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System Dynamics modeling of the impact of Internet-of-Things on intelligent urban transportation

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Abstract

Urban transportation systems are at the cusp of a major transformation that capitalizes on the proliferation of the Internet-of-Things (IoT), autonomous and cooperative vehicular and intelligent roadway technologies, advanced traffic management systems, and big data analytics. The benefits of these smart-transportation technologies were investigated using System Dynamics modeling, with particular emphasis towards vehicle sharing, intelligent highway systems, and smart-parking solutions. The modeling results demonstrate that these solutions offer the potential to deliver tremendous opportunities to improve the efficiencies in urban transportation systems. However it is also observed that by improving the overall utility of roadway transportation, it is likely that there will be an increase in roadway usage that potentially negates the benefits that planners are seeking. As a consequence, when smart-transportation technologies are adopted, they must be implemented in conjunction with solutions and incentive plans that encourage the desired commuter behaviors.

Introduction

Traffic engineering is as much an art as it is a science and requires strategies to optimize infrastructure utilization with policies that incentivize favorable behaviors, and capital investments that anticipate and address traffic bottlenecks. Traditionally traffic engineering has relied on the careful extrapolation of historical data, and has lacked real-time feedback from sensors and the support of remote semi-autonomous functions in the field. However this is set to change with the emergence of the Internet-of-Things (IoT) and advancements in autonomous and cooperative vehicles, intelligent roadway and traffic management systems, and big data analytics.

IoT essentially augments physical objects and environments with connectivity, and intelligent functionality including sensors, storage, microprocessors and software. This enables a variety of smart-transportation capabilities which are being used to address urban traffic challenges.

Notable examples include IoT sensor technologies and solutions for:

- Autonomous and cooperative vehicles and intelligent highway systems – which progressively automate vehicle operations towards an ultimate goal of delivering self-driving cars with cooperative functionality to optimize traffic flow and enhance safety.

- Intelligence to enable the accurate real-time tracking and reporting of vehicle locations for cooperative vehicle sharing solutions. The solutions that have already been implemented and are disrupting traditional taxi services and are expected to drive broader vehicle sharing scenarios in the future.
- Smart-parking solutions which today enable commuters to identify free parking spaces and in the future will have added functionality to optimize the allocation of parking spaces as vehicles arrive in urban centers.
- Traffic monitoring to enable real-time signaling optimization, such as the phasing of traffic signals. This contrasts traditional approaches where historical data is used to optimize signaling on a periodic basis – in many cases annually. During the interceding period the signaling remains static and largely suboptimum.
- Real-time updates to train and bus schedules that are reported to consumers' smart-phone devices so as to minimize wait-times.

As urban planners and policy makers refine regulations and prioritize future infrastructure investments, they must pay careful attention to the impact of smart-transportation solutions. However, this is challenging because these solutions are nascent and there is a lack of empirical data to quantify their impact. In this paper a model is developed so that the sensitivity of urban traffic to smart-transportation systems can be assessed.

A theoretical system dynamics model for urban traffic

System dynamics is a modeling methodology developed in the 1970's for characterizing the aggregate behavior and dynamics of complex systems [1]. System Dynamics is well suited to identify the behavior of particular systems and also provides a framework for theoretical analyses for researchers to investigate the sensitivity of systems to structural changes. Several authors have used System Dynamics to investigate various facets of transportation systems [2,3,6,7]. In this paper a System Dynamics model was developed in Vensim and used to investigate the theoretical implications of smart-transportation solutions on urban traffic flows, based on the causal system illustrated in Exhibit 1. In the model, the traffic demand consists of three modes of transport, namely private vehicles and public trains and buses. For the sake of simplicity it was assumed that each transport mode is independent, with relative adoption defined by a basic choice based logistic regression (Logit) model. The Logit model estimates the relative utility of each transport mode in terms of the cost of each trip and door-to-door transit time. In particular, the utility of each transportation mode U_m can be expressed as $U_m = \beta_m x_m + \epsilon_m$, where β_m and x_m are vectors that represent the relative importance and estimated values of the trip cost and door-to-door transit times, respectively and ϵ_m represents the error between the estimated and actual utility for the m^{th} transportation mode. The probability of the m^{th} transportation mode being adopted, $Pr(m)$ can be estimated by:

$$Pr(m) = \exp(\beta_m x_m) / (1 + \exp(\beta_m x_m)) \quad ..(1)$$

where $\sum_{m=1}^3 Pr(m) = 1$ since the model assumes there are three possible transportation modes.

