Vehicle Modeling for Future Generation Transportation Simulation

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One-paragraph abstract:

Transportation systems in the 21st century are facing many critical issues including mobility and safety problems. Critical issues call for innovative technologies and solutions. Systems soon to be launched under the United States Department of Transportation (USDOT) Vehicle Infrastructure Integration (VII) Initiative are directed toward addressing these critical issues. To facilitate an understanding of the VII initiative and to assess future VII-enabled transportation systems, future generation transportation simulation tools will be required. In response to this need for simulation tools, this research proposes to develop a dynamic vehicle model as the first step toward achieving long-term VII goals. Such a model is practically unavailable but particularly needed in a VII setting because many VII-enabled vehicle and traffic control strategies work directly on vehicles and the dynamic response of these vehicles determines the effect and overall performance of the VII strategies. This project is proposed with Federal, State, and local transportation research interests in mind. In addition, this project addresses the UMass Transportation Center theme "*Improving Transportation Mobility and Safety with Innovative Technologies and Strategies*" and this research responds to a national priority by contributing to the VII initiative.

Statement of Project Objectives

The Objective of this project is to develop a dynamic vehicle model for future generation transportation simulation. The nature of such an application requires that the model be analytical, reasonably accurate, and computationally efficient.

Transportation systems in the 21st century are facing many critical issues, the foremost among which are traffic congestion/*mobility* and accidents/*safety*. As a matter of fact, traffic congestion accounts for about $63.1 billion annually in terms of wasted time and fuel. Meanwhile, more than 40,000 lives are lost every year in highway crashes and this number is more than the total casualties in Iraq since 2003. Critical issues call for *innovative technologies and solutions*. Systems soon to be launched under the United States Department of Transportation (USDOT) Vehicle Infrastructure Integration (VII) Initiative are directed toward addressing these critical issues. However, we have been limited to gain a better understanding of operational improvements brought about by VII, nor are we well-equipped to reasonably assess the benefits resulted from such improvements. This is because the prohibitive capital investments prevent us from deploying large scale VII field tests. On the other hand, our state-of-the-art transportation simulation tools are not powerful enough to model new operational scenarios under VII. Therefore, new generation transportation simulation tools are called for to help understand and assess future VII-enabled transportation systems. Developing such a simulation tool is a long-term goal and involves systematic efforts. The modeling of vehicle dynamics is the first step toward such a goal. Such a model is practically unavailable but particularly needed in a VII setting because many VII-enabled vehicle and traffic control strategies work directly on vehicles and the dynamic response of these vehicles determines the effect and overall performance of the VII strategies.

This project is proposed with Federal, State, and local transportation research interests in mind. In addition, this project addresses the UMass Transportation Center theme "Improving Transportation Mobility and Safety with Innovative Technologies and Strategies" and this research responds to a national priority by contributing to the VII initiative.

Research Contribution

This research contributes to the state of the art by developing a new mathematical model to describe vehicle dynamics in the context of transportation simulation. This research also contributes to the state of the practice by providing a tool which can be readily adopted by existing microscopic simulators to enhance their modeling capabilities.

The vehicle model proposed in this research is unique in that it is historically not sufficiently addressed in traditional transportation and automotive arenas. In transportation arena, the complexity resulted from simulating hundreds or even thousands of vehicles necessitates a simple kinetic vehicle model or none at all. In contrast, vehicle models developed in automotive engineering arena are far too cumbersome to apply to transportation simulation. To deal with challenges in modeling VII-enabled transportation systems, a vehicle model that is analytical, reasonably accurate, and computationally efficient is called for. The model should be analytical because models based on look-up table are memory-consuming and calibration-intensive. Accuracy and efficiency are competing goals, yet both of them are desirable.

