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A System-of-Systems Model to Simulate the Complex Emergent Behavior of Vehicle Traffic on an Urban Transportation Infrastructure Network

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Abstract

Transportation agencies face escalating challenges in forecasting the traffic demand. Traditional prediction methods focused on individual transportation sectors and failed to study the inter-dependencies between the different transportation systems. Hence, there is a need for more advanced and holistic modeling techniques. To this end, this paper models and analyses an urban transportation system-of-systems incorporating seven various systems: population and GDP, CO2 emission, gasoline price and total vehicle trips, traffic demand, public and private transportation, transportation investment, and traffic congestion. Accordingly, this research simulates transportation networks as a collection of task-oriented systems that combine their resources to form a complex system with increased functionality. The goal of this paper is to understand the traffic complex behavior of urban transportation networks and to study the interdependencies between the different variables. The proposed framework could be implemented to any urban city, county, state, or country. The developed model incorporates a hybrid modeling approach that includes: logistic model, system dynamics, stochastic cellular automata, chaos theory, and Lotka-Volterra model. The final model is demonstrated using a case study. The contribution of this paper lies in modeling the transportation network as a dynamic system of systems rather than as static model as provided in previous studies.

Keywords: urban transportation network; system-of-systems; complex adaptive modeling; traffic simulation; system dynamics; infrastructure

1. Introduction

Transportation is one of the most important sectors that affect the economies of nations. Infrastructure assets are integrated networks of private and public works that establish the essential needs and services to maintain a modern society and to provide a competitive advantage within the global economy [1]. In fact, transportation systems are crucial for transporting individuals, conveying goods and services, establishing energy generation and distribution, and supplying water [2].

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The need for sustainable transportation systems is increasing as the population growth and scarcity of resources put pressure on the available transportation assets. Urban transportation agencies face escalating challenges in forecasting the traffic demand. Traditional prediction methods focused on individual transportation sectors and failed to study the inter-dependencies between the different transportation systems. Hence, there is a need for more advanced and holistic modeling techniques. To this end, this paper models and analyses an urban transportation system-of-systems incorporating seven various systems such as: population and economy, traffic congestion, CO2 emission, etc. Accordingly, this research simulates a transportation network as a collection of task-oriented systems that combine their resources to form a complex system with increased functionality.

Dynamic modeling is useful in understanding the behavior of complex systems over time [3]. System dynamics is a technique that uses interdependencies, feedback loops, and time delays to represent the behavior of a whole system. To formulate a system dynamics model, the system under investigation is represented as set of stocks and flows. Variables presented as stocks represent their accumulation quantities. This is the reason why system dynamics models are said to possess memory or history. For the flow variables, they are two types: inflows (rate of increase of a stock) and outflows (rate of decrease of a stock).

The developed model incorporates a hybrid modeling approach that includes: logistic model, system dynamics, stochastic cellular automata, chaos theory, and Lotka-Volterra model (or predator-prey model). The proposed framework in this paper will help governments, departments of transportation, and transportation agencies in the future planning and management of their urban transportation infrastructure networks. The developed model could be implemented to any urban city, county, state, or country.

2. Problem Formulation and Model Development

The goal of this paper is to understand the traffic complex behavior of urban transportation networks and study the interdependencies between different variables as related to the infrastructure planning. The urban transportation system in this paper is developed as a combination of seven different systems: (1) population and GDP, (2) Carbone dioxide (CO2) emission, (3) gasoline price and total vehicle trips, (4) traffic demand, (5) public and private transportation, (6) transportation investment, (7) traffic congestion. The details for each system is provided in the following sub-sections.

2.1. System 1: Population and GDP

According to Hutchinson [4], a model that describes the evolution of any population should have the following characteristics: (1) any living organism shall possess one parent of like kind; and, (2) due to the capacity of any finite environment, there shall be an upper limit to the number of organisms that can occupy this space.

As such, one of the commonly used models that satisfy these requirements is named the logistic model that was used for the first time by Pierre François Verhulst to model population growth [5]. The logistic equation is presented in Equation (1).

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) \tag{1}$$

Where N is the number of inhabitants of a given area at time *t*, *r* is a constant referred to as the intrinsic rate of increase, and K is the carrying capacity representing the population size that the resources of the environment can carry.

