehicles in the network. In contrast, a series connection implies that every sub-component must function. Failures of individual parts may cause the breakdown of the whole system (i.e. power outage). A series-parallel connection is a combination of the former two connection types. One good example can be the loss of internet connection to a central remote server that receives all data transmissions from CAVs. In this case, V2V communication is still working, however, no data will be transmitted to the central server and roadside infrastructures.



(a) Parallel connection (b) Series connection (c) Series-parallel connection

FIGURE 3 Parallel, series, and series-parallel connections.

Next, time to failure is computed for the sub-component with a highest ranking and the whole system. For most of the new technologies, such as CAV, lack of reliable field data is one of the leading issues to obtain failure rate information. An alternative method similar to *(18, 20)* is to utilize a theoretical probability distribution such as Weibull to estimate mean time to failure (MTTF) and mean time to repair (MTTR) in this step. A probabilistic approach is suggested in these estimations due to the nature of ITS as many input parameters are subject to a different level of uncertainty. Stochastic treatment for the input parameters, such as Monte Carlo simulation method, is needed to proceed with this probabilistic approach *(24)*.

Once the failure estimation is completed, the total expected life-cycle cost (LCC) up to the lifespan T of a designed ITS system and the expected replacement cost can be formulated as follows (modified based on *(25)*):

$$\boldsymbol{E[LCC(X,T)] = \sum_{j=1}^{J} C_{Ij}(X) + \sum_{t=1}^{T} \left[\frac{\sum_{j=1}^{J} E[C_{Mj}(X,t)] + \sum_{k=1}^{K} E[C_{Fk}(X,t)]}{(1+r)^{t}} \right]} \tag{1}$$

$$\boldsymbol{E[C_{Fk}(X,t)] = (C_{Ak}(X) + C_{Uk}(X)) \cdot p_{Fk}(X,t|T_s)} \tag{2}$$

where $E[LCC(X,T)]$= *total expected life cycle cost which are functions of the design ITS system X and life span T;* $C_{Ij}(X)$= *initial cost for ITS equipment type j;* $E[C_{Mj}(X,t)]$= *expected maintenance costs for ITS equipment type j;* $E[C_{Fk}(X,t)]$ = *expected replacement cost for limit state k; and r = discount rate, k = index for a failure limit state;* $C_{Ak}(X)$= *Agency cost of equipment replacement for failure limit state k;* $C_{Uk}(X)$= *User and social cost of equipment replacement for failure limit state k;* $p_{Fk}(X,t|T_s)$= *updated probability of failure at any time t (i.e., probability that the failure will occur during time interval* t_1 *conditional on updated loads or resistance); and* T_s = *survived time duration which can be expressed as* $t - t_1$.

The proposed ITS LCCA framework suggests to include both user and social costs since the downtime of the ITS equipment does not only have the potential of increasing traffic congestion and vehicle operation costs but also can create safety issues. A simulation-based approach is proposed in the later section for a closer consideration of the user costs in ITS.

Furthermore, an evaluation measurement is considered in this framework to capture the trade-off between the cost and the effectiveness. System effectiveness is defined as follows *(18)*:

System Effectiveness = Effectiveness/LCC (3)

Effectiveness = Reliability x Availability x Maintainability x Capability (4)

where the reliability, availability, maintainability, and capability of the effectiveness equation is a value that lies between 0 and 1.

The definition or formulation of RAMC may vary, but the general concept can be summarized as follows: 1) Reliability is the probability that the ITS sub-component or the whole system is fulfilling its purpose adequately for the intended period *(19)*, 2) Availability is defined as a measurement of system reliability that combines both the outage time and the frequency of outage *(20),* 3) Maintainability deals with the duration of maintenance outages and the maximum repair time. 4) Capability in this ITS LCCA framework can be defined as a probability of intelligent transportation system that is capable of meeting the minimum requirement of its users *(19).*