The network capacity of the urban roadway system was estimated using A modified Bureau of Public Roads (BPR) model which predicts the network congestion ratio according to the following formula [2]:

$$\bar{s}(F_a) = \bar{s}_0 / (1 + \alpha (F_a / C_c)^\beta) \quad ..(2)$$

where:

$\bar{s}(F_a)$ is the average speed on the road network (miles/hour)

\bar{s}_0 is the average free flowing speed on the road network (miles/hour)

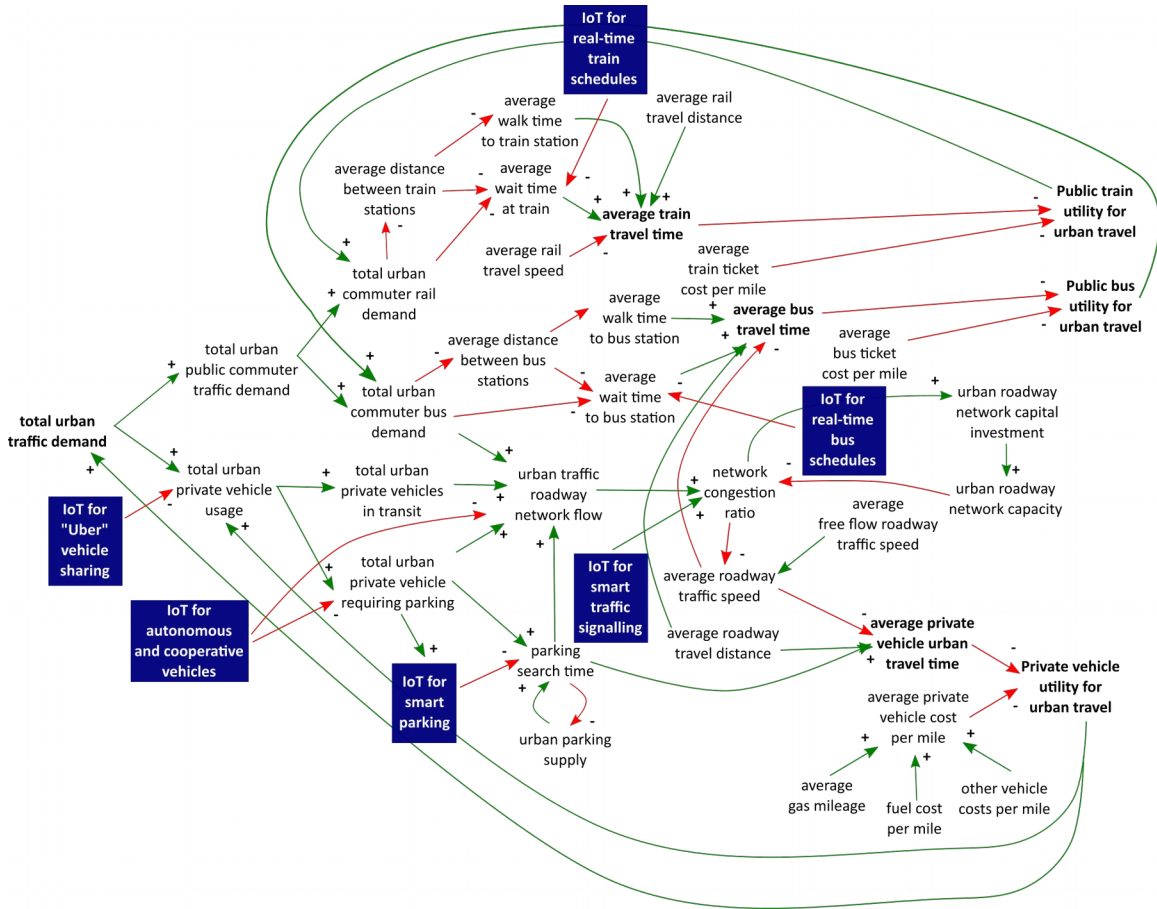
F_a is the average traffic flow (vehicles/day)