Since there is no definite way to calculate the intrinsic rate of increase, it is best determined in the calibration stage based on actual historical data. In addition, the carrying capacity *K* could be estimated using Equation (2).

$$\mathrm{K} = \text{Available Land Area} * \text{Maximum Population Density} \tag{2}$$

The number of people affects the total vehicles present in a year as well as the total annual trips. The total number of vehicles could be calculated as the product between the total population and the number of vehicles per capita. Moreover, the number of vehicles per capita is calculated using the Gompertz equation [6] shown in Equation (3).

$$\text{Vehicles per 1000 people} = \mathrm{a} * \mathrm{e}^{-\mathrm{b}\mathrm{e}^{-\mathrm{c}*\mathrm{g}\mathrm{t}}} \tag{3}$$

Where g_t is the GDP per capita in year *t* and *a, b,* and *c* are parameters calculated for each geographical location such as: US, Canada, Austria, China, etc.

The variables used in the population and GDP system and their interdependencies are presented in Figure 1.

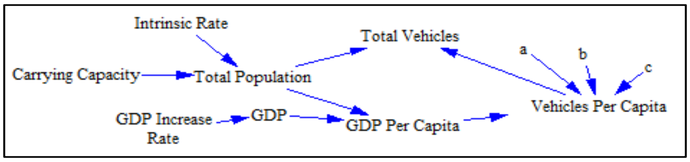

Fig. 1. Variables used in the population and GDP system

2.2. System 2: CO2 Emission

The transportation sector is the highest contributor to the greenhouse gas emissions in the U.S. among the different economic sectors [7]. The greenhouse gas emissions from vehicles are usually expressed in terms of metric tons of CO2 [8]. As far as the transportation network is concerned, the construction of new roads contributes to the emission of CO2 due to site cleaning, sub-grade preparation, production of construction material, site delivery, construction works, etc. [9]. The used variables in the CO2 emission system and their interdependencies are presented in Figure 2.

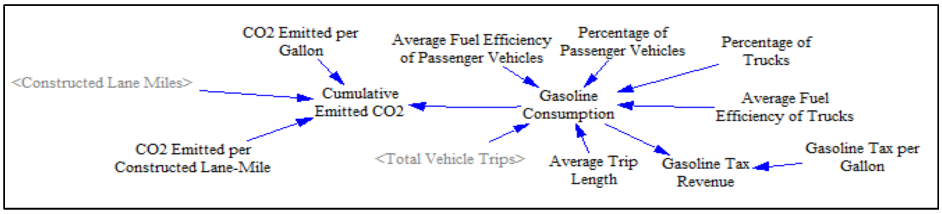

Fig. 2. Variables used in the CO2 emission system

It is worth noting that variables present between two angle brackets in Figure 2 mean that they belong to a different system than the one presented in the corresponding figure. The details for the total vehicle trips variable and the constructed lane-miles variable are presented in the following subsections.

2.3. System 3: Gasoline Price and Total Vehicle Trips

The gasoline price has been proved to possess a chaotic behavior due to its high and unexpected volatility [10]. As such, a chaotic model is proposed in this paper to model the price of gasoline. The used function to study the chaotic behavior of the gasoline price is shown in Equation (4) that was coded in Java language as a separate class in AnyLogic. It is worth noting that the gasoline price is modeled as a ratio in this paper by dividing the actual price by a base gasoline price of US $3. The used variables in the gasoline price and total vehicle trips system and their interdependencies are presented in Figure 3.

$$f\ (n, r, \propto, \beta) = \frac{r}{e^{\sqrt{|\alpha * n(1-n) * \beta|}}} \tag{4}$$

Where *n* is the gasoline price ratio at time *t*; the function *f* represents the gasoline price ratio at time *t+1*; and *r, α*, and *β* are parameters to be determined when calibrating the model using historical data on the gasoline price.

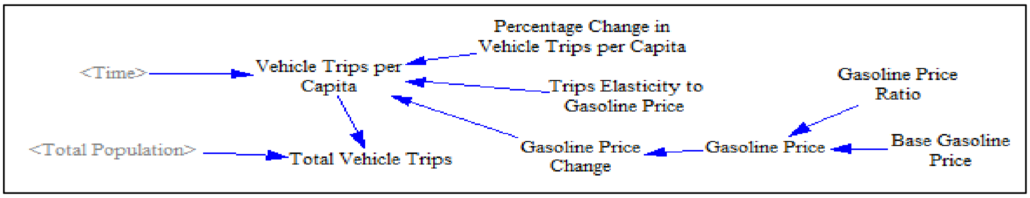

Fig. 3. Variables used in the gasoline price and total vehicle trips system

2.4. System 4: Traffic Demand

One of the most important metrics to measure the traffic demand is the average annual daily traffic (AADT). AADT is a measure that is used in the processes of transportation planning, transportation engineering, and retail location selection. The AADT is calculated as the total volume of vehicle traffic for a year divided by 365 days. The private transportation and public transportation could be computed based on the AADT. The used variables in the traffic demand system and their interdependencies are presented in Figure 4.