To improve system effectiveness, two additional sub-systems are taken into consideration: Obsolescence Risk Management and Spare Parts Inventory Management. Obsolescence may be a problem due to the rapid development of technology-based products, especially in the emerging CAV market. For example, several companies have gone out-of-business in the US over the past decade, creating issues for equipment replacement (29). Effective obsolescence risk management usually contains multiple-level management *(26)*: 1) reactive management that immediately reacts to the problem of an obsolete ITS component and executes mitigation plans, 2) proactive management that usually evaluates system health and forecasts the obsolescence risk for its components, and 3) strategic management that usually includes design refresh planning to enable life-cycle cost optimization. Life-cycle planning models with technology obsolescence such as Poter's model *(27)* which design refreshes as a function of future date or Mitigation of Obsolescence Cost Analysis (MOCA) *(28)* that optimizes over multiple obsolescence mitigations can be adopted into the framework. However, in the case of ITS LCCA, both short-term and long-term mitigation plans need to be evaluated carefully since instead of increasing existing stock, a full replacement may be more cost-effective due to the rapid development of ITS technology.

Finally, a spare parts inventory management system is also introduced in the framework. Such a system, can be used with reliable failure data to predict future failures using a stochastic spare parts inventory control (SSIC) system. This type of system is capable of accounting for the optimal amount of stored spare parts that will maximize the ITS performance with minimum cost and safety stock of spare parts given possible constraints such as supplier related disruptions or labor limitations. The mathematical formulation of the SSIC approach is shown below *(17)*:

$$\min\left\{\sum_{l=1}^{r} g^{(l)}(M^{(l)}) + \frac{1}{T}\sum_{u\in U} p_u \left[f^{(l)}(m_u{}^{(l)}) + \sum_{i=1}^{n}(q_i{}^{+(l)} + q_i{}^{-(l)}) \int_{m^{(l)}+m_u{}^{(l)}}^{\infty} \left(1-\Phi(\frac{z-\mu_{iu}^{(l)}}{\sigma_{iu}^{(l)}})\right) dz \right]\right\} \quad (5)$$

s.t.

$$\prod_{l=1}^{r} \Phi(m^{(l)} + m_u^{(l)} - \mu_{iu}^{(l)}, i = 1,\ldots n-1, \sum(\mathrm{g}^{(l)})) \geq 1-\varepsilon \quad (6)$$

$$m^{(l)} + m_u^{(l)} \leq M^{(l)}, u \in U, l = 1,\ldots,\mathrm{r} \quad (7)$$

$$m_u^{(l)} \geq 0, u \in U, l = 1,\ldots,\mathrm{r} \quad (8)$$

$$\sum_{l=1}^{r} a^{(l)}(M^{(l)}) \leq M \quad (9)$$

Where,

$m_u^{(l)}$: Additional amount of safety stock required to satisfy the needs for the vital supplies

$M^{(l)}$: Storage capacity for each spare part

n, l : Number of deliveries and commodities

$m^{(l)}$: Initial safety stock

$\mu_u^{(l)}, \sigma_u^{(l)}$: Approximate normal distribution variables of the random consumption and delivery distributions

$g^{(l)}, \mathrm{f}^{(l)}, \mathrm{q}^{+(l)}, \mathrm{q}^{-(l)}$: Associated costs

$a^{(l)}$: Space occupied by the commodity

M: Total Capacity

ε : Probability of disruption

In this system, demand is defined as the need for spare parts replacements due to ITS sub-component failures, while delivery represents delivering the spare parts that are not yet available in the spare parts inventory. This problem has two stages that the storage capacity of each spare part $M^{(l)}$ is the decision variable for the first stage while $\mathrm{m}_u^{(l)}$, the additional safety stock for each spare part, is the decision variable for the second stage. The objective function is to minimize the sum of individual costs including costs of storage ($g^{(l)}$), surplus ($\mathrm{q}_i^{+(l)}$), shortage ($\mathrm{q}_i^{-(l)}$), and adjustment ($f^{(l)}$)). This self-controlling model *(16)* also takes account the stochastic feature of the demand and delivery processes by adding probabilistic constraints to ensure the minimal disruption of spare parts usage for the ITS equipment with a given probability (equation (6)). More details can be found in *(17)*. The optimal number of spare parts estimated by this model can be used in the objective function of the LCCA to reflect the costs associated with operating highly time sensitive transportation system where certain level of spare part inventory has to be maintained. This approach will ensure that system down times will be minimized but also the cost of doing so will be adequately included into the life cycle cost function.