C_c represents that aggregate roadway network capacity, and

α and β are scaling parameters, where $\alpha = 0.2$ and $\beta = 10$ for the theoretical simulations presented in this report. These values can be calibrated for actual reported traffic and flow information when empirical data is used.

Exhibit 1: A causal schema for IoT smart-transportation solutions in urban environments

Source: Tolaga Research, 2015



The urban roadway traffic flow is impacted by the capacity of the roadway network and the search time required for private vehicles to locate free car parks in the urban centers. In the model, the average time taken to locate a free car park was estimated according to the following [3,5]:

$$\bar{st} = \alpha (\exp(D/S) / \exp(1)) \quad \dots(3)$$

where α is the search time when parking demand D equals supply S . For modeling purposes it is assumed that $\alpha = 3.3$ minutes prior to the introduction of IoT based smart-parking solutions [5].

IoT drives smart transportation

A variety of IoT based smart transportation solutions are being adopted to address urban congestion problems and improve the utility of the various modes of transportation. The

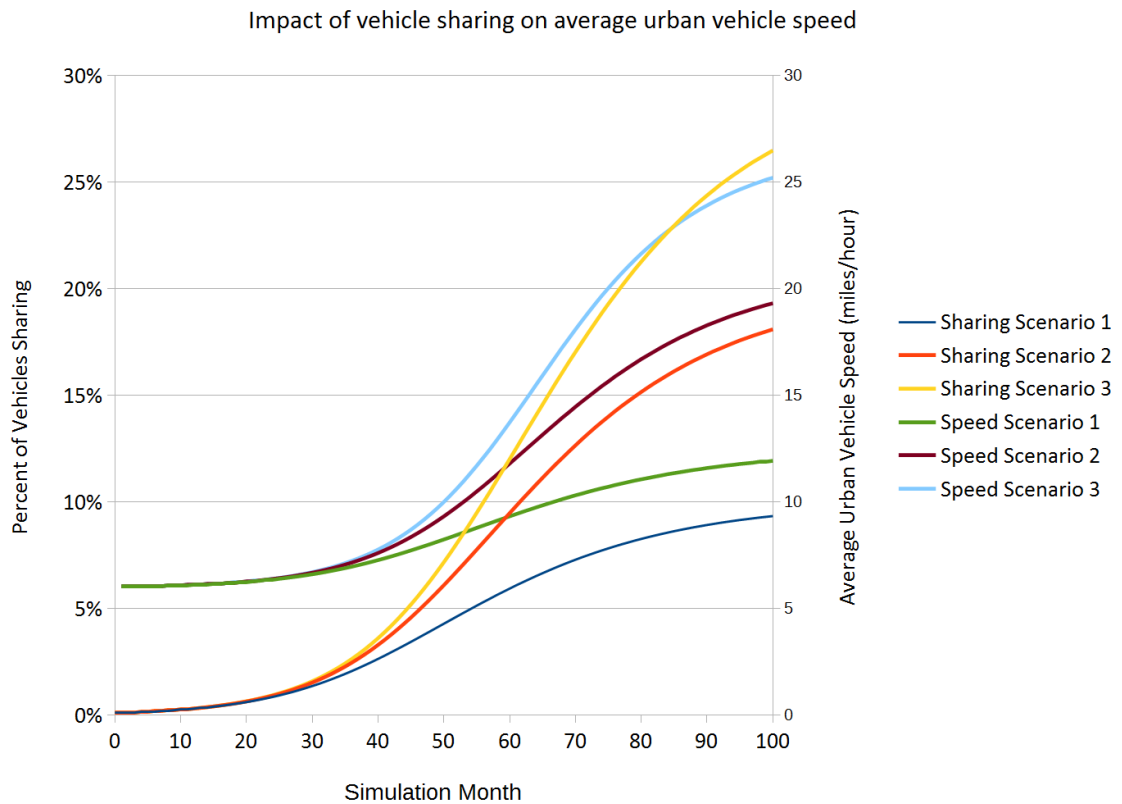
solutions that were assessed in this paper include, private vehicle sharing, autonomous and cooperative vehicles and smart-parking, and smart traffic signaling.