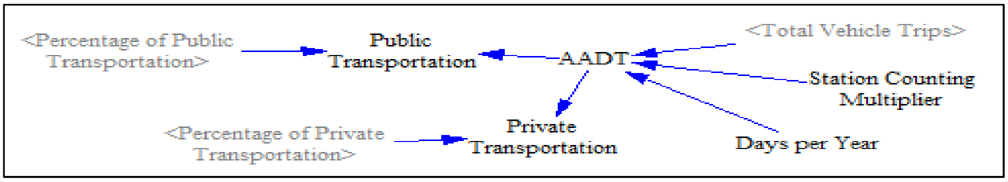

Fig. 4. Variables used in the traffic demand system

A station counting multiplier is introduced to account for the possibility of vehicles' double counting and other errors related to the counting stations. The percentages of the public and private transportation are obtained using the Lotka-Volterra (or predator-prey) model discussed in the next subsection.

2.5. System 5: Public and Private Transportation System

Public vehicles and private vehicles share the same transportation resources such as: highways, roads, freeways, expressways, etc. As such, public and private transportation compete on these shared resources due to the capacity limitation of transportation networks as shown in Figure 5. To this end, the interaction between private and public transportation could be represented by a predator-prey model with the lattice being the transportation network. In the developed model, private transportation is referred to as predator and public transportation as prey. The variables used in the public and private transportation system and their interdependencies are presented in Figure 6.

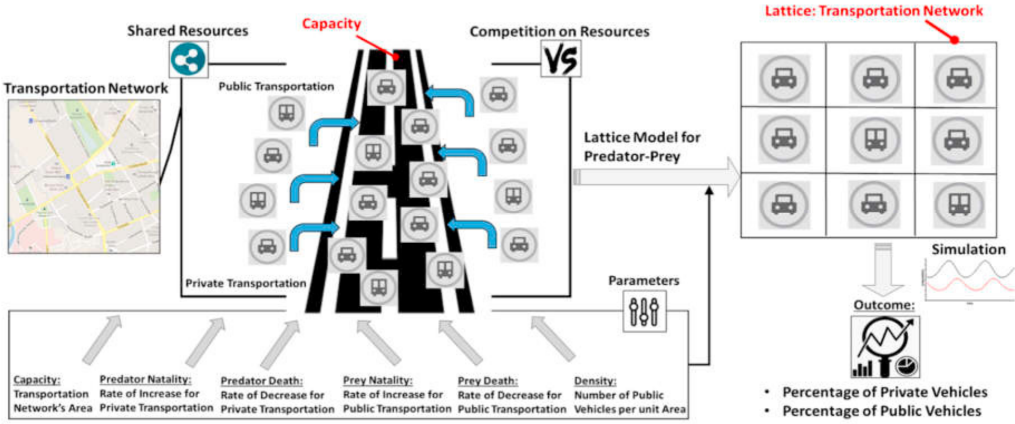

Fig. 5. Lotka-Volterra model for private and public transportation

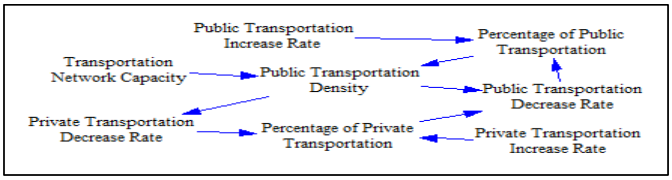

Fig. 6. Variables used in the public and private transportation system

2.6. System 6: Transportation Investment

The allocated funds for the transportation networks could be divided into two parts: construction of new lane-miles and maintenance of the existing lane-miles. The construction budget will affect the amount of lane-mile constructed per year. In addition, the transportation network utilization could be calculated as the ratio between the vehicle miles traveled per lane-mile and the capacity per lane-mile. The variables used in the transportation investment system and their interdependencies are presented in Figure 7.

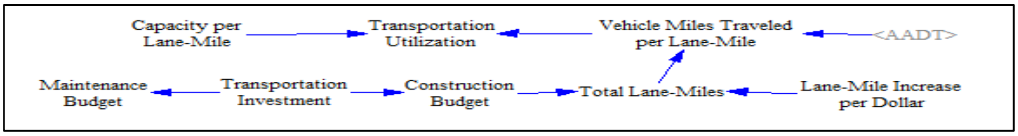

Fig. 7. Variables used in the transportation investment system

2.7. System 7: Traffic Congestion

Cellular automata could be used to simulate the traffic congestion level of a transportation network since vehicle traffic can be treated as a system of interacting particles. The so-called particle-hopping model describes car traffic in terms of stochastic cellular automata. An early model of this type was proposed by Nagel and Schreckenberg [11]. The used variables in the traffic congestion system and their interdependencies are presented in Figure 8.