In-depth Discussion of Inflation Rate

In LCCA, there are many factors that affect the time-dependent behavior of costs, one of the most significant factors is inflation rate. The compounding effect of inflation rate becomes even more crucial with analysis period or more substantial amount of equipment purchased.

The general inflation rate, estimated from the proportionate change in the gross domestic product is often used in conventional transportation projects *(29)*. This practice is generally appropriate as the upward trend in the National Highway Construction Cost Index (NHCCI) 2.0 *(30)* that measures the average changes in the prices of highway construction costs over time is consistent with that of Consumer Price Index (CPI) for all urban consumers and Producer Price Index (PPI) for transportation industry. CPI is used to measure the average changes in the prices paid by urban consumers while PPI measures the average changes in the selling prices received by domestic producers for all commodities *(31)*. During 2010-2016, the NHCCI 2.0 grew by 2.5% annually, CPI grew by 1.6% annually, and the PPI for transportation industry rose by 1.5% annually.

Next, the inflation behavior of ITS costs is examined to investigate whether the price index trend of the ITS components is consistent with the CPI/PPI performance. To calculate the price index for any industry, a general practice is to break up the industry into its essential components *(13)*. For example, NHCCI is a composite price index of its basic components such as construction material, labor, or service *(13)*. In the same manner, this study breaks ITS into several components including communication technologies, information processing, electronics, highway and street construction, and labor needed for installation, maintenance, and operation of ITS. The price index for these components was collected and estimated by BLS (TABLE 1). The method is substantially similar to what is used by *(13)* with modifications on the specific components due to discounted series reported by BLS and the recent rapid development and importance of wireless communication.

TABLE 1 Price Index of ITS Main Components

Year	Wireless telecommunication services	Electronic components and accessories	Electronic computers and equipment	Installation, maintenance, and repair occupations	Professional, scientific, and technical occupations	Other nonresidential construction
2010	96.4	73.5	35.8	112	117.4	100.7
2011	93.0	71.0	34	115.3	119.9	108.6
2012	90.7	69.3	32.8	118	122.3	110.5
2013	89.8	69.0	31	120.1	124.2	110
2014	87.1	68.6	30.3	123.9	126.5	110.7
2015	79.4	68.2	29.1	125.2	128.5	N/A
2016	73.3	67.2	27.9	127.3	130.5	N/A
Avg. Annual Change	-4.4%	-2.3%	-6.8%	2.2%	1.8%	2.4%

As shown in TABLE 1, wireless telecommunication, electronics components, and computers have a downward trend (a negative inflation behavior), while specialists' employment and highway and street construction price indexes exhibit an increasing trend (a positive inflation rate). Apparently, this does not follow the general upward trend of CPI or PPI.

Furthermore, future estimates of the unit cost of ITS devices or subsystems in the CAV environment are summarized as well (TABLE 2). The cost information were conducted by studies from National Highway Traffic Safety Administration (NHTSA) and automotive industry surveys and were extracted from the ITS cost database published by the USDOT Joint Program Office *(22)*. The preliminary unit costs of the V2V system and OBU required to achieve V2V such as Dedicated Short Range Communications (DSRC) device also show a declining trend. Therefore, assuming the project-specific inflation rates to be the same as the general inflation rate is not appropriate for ITS projects. However, as stated in the price index of ITS main components (TABLE 1), ITS projects usually contain various cost categories such as labor and construction costs that can have an upward trend. A cost breakdown of a typical ITS project may include equipment installation, labor, traffic staging, preliminary engineering, maintenance and operation (or upgrading) cost and salvage value. Thus, a detailed investigation would be needed for each cost component.