Private Vehicle Sharing

Although car pooling and vehicle sharing has been promoted for decades, it has seen minimal adoption, largely because of pre-planning needed and lack of versatility of the schemes that have been used. However since being established in 2009, Uber Technologies has been revolutionizing vehicle sharing by using intelligent scheduling, vehicle tracking and driver certification solutions that address the shortcomings of conventional solutions. As vehicle sharing is adopted, it effectively reduces the number of private vehicles needed to address specific traffic demands, and depending on whether roadways are congested, provides a means for improving urban traffic flow.

Exhibit 2: Impact of vehicle sharing on urban traffic speed

Source: Tolaga Research, 2015



The impact of vehicle sharing on urban traffic flow is assessed in Exhibit 2 for three scenarios with different rates of adoption. Without private vehicle sharing, the average urban vehicle speed for the theoretical model that was used predicted to be 5.9 miles/hour. For Scenarios 1, 2

and 3 private vehicle sharing reaches 9.3, 18.1 and 26.4 percent of the total private vehicles, over the simulation period, resulting in average urban speeds reaching 12.0, 19.4 and 25.3 miles/hour, respectively, without any roadway expansions.

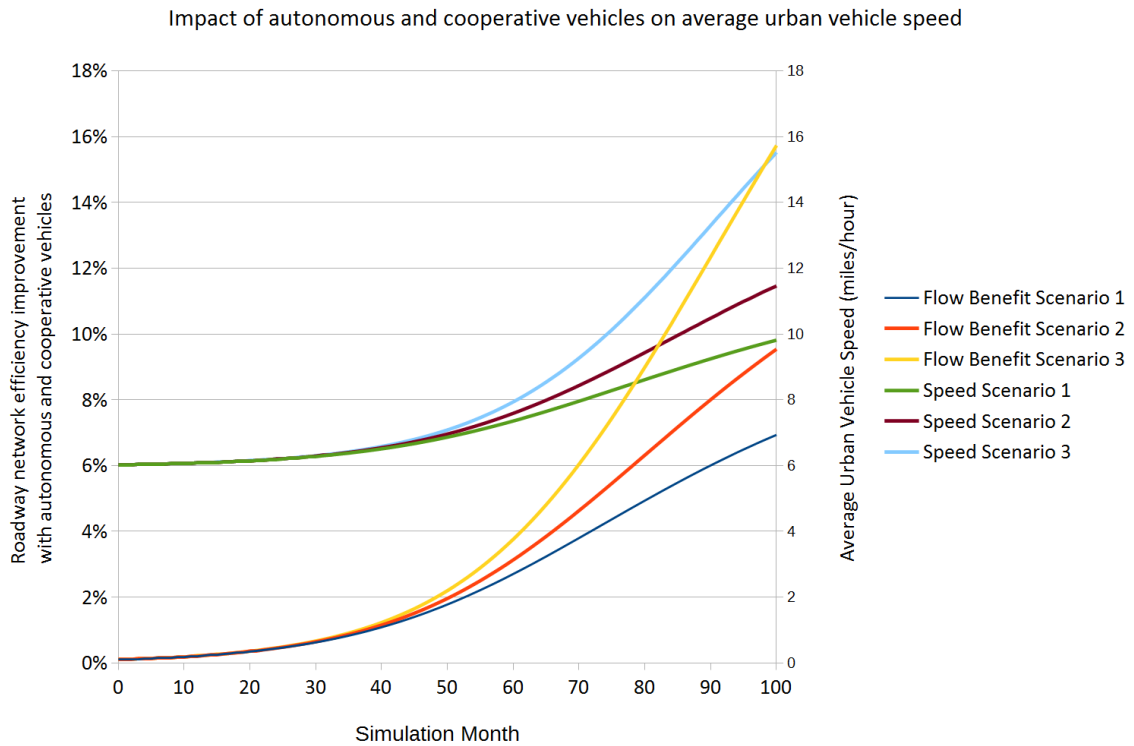
Autonomous and cooperative vehicles

For every mile driven by self-driving vehicles that are operated by companies like Google, the automotive industry is slowly moving towards a future with autonomous and cooperative vehicles. This is supported by a variety of industry initiatives that focus on advancements in vehicle intelligence and emerging standards such as VANET (vehicle adhoc networking). Vehicle manufacturers have been accelerating the development of autonomous vehicles, and commercial solutions are expected to become available over the next 24 months. Even as this occurs, it is likely to take many years for autonomous and cooperative vehicles to reach sufficient penetration to have a meaningful impact on urban traffic flows. However the long term benefit is likely to be tremendous by eliminating the limitations associated with human reaction times and coordinating traffic flows based on the combined knowledge of the destinations of all vehicles. From a modeling perspective, the autonomous and cooperative vehicle capabilities are assumed to have a positive impact on the efficiency of roadway traffic flows and when combined with vehicle sharing scenarios, the need for urban parking.