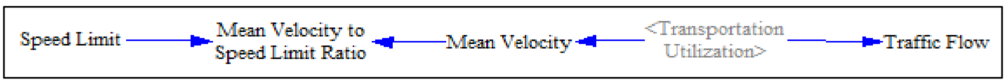

Fig. 8. Variables used in the traffic congestion system

In the developed probabilistic cellular automata, the transportation network is considered as a finite lattice of length L with periodic boundary conditions. Each cell is either empty or occupied by a car with velocity V, where V = 0, 1, . . . , Vmax. If d_i is the distance between cars i and $i+1$, car velocities are updated in parallel according to the rules present in Equations 5 and 6. If $x_i(t)$ is the position of car i at time t, then cars are moving according to the rule present in Equation 7. Equations 5, 6, and 7 mean that, at each time step, each car increases its speed by one unit (acceleration = 1) while respecting the speed limit and avoiding collisions. In addition, the model also includes some noise: with a probability p, each car decreases its speed by one unit. Although the equations are simple, the model is believed to exhibit features observed in real highway traffic [12].

$$V_i\left(t+\frac{1}{2}\right) = \min(V_i(t)+1, d_i(t)-1, V_{max}) \tag{5}$$

$$V_i(t+1) = \begin{cases} \max\left(V_i\left(t+\frac{1}{2}\right)-1, 0\right) & \text{with probability } p \\ V_i\left(t+\frac{1}{2}\right) & \text{with probability } 1-p \end{cases} \tag{6}$$

Where Vi(t) is the velocity of car i at time t.

$$x_i(t+1) = x_i(t) + V_i(t+1) \tag{7}$$

To calculate the traffic flow and the mean velocity on a transportation network, the traffic fundamental diagrams (density-flow and density-mean velocity) were generated as outputs from the simulated stochastic cellular automata. Python programing language was used to simulate the traffic congestion where the NumPy package and the Matplotlib library were used. After that, the generated graphs were fitted using MATLAB curve fitting toolbox where the chosen best fitted functions had the highest R-square.

2.8. Limitations

As any developed model, some limitations exist as related to the proposed framework. For instance, the model assumes that the capacity of the transportation network is unchanged. In addition, the model considers that a variation in the private transportation affects the public transportation and vice-versa; this might not always be the case. Further, the proposed model does not account for restrictions such as high-occupancy vehicle (HOV) lanes.

3. Results, Analysis, and Discussion: Model Application

The proposed model was applied for Hillsborough County located in the state of Florida. The obtained results for the years 2007 to 2017 are presented below. The actual gasoline price was obtained from the energy information administration [13]. The obtained parameters of the gasoline price function are: r = 1.2188, α = 0.7285, and β = 1.2258. Figure 9(a) shows the actual gasoline price and the gasoline price using chaos theory. The average error for the years 2007 till 2017 is 9.31% which is less than 10%, and thus it is considered to be acceptable given the randomness and the chaotic behavior of gasoline prices in general. To prove that the gasoline price possesses a chaotic behavior, the bifurcation diagram, shown in Figure 9(b), was plotted using Python. As it could be seen from Figure 9(b), for the obtained r = 1.2188, the bifurcation diagram shows great variability in the value of the gasoline price ratio. This indicates that the developed model exhibits a chaotic behavior for the gasoline price.

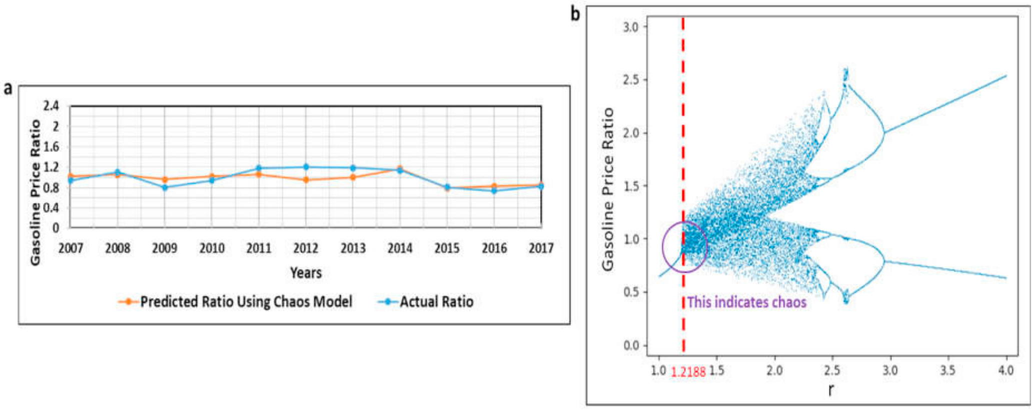

Fig. 9. (a) Chaos model for gasoline price; (b) Bifurcation diagram for gasoline price