TABLE 2 Estimated Preliminary Costs for V2V Implementation

Subsystem/ Unit Cost Element (Data Source: 2012, Automotive industry survey)	Median	%Change	Mean	%Change
Cost to Vehicle Manufacturers of Embedded DSRC				
2017	175		75	
2022	148	-15.4%	73	-2.7%
Cost Added to Base Vehicle Price for Connected Vehicle Technology				
2017	350		335	
2022	300	-14.3%	260	-22.4%
Consumer Cost to Add DSRC as Aftermarket Equipment				

2017	200		233	
2022	75	-62.5%	113	-51.5%
Subsystem/ Unit Cost Element (Data Source: 2014, NHTSA)	Mean		%Change	
Total cost per vehicle including vehicle equipment, fuel economy impact, communications costs, and Security Credentials Management System (SCMS)				
2020	$341 to $350			
2058	$209 to $227		-36.9%	
Cost per vehicle for on-board equipment necessary to support the V2V safety applications				
2020	329			
2022	260		-21.0%	
2058	186		-28.5%	

USER COST IN CONNECTED VEHICLE ENVIORNMENT

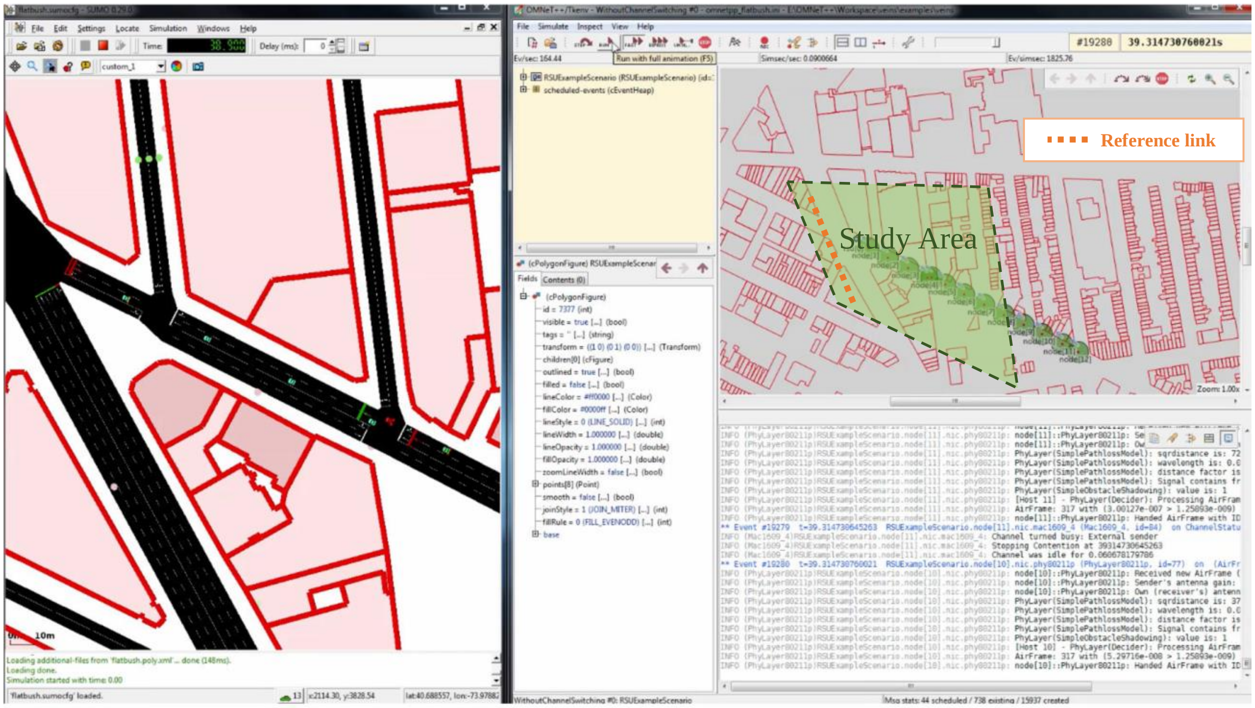
User costs are all those costs incurred by the road users that often include traffic delay, vehicle operation, and crash risk costs. Quantifying the monetary value of user costs is usually not straightforward and can become extremely complicated when it comes to ITS CAV applications. This section introduces a viable alternative to utilize the output from traffic simulations combined with well-developed cost models and tests its feasibility for quantifying user costs under CAV environment. The idea is that if such approach is feasible, it can be incorporated into the LCCA framework discussed in the previous section when actual failure rate information becomes available. Depending on the type and severity of the ITS equipment failures, various hypothetical failure rate scenarios are examined using Simulation of Urban MObility (SUMO) open-source traffic simulation software *(32)*. Traffic Control Interface (TraCI) *(33)*, giving access to a running SUMO traffic simulation, along with two open-source communication simulator, Veins *(34)* and OMNeT++ *(35)*, are used to achieve connected vehicle environment in this study. The study area (FIGURE 4) contains 8 intersections and 10 roadway sections (links).