Unfortunately, our state-of-the-art simulation tools are not well-prepared to meet the above requirements. In transportation engineering arena, simulation tools capable of modeling a transportation system are available with varying degrees of modeling details. Macroscopic tools such as LWR [1, 2], FREFLO [3, 4], KRONOS [5], FREQ [6, 7], CTM [8-11], and KWaves [12-15] are too coarse because they ignore individual vehicle behavior and treat traffic flow as a one-dimensional fluid. Mesoscopic tools such as TRANSIMS [16, 17] are able to trace the movement of individual vehicles, but they are modeled as particles hopping with discrete speeds in a uniform manner. Microscopic tools such as INTEGRATION [18, 19], CORSIM [20, 21], VISSIM [22], HUTSIM [23, 24], Paramics [25, 26], AIMSUN [27, 28], MITSIM [29, 30], ARTEMiS [31-33], and DRACULA [34-36] represent the state-of-the-art transportation simulators and provide more modeling details by incorporating drivers' car-following, gap-acceptance, and lane-changing behaviors. Though these tools have been successful in replicating traffic operations for transportation planning and traffic control purposes, they are not well-suited to address the above requirements. Across these simulators are their lack of modeling details in vehicle dynamics and their inability to incorporate advanced vehicle and transportation technologies into simulation. Sub-microscopic simulator PELOPS [37, 38] appears to match well the aforementioned requirements, but the simulator is proprietary and technical details about the simulator itself is unclear. In automotive engineering arena, detailed dynamic vehicle models and associated driver models were developed [39-65]. Also available are many powerful simulation tools such as HVHP [66], CarSim [67, 68], VDANL [69], LVDS [70], VDMS [71], ASM [72, 73], MEDYNA [74], ADAMS [75], and AUTOSIM [76]. These models and tools are well-suited for studying a single vehicle with great level of detail, e.g. vehicle design, handling, and stability. However, they would be too cumbersome to be applied in transportation simulation which involves many vehicles sharing the same traveling environment. In addition, these models and tools typically involve proprietary vehicle parameters (such as moment of inertia of the driveshaft and suspension roll stiffness) which are typically inaccessible to the public.

Technical Approach or Methodology

Figure 1 presents the concept of future generation transportation simulation. In this concept, the driver receives information from the environment such as roadways, traffic control devices, and the presence of other vehicles. The driver receives information from his/her own vehicle such as speed, acceleration, and yaw rate. These sources of information, together with driver properties and goals, are used to determine driving strategies (such as steering and gas/brake). The driving strategies are fed forward to the vehicle which also receives roadway information from the environment. These sources of information, together with vehicle properties, determine the vehicle's dynamic responses based on vehicle dynamic equations. Moving longitudinally and laterally, the vehicle constitute part of the environment. Other vehicle dynamic responses such as speed, acceleration, and yaw rate are fed back to the driver for determining driving strategies in the next step. Therefore, in this transportation environment, each driver-vehicle unit is an autonomous agent which is driven by goals and is able to achieve these goals by interacting and moving through the environment. Thus traffic operation is simply the movements and interactions of all vehicles in the environment.