Exhibit 3 investigates the impact of traffic flow improvements that might be attributable to autonomous and cooperative vehicles (ACV). For Scenarios 1, 2, and 3 ACVs are assumed to impact network traffic flows by 7.0, 9.5 and 15.7 percent, over the simulation period, resulting in average urban speeds increasing from 5.9 to 9.8, 11.5 and 15.5 miles/hour, respectively without any roadway expansions.

Exhibit 3: Impact of autonomous and cooperative vehicles on urban traffic speed

Source: Tolaga Research, 2015



Smart-Parking

Smart-parking solutions have already been adopted in many urban centers across the globe. These solutions provide private vehicle commuters with real-time updates of available parks to reduce the parking times for vehicles with trips that terminate in urban centers. Obviously these solutions are particularly beneficial in situations where urban congestion is attributable to vehicles seeking parking spaces. This contrasts the scenarios investigated in Exhibits 2 and 3, where congestion was primarily attributable to the volume of traffic entering the urban center. The parking demand to supply ratio in the model was assumed to be 1.58, which in the model corresponded to an average of 5.57 minutes for private vehicle commuters to find parking. As smart-parking solutions become more advanced, the average time to find parks diminishes and with advancements in autonomous vehicles and vehicle sharing, the availability of car parks will also increase.

The unintended consequences of innovation

For the scenarios presented in Exhibits 2 and 3 above, it was assumed that the urban traffic volumes remained static over the forecast period. However in practice as innovations and infrastructure investments reduce congestion, traffic volumes tend to increase. This is reflected in the causal diagram in Exhibit 1, where improvements in the utilities of the various modes of

transport are assumed to increase demand. This results in increased traffic volume until it converges on the maximum tolerable congestion levels.