For the base case scenario, the following settings are chosen:

- 1000 connected vehicles with perfect communication conditions and 100% market penetration rate.
- Vehicle to Infrastructure (V2I) communication: RSU receives travel time information from vehicles and sends link queue length and average link travel time to vehicles. With V2I in effect, vehicles are able to reroute according to the traffic condition.
- Vehicle to Vehicle (V2V) communication: Vehicle receives information regarding delay and status (i.e. vehicle stopping, accident) from other vehicles. When only V2V is in effect, vehicles only receive delay information, but will not reroute.
- Vehicles can decide their route based on the received link travel time from RSUs, and change travel speed based on the queue length from RSU to waive conflicts and stop.
- V2I message has higher priority than V2V.

Different failure rates scenarios for OBU and RSU are developed as follows. For simplicity, assumptions of failure rate are kept at 10%, 20% and 30% and simple traffic delay cost, vehicle operation cost and crash risk cost models are applied.

- Scenario O1-1, O1-2, O1-3: OBU are not functional on 10%, 20%, and 30% of the vehicles
- Scenario R1-1, R1-2: All RSU are not functional at 10% and 20% of the time



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INFO (PhyLayer80211p)RSUExampleScenario.node[11].nic.phy80211p: PhyLayer(SimpleObstacleShadowing): value is: 1
INFO (PhyLayer80211p)RSUExampleScenario.node[11].nic.phy80211p: [Host 11] - PhyLayer(Decider): Processing AirFram
INFO (PhyLayer80211p)RSUExampleScenario.node[11].nic.phy80211p: AirFrame: 317 with (3.00127e-007 > 1.25893e-009)
INFO (PhyLayer80211p)RSUExampleScenario.node[11].nic.phy80211p: node[11]::PhyLayer80211p: Handed AirFrame with ID
** Event #19279  t=39.314730645263  RSUExampleScenario.node[11].nic.mac1609_4 (Mac1609_4, id=84)  on ChannelStatu
INFO (Mac1609_4)RSUExampleScenario.node[11].nic.mac1609_4: Channel turned busy: External sender
INFO (Mac1609_4)RSUExampleScenario.node[11].nic.mac1609_4: Stopping Contention at 39314730645263
INFO (Mac1609_4)RSUExampleScenario.node[11].nic.mac1609_4: Channel was idle for 0.060678179786
** Event #19280  t=39.314730760021  RSUExampleScenario.node[10].nic.phy80211p (PhyLayer80211p, id=77)  on  (AirFr
INFO (PhyLayer80211p)RSUExampleScenario.node[10].nic.phy80211p: node[10]::PhyLayer80211p: Received new AirFrame (
INFO (PhyLayer80211p)RSUExampleScenario.node[10].nic.phy80211p: node[10]::PhyLayer80211p: Sender's antenna gain:
INFO (PhyLayer80211p)RSUExampleScenario.node[10].nic.phy80211p: node[10]::PhyLayer80211p: Own (receiver's) antenn
INFO (PhyLayer80211p)RSUExampleScenario.node[10].nic.phy80211p: PhyLayer(SimplePathlossModel): sqrdistance is: 37
INFO (PhyLayer80211p)RSUExampleScenario.node[10].nic.phy80211p: PhyLayer(SimplePathlossModel): wavelength is: 0.0
INFO (PhyLayer80211p)RSUExampleScenario.node[10].nic.phy80211p: PhyLayer(SimplePathlossModel): distance factor is
INFO (PhyLayer80211p)RSUExampleScenario.node[10].nic.phy80211p: PhyLayer(SimplePathlossModel): Signal contains fr
INFO (PhyLayer80211p)RSUExampleScenario.node[10].nic.phy80211p: PhyLayer(SimpleObstacleShadowing): value is: 1
INFO (PhyLayer80211p)RSUExampleScenario.node[10].nic.phy80211p: [Host 10] - PhyLayer(Decider): Processing AirFram
INFO (PhyLayer80211p)RSUExampleScenario.node[10].nic.phy80211p: AirFrame: 317 with (5.29716e-008 > 1.25893e-009)
INFO (PhyLayer80211p)RSUExampleScenario.node[10].nic.phy80211p: node[10]::PhyLayer80211p: Handed AirFrame with ID
```

FIGURE 4 Connected vehicle simulation in SUMO via Veins/OMNet++ graphic interface (32-35)