The actual fractions of private transportation and public transportation compared to the fractions obtained from the Lotka-Volterra model for predator-prey are presented in Figure 10. It is worth noting that the summation of the fractions is not equal to 1 because trucks are counted neither as private transportation (which includes only passenger vehicles in this paper) nor public transportation. As it could be seen from Figure 10, the maximum difference for the private transportation is 0.68% and 0.0235% for the public transportation. This shows that the developed model fits well the actual historical data obtained from Florida's department of transportation for the Hillsborough County [14].

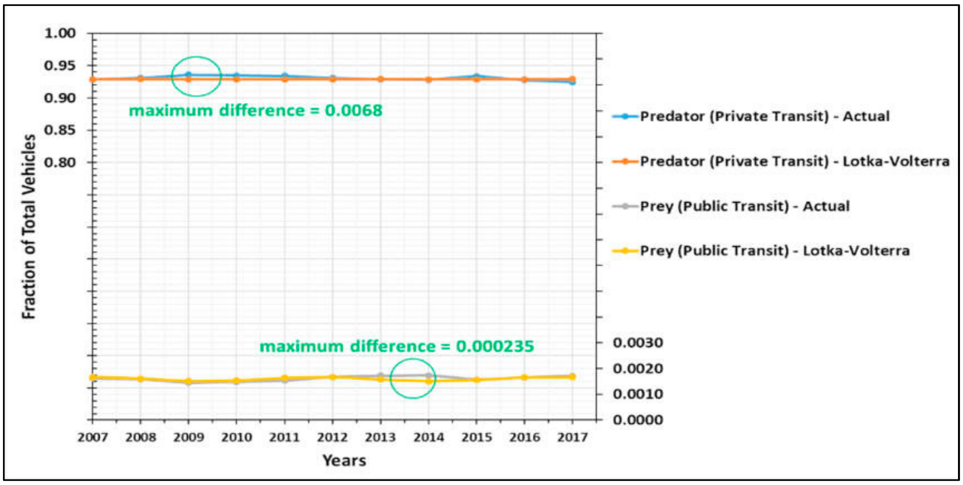

Fig. 10. Lotka-Volterra model for the fractions of private and public transportation

The obtained graphs for the traffic flow and the mean velocity from the stochastic cellular automata as well as the fitted curves are shown in Figure 11(a) and Figure 11(b), respectively. The best fitted functions for both the traffic flow and the mean velocity were the sum of eight sinusoidal functions. The obtained R-square values are very close to 1. The developed model will help decision makers in simulating the actual dynamics of an urban transportation system as a combination of systems for a better management of transportation networks.

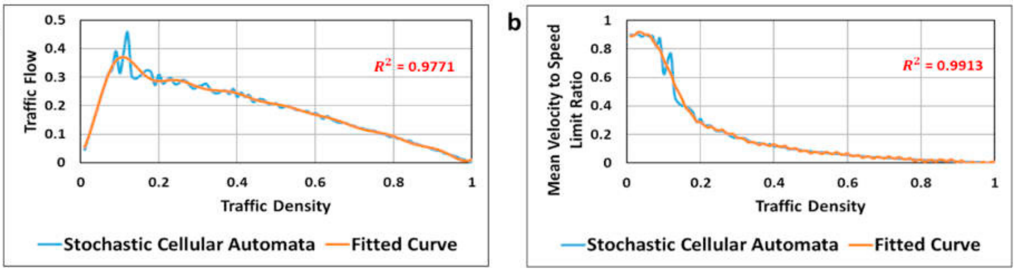

Fig. 11. (a) Traffic flow; (b) Mean velocity to speed limit ratio

4. Conclusion

This paper presented a model that reflects the inter-dependencies between seven transportation systems by incorporating a hybrid modeling approach that includes: system dynamics, stochastic cellular automata, chaos theory, and Lotka-Volterra model. The proposed framework could be implemented to any urban city, county, state, or country. The presented results showed the applicability and the usefulness of the developed model in simulating the actual dynamics of an urban transportation system as a combination of systems. Based on the presented results and analysis in this paper, the traffic demand could be predicted for a better management of transportation networks. The contribution of this paper lies in modeling the transportation network as a dynamic system of systems rather than as a static model as provided in previous studies.

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