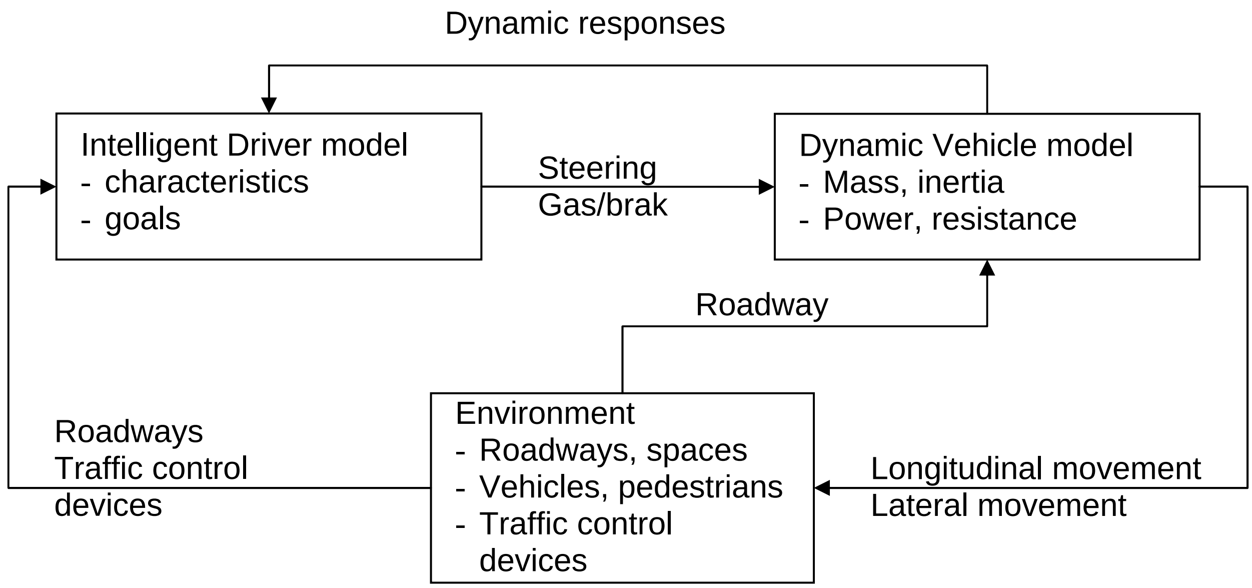

Figure 1 The concept of future generation transportation simulation

A vehicle is a deterministic component in a transportation system because, given an input, the vehicle response is predictable. The vehicle is also a dynamic component because its response changes as driver control varies. The vehicle has properties and behaves according to driver control. Vehicle properties include mass, power, dimensions, etc. The behavior of the vehicle can be described using a set of dynamic equations. These equations map driver control strategies/inputs to vehicle responses/outputs. Figure 2 sketched the structure of the vehicle model. To be consistent with human driving experience, the inputs to the vehicle include steering wheel angle, throttle opening, and braking force. The vehicle outputs include longitudinal acceleration/movement, lateral acceleration/movement, and other vehicle dynamic responses such as yaw velocity which affect driver decision making.

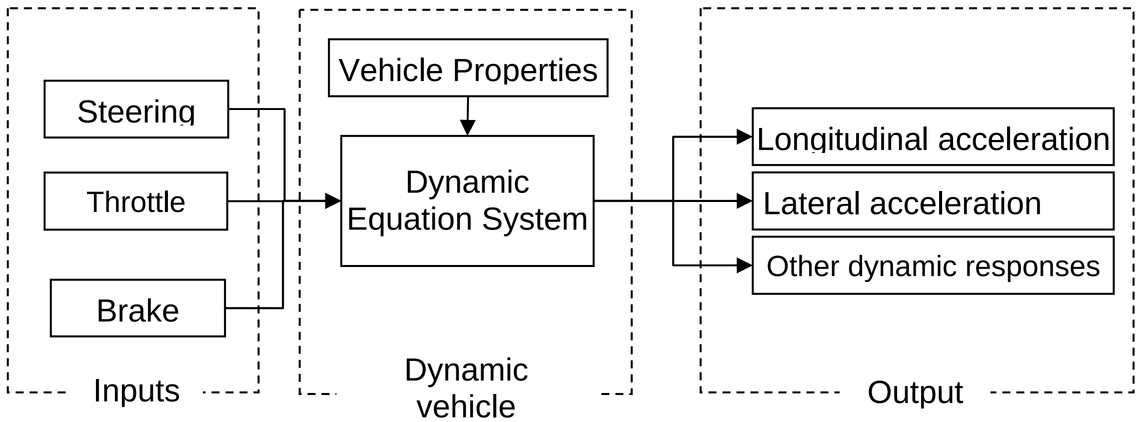

Figure 2 The dynamic vehicle model

A preliminary study [77] [78] has been conducted on the vehicle model. The objective of this study was to obtain some initial insights into the feasibility of the above modeling approach. The resulting Dynamic-Interactive-Vehicle (DIV) model was successful in achieving this objective and prepared a solid foundation, built on which the research proposed on this project will be conducted. This study also identified several future directions which will serve as the focus of this project. These future directions include:

- **Powertrain modeling**. Powertrain is a critical component in a vehicle which burns fuel and generates driving forces. Applying on the Bernoulli's principle, the preliminary study developed a simple engine model based on some simplifying assumptions. Later, we found that some of these assumptions may not hold under real world condition and the performance of this engine model does not conform to those of commercial engines. The engine model needs to be revisited and revised to be more realistic.
- **Lateral movement**. The DIV does a relatively good job of representing the lateral movement of a vehicle but at low speeds. When representing a vehicle's lateral motion, the DIV model does not account for slippage at the tire-road interface. This is because, under high speeds, lateral acceleration will be present and the vehicle will develop lateral force (which results in slippage) to counteract the lateral acceleration. At low speeds slippage is negligible and as result does not affect the motion of a vehicle. But at a high speeds, a large slippage can occur and as a result it greatly influences the motion of a vehicle. Therefore the next step for the DIV model is to account for slippage at the tire-road interface.
- **The braking system**. Currently, the DIV model treats the brake system of a vehicle according to the result from a Driver-Vehicle Braking Performance study conducted in 1970. Not only is this study due an update - given the advances in the brake technology used on today's vehicles, but also this

treatment of the braking system is not vehicle specific. The next step for DIV model in representing the brake system of a vehicle is to utilize simplified mathematical representations of how a driver places his/her foot on the brake pedal and produce a force on the wheels to retard the motion of a vehicle.