__Traffic delay cost__ is the monetary value of travel delay time during the analysis period. In this paper, traffic delay cost is computed based on the value of time (VOT) multiplied by the total time lost due to driving slower than desired speed (include time spent standing). VOT represents the monetary value that users associate with their individual time spent in traffic *(36)* and the total time lost due to driving slower than desired is generated by micro-simulator SUMO.

__Vehicle operating costs__ (VOC) are the monetary value incurred by road users as a result of using their vehicles. Those costs usually include fuel consumption, engine oil consumption, tire wear, repair and maintenance, and mileage-related vehicle depreciation *(36)*. The VOC model in this study is based on NCHRP Report 133 method *(37)* on road user costs, considering both VOC due to stopping and VOC due to queue idling.

__Crash risk cost__ has relied on historical data of actual crashes and estimated crash rate for conventional transportation projects. However, due to the relatively short service life of ITS equipment, this type of crash analysis might not be easy to apply. Instead, surrogate measurements such as Time to Collision (TTC) and traffic conflict techniques in conjugate with microsimulation model *(38)* can be used to estimate potential crash risk and approximate its associated cost. The most commonly used surrogate safety measure TTC was first introduced by Hayward *(39)*. For a leading vehicle $i+1$ and a following vehicle i, TTC can be calculated as:

$$TTC = \frac{d_i - d_{i+1} - L}{V_{i+1} - V_i} \qquad (12)$$

where d is the location of the vehicle, V is the speed, and L makes sure the distance between the vehicles is bumper to bumper. A python code is developed to calculate TTC values per time step using simulated trajectories. In this study, a “conflict” is defined as TTC becomes less than 1.5 seconds. Although the conflicts to actual crash ratio is pretty small, surrogate measures are still a good comparative indicator of safety. The assumption in this paper is that if the total number of conflicts is increased by a particular ratio between the two scenarios, then the increase in the number of crashes can be calculated by using the same proportion. For instance, assuming that 20,000 conflicts correspond to one actual crash as stated in the surrogate safety measures studies by Gateman *et. al (40, 41)*.

Simulation-based experimental results are shown in the following table. The first three OBU scenarios confirmed that traffic delay and vehicle operation costs increase with the increase of unfunctional OBU devices. These two costs increase dramatically if 30% of the OBU devices are experiencing downtime. However, the number of conflicts per vehicle are almost the same in different scenarios which results in a minor difference regarding crash risk cost on the network level. This is a reasonable assumption based on the current base scenario settings as the number of conflicts may increase on some of the road links while decreasing on the others as vehicles switches between different routes. Thus, the overall increases and decreases are assumed to cancel out at the network level. At the local level, for example, for reference link (FIGURE 4), crash risk cost increases by 26%, 42% and 47% compared with the base scenario, respectively. Minimum gap between cars and variation of the speed limit may be considered in the future to achieve network level savings in terms of crash risk costs. A trade-off exists between crash risk and traffic delay, so careful attention is needed when designing what types of messages will be sent to vehicles.