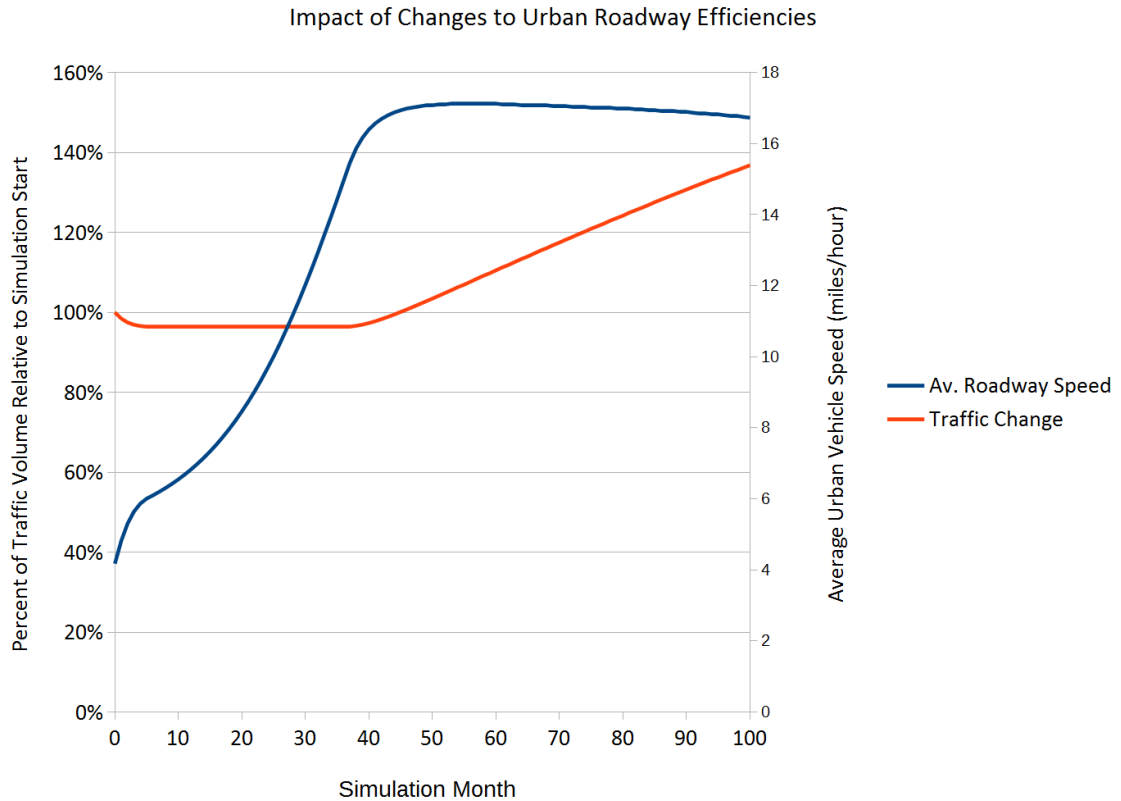
To illustrate these dynamics, a modeling scenario was simulated with the following characteristics:

1. A free-flowing roadway speed of 30 miles/hour was assumed. It was also assumed that traffic volumes increase for roadway speeds in excess of 15 miles/hour during congested periods.
2. If average roadway speeds were less than 6 miles/hour during congested periods, it was assumed that commuters would find alternative means of transport.
3. The roadway capacity increased by 0.5 percent per annum through infrastructure investment, and also benefited from the gains reflected for Scenario 3 in Exhibits 2 and 3.

Exhibit 4 shows the simulation results derived from a model with the assumptions listed above. Since the initial roadway speed is assumed to be less than 6 miles/hour, estimated traffic volumes decrease for the first six months of the simulation and stabilized while the average roadway speed increases towards the 15 mile/hour threshold. When this threshold is exceeded after 36 months in the simulation, the traffic volumes increased accordingly.

The simulation results in Exhibit 4 suggest that the benefits of innovative smart-transportation solutions might be mitigated by changes in commuter behaviors. Accordingly, it is crucial for urban planners and policy makers to anticipate the of these behaviors as they prioritize investments and incentive strategies.

Exhibit 4: Impact of roadway network changes on traffic volumes and congested roadway speed
Source: Tolaga Research, 2015



Conclusions

A theoretical model was developed using System Dynamics to investigate the impact of IoT based smart-traffic solutions on urban traffic flows. The results of the model simulations demonstrate that the various smart-traffic solutions that are being proposed can bring tremendous benefits to address urban congestion, and must be incorporated in the strategies adopted by urban planners and policy makers.

As innovative solutions are adopted, care must be taken to ensure that they do not result in unintended consequences that negate their anticipated benefits. Of particular concern are situations where improvements in the utility of roadway transportation systems cause an increase in private vehicle traffic. This creates challenges for urban planners, who must adopt strategies that leverage innovative technologies while encouraging the intended commuter behaviors. This will be investigated in future research, with the benefit of case studies that incorporate relevant empirical data.

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