- **Validation procedure**. The current performance tests involved in the validation procedure only test performances with maximum driver input, i.e. maximum gas and brake pedal displacement and maximum steering angle. The next step would be to conduct performance test on both a real vehicle and the DIV model where maximum driver input is rare.

Based on the above discussion, tasks to accomplished the objectives of this project are outlined as follows:

Task 1: Review of literature

Although the preliminary study has synthesized historical literature to certain extent, a systematic review of existing work and cohesive assembly of these documents is far from completion. Technical reports, journal articles, and other written documents as well as internet based sources shall be reviewed and synthesized for the purposes of identifying major issues, challenges, practices, and lessons associated with vehicle modeling. The product of this task shall be the literature synthesis summarizing findings of the literature survey.

Task 2: Modeling vehicle powertrain

The powertrain of a vehicle determines the vehicle's acceleration performance. Key to powertrain modeling is the modeling of internal combustion engines. Though there has been a wealth literature in the area of modeling internal combustion engines, these engine models were developed with a special interest in assisting engine design, analysis, control, and diagnosis. While these models are generally accurate with varying degrees, they are unnecessarily complicated to suit for transportation applications. For example, a typical transportation application may involve hundreds or even thousands of vehicles. A conventional engine model would render such an application way beyond the capacity of a contemporary personal computer. In addition, these engine models require some information which is prohibitive for a transportation analyst. For example, some models involve proprietary engine parameters such as throttle body size and engine inertia which are inaccessible to non-automotive users; some model may also require variables, such as manifold pressure and temperature, which are difficult to measure from a transportation perspective. Therefore, special criteria apply to an ideal engine model suited for transportation applications. Most salient of these criteria are (1) Accuracy: The engine model must provide reasonable accuracy to predict engine performance with throttle and engine speed as inputs and engine power and torque as outputs. (2) Efficiency: The engine model must be simple enough to model large number of vehicles/engines in a transportation setting. (3) Accessibility: The engine model should not rely on proprietary parameters and variables that are difficult to measure. All the information needed to run the model (such as peak engine power, torque, and their associated engine speeds) should be publicly available (e.g. http://www.cars.com). (4) Formulation: The engine model should be analytical. Engine models based on look-up tables are not only prohibitive to prepare for thousands of vehicles but also resource-demanding in a computation environment. (5) Calibration: The engine model should involve the least calibration effort - no calibration is most desirable. Again, it would be a daunting task to calibrate thousands of vehicles in a single transportation application. With the above list of criteria, this research will develop a simple engine model that is suited for transportation applications. Built on the engine model, a powertrain model will be developed to describe a vehicle's acceleration performance.

Task 3: Modeling vehicle steering system

The steering system of a vehicle determines the vehicle's lateral and yawing movement. This is the mechanism for the vehicle to track course and change lanes. It is also the cause of vehicle overturn under some unfavorable situation. Vehicle steering has been studied extensively in automotive engineering because it is closely related to vehicle handling and stability. Unfortunately, the subject has been missing in transportation simulation. This partly gives rise to the inability of transportation simulators to realistically replicate real world traffic operation.

Under low speeds, the vehicle's steering performance is dictated by Ackerman Geometry (a geometry formed by vehicle base, steering angle, and vehicle turning center). A steering model is quite simple and has been address in the preliminary study.

Under high speeds, lateral acceleration will be present. To account for this, the vehicle will develop lateral force which causes tire slippage. Therefore, the equation for high-speed turning will be different than that under low speeds. Many high-speed vehicle steering models have been developed in the past. However, these models typically involve proprietary data such as tire cornering stiffness and such data is frequently given in the form of empirical curves or look-up tables. These issues pose challenge in applying these models in a transportation simulation. The major focus of this task is to develop a simple, closed-form steering model. Given the nature of transportation applications where modeling accuracy is important, other modeling criteria such as computation efficiency is equally indispensable. Therefore, there will be a trade-off among these criteria in the development of the steering model.

Meanwhile, efforts will also be attempted to unite the low-speed and high-speed steering models into an integrated one. A united model will greatly facilitate and simplify future implementation.