Regarding RSU failure scenarios, percentage changes in all three costs are noticeable, as vehicles do not receive queueing and link travel time information from RSUs. As these findings point out, failures of a RSU would have a significant impact on user costs. Consequently, agencies need to be well prepared in reducing repair times and providing adequate spare part inventory for various RSU equipment.

TABLE 3 Simulation (SUMO) based Experimental Results (Network-wide)

Percentage change compare with base scenario	O1-1	O1-2	O1-3	R1-1	R1-2
	OBU 10%	OBU 20%	OBU 30%	RSU 10%	RSU 20%
Traffic Delay Cost	17.3%	70.8%	430.6%	71.0%	279.6%
Vehicle Operation Cost	13.1%	69.3%	370.0%	82.3%	275.7%
Crash Risk Cost	-0.3%	-6.5%	-2.5%	7.6%	30.2%

CONCLUSION AND FUTURE WORK

In this paper, a conceptual LCCA framework is proposed for technology-oriented emerging Intelligent Transportation Systems based on connected and autonomous vehicles. The proposed framework highlights five fundamental differences in terms of inflation, uncertainty, out-of-pocket costs, technical obsolescence and inventory management between a conventional transportation infrastructure project and ITS regarding LCCA. These key differences are based on the observation that ITS equipment has different inflation behavior than typical infrastructure projects, higher uncertainty, more emphasis on out-of-pocket costs, higher risks in terms of technical obsolescence, and a need for very effective inventory management to reduce downtime costs due to equipment failures. A closer investigation of the inflation rate at the macro-level reveals that inflation rate of ITS components such as telecommunication devices does not follow the general upward trend of CPI, PPI and NHCCI. For example, the estimated unit cost of DSRC chip for future years by both researchers and industry experts is consistent with the macro-level observation of a downward trend.

Next, a practical method that employs outputs from microscopic traffic simulation combined with realistic cost models is introduced to quantify overall user costs for future ITS projects. This approach is shown to be feasible in a CAV environment that has the potential to be incorporated into the proposed ITS LCCA framework. In this approach, a surrogate safety measure is presented when calculating crash risk cost. The advantages of using simulation-based user cost approach include: 1) it is easier to collect network level statistics for future CAV scenarios for which field data is not yet available, and 2) impact of different equipment failure rate scenarios can be easily implemented at both component and system levels.

The research team expects that the proposed ITS LCCA framework will provide transportation agencies and researchers insights for better quantifying the costs associated with infrastructure based ITS, especially in emerging connected and autonomous vehicle environments. Future work will evaluate readily available models for each sub-system in the proposed framework with sample field data once becomes available, identify the needs for any modifications under CAV environment, apply Monte-Carlo simulation approach to achieve more realistic probabilistic results, and develop a systematic workflow and guidelines for ITS LCCA.

ACKNOWLEDGMENTS

The work in this paper is partially funded by RE-CAST, a Tier 1 University Transportation Center led by Missouri S&T. Additional funding was provided by C2SMART, a Tier 1 University Transportation Center at New York University. The contents of this paper only reflect views of the authors who are responsible for the facts. The presented findings in the paper do not represent any official views or policies of any sponsoring agencies.

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