Task 4: Modeling vehicle braking system

Vehicle braking system, together with vehicle powertrain, determines the vehicle's longitudinal acceleration. As discussed above, the preliminary study modeled vehicle braking system based on the result from an early Driver-Vehicle Braking Performance study which needs to be updated. In addition to braking forces, it is also important to take into consideration other effects such as wind resistance, rolling resistance, driveline drag, and grade in a vehicle's braking performance. Considering that most contemporary vehicles are equipped with anti-lock braking systems. This anti-lock effect needs to be factored into the modeling of braking system.

Task 5: Integrating the above to formulate a vehicle model

Models of the above key components of a vehicle, i.e. the powertrain, steering system, and braking system, needs to be integrated into a single vehicle model. The vehicle model will be expressed as a system of dynamic equations, preferably in a standard form such as State-Space equations, to facilitate computation.

Task 6: Validating the vehicle model

As conducted in the preliminary study, the vehicle model will be validated utilizing vehicle testing data and results published by automobile manufacturers, U.S. Environmental Protection Agency (EPA), and National Highway Traffic Safety Administration (NHTSA). Emphasis will be laid on ensuring that the vehicle model meets the requirements set forth above. If additional resources become available, vehicle road tests will be conducted to further validate the vehicle model.

Task 7: Implementing the vehicle model

Depending on available time and resources, the vehicle model will be implemented as a stand-alone module ready for adoption by existing simulators or integration into future generation simulation tools.

Project Timeline

The timeline of the project is indicated in the following Gantt chart:

Task \ Month	1	2	3	4	5	6	7	8	9	10	11	12
1	■	■										
2		■	■	■								
3				■	■							
4					■	■						
5						■	■					
6							■	■	■	■	■	
7												■

Task 1: Review of literature
Task 2: Modeling vehicle powertrain
Task 3: Modeling vehicle steering system
Task 4: Modeling vehicle braking system
Task 5: Integrating the above to formulate a vehicle model
Task 6: Validating the vehicle model
Task 7: Implementing the vehicle model

Anticipated Results

At the end of this project, a new vehicle model will be developed which is able replicate real world vehicle behavior with reasonable fidelity. The model will be in an analytical form and computationally efficient. The vehicle model developed in this research will be readily adoptable by existing transportation simulators to improve their performance or be used as the basis to develop future generation of transportation simulators.

Deliverables of this project include (1) mathematical formulation of the dynamic vehicle model which takes as inputs desired level of acceleration, deceleration, and steering and outputs the vehicle's longitudinal acceleration, lateral acceleration, and yaw velocity; (2) a report which documents in detail the model development and calibration and validation results; (3) associated software code which implements the dynamic vehicle model if time and budget allows; (4) journal and conference publications which are derived from this research.

Technology Transfer

Research results of this project will be of interests to transportation professionals, policy makers, and automotive manufacturers. A written report will be provided which documents the research and its findings in details. In addition, to the maximum extend possible, efforts will be made to disseminate the research results in forms of technical presentations, papers in conference proceedings, and articles in archival journals.

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CURRENT APPOINTMENTS

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RESEARCH INTERESTS

Traffic Flow Theory and Simulation
Intelligent Transportation Systems (ITS)
Traffic Sensing and Information Technology
Transportation Logistics and Optimization

EDUCATION

Ph.D. (2004) Georgia Institute of Technology (Transportation / Operations Res.)
M.Sc. (2003) Georgia Institute of Technology (Industrial Engineering)
M.Sc. (2001) Georgia Institute of Technology (Transportation)
M.Sc. (1994) Beijing Agricultural Engineering University (Mechanical Engineering)
B.Sc. (1991) Jilin University of Technology (Mechanical Engineering)

SELECTED PUBLICATIONS AND PRESENTATIONS

1. Daiheng Ni. Determining Traffic Flow Characteristics by Definition for Application in ITS. Accepted by IEEE Transactions on Intelligent Transportation Systems. 2006.
2. Daiheng Ni. Challenges and Strategies of Transportation Modeling and Simulation under Extreme Conditions. International Journal of Emergency Management (IJEM), Vol 3, No 4, pp. 198-312, 2006.
3. Daiheng Ni, John D. Leonard, and Billy M. Williams. The Network Kinematic Waves Model: A Simplified Approach to Network Traffic. Journal of Intelligent Transportation Systems: Technology, Planning, and Operations. Volume 10, Issue 1, pp. 1-14, 2006
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