Traffic and Transportation Simulation

Looking Back and Looking Ahead:
Celebrating 50 Years of Traffic Flow Theory,
A Workshop

January 12, 2014
Washington, D.C.

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Preface

In 1963, the TRB Committee on Traffic Flow Theory (TO-9) and the Committee on Characteristics of Traffic Flow (TO-12) were formed, with D. L. Gerlough and H. L. Michael as chairs, respectively. In 1971, the two committees merged to form the Committee on Traffic Flow Theory and Characteristics (AHB45). In recognition and celebration of these 50 years of traffic flow theory, several special events were organized in 2014, including a Sunday workshop held on January 12, 2014, at the Marriott Wardman Park Hotel in Washington, D.C.

With the accomplishments of the past 50 years in mind, the workshop focused on traffic and transportation simulation—looking back and looking ahead. Coincidentally, this theme was also consistent with the Transportation Research Board 93rd Annual Meeting theme, *Celebrating Our Legacy, Anticipating Our Future*. That year's theme was adopted because it was the year of the final TRB Annual Meeting at the Connecticut Avenue hotels, where it was held for nearly 60 years.

It was an appropriate time to recognize past accomplishments in the simulation field, reflect on the present state of the research community, and identify key future directions.

The committee invited top experts in the field to provide discussion papers on the history, current status, and future of traffic simulation. The audience was asked to provide input and frame a forward-looking discussion of future trends and research needs. We are very pleased to publish eight of these papers in this e-circular as part of our legacy.

The views expressed in the technical papers are those of the individual authors and do not necessarily represent the views of TRB or the National Research Council. The papers have not been subjected to the formal TRB peer review process.

—Constantinos Antoniou, *National Technical University of Athens, Greece*
George List, *North Carolina State University*
Robert Lawrence Bertini, *Portland State University*

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FEMKE VAN WAGENINGEN-KESSELS
SERGE P. HOOGENDOORN
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HANS VAN LINT
Delft University of Technology

Eighty years ago, Bruce Greenshields presented the first traffic flow model at the Annual Meeting of the Highway Research Board. Since then, many models and simulation tools have been developed. We show a model tree with four families of traffic flow models, all descending from Greenshields' model. The tree shows the historical development of traffic flow modeling and the relations between models. Based on the tree we discuss the main trends and future developments in traffic flow modeling and simulation.

INTRODUCTION

Traffic flow models have been applied for almost a century to describe, simulate, and predict traffic. The first model showed a relation between the distance between vehicles and their speed (*1*). Later, dynamics were included in the models and models were applied for predictions (*2*, *3*). Now, traffic flow simulation tools are used for long-term planning as well as for short-term predictions based on actual traffic data. In the future, the models and simulation tools may be developed further to (better) support, for example, adaptive cruise control, dynamic traffic management, and evacuation planning.

In this contribution, we give an overview of past developments in traffic flow modeling and simulation in the form of a model tree showing the genealogy of traffic flow models (Figure 1). It shows how four families of traffic flow models have developed from one common ancestor: the fundamental diagram by Greenshields (*1*). Each of the families, namely the fundamental diagram, microscopic models, mesoscopic models, and macroscopic models, will be discussed in separate sections below. Finally, using the model tree, we identify the main trends and give an outlook for future developments.

FUNDAMENTAL DIAGRAM

The fundamental diagram, as it was originally introduced at the 13th Annual Meeting of the Highway Research Board in 1934, relates the distance between two vehicles (spacing) to their speed (*1*) (Figure 2). However, the author, Bruce Greenshields, became famous for the fundamental he introduced 1 year later at the 14th Annual Meeting (*4*). This fundamental diagram relates the number of vehicles on one unit length of road (density) to their speed (Figure 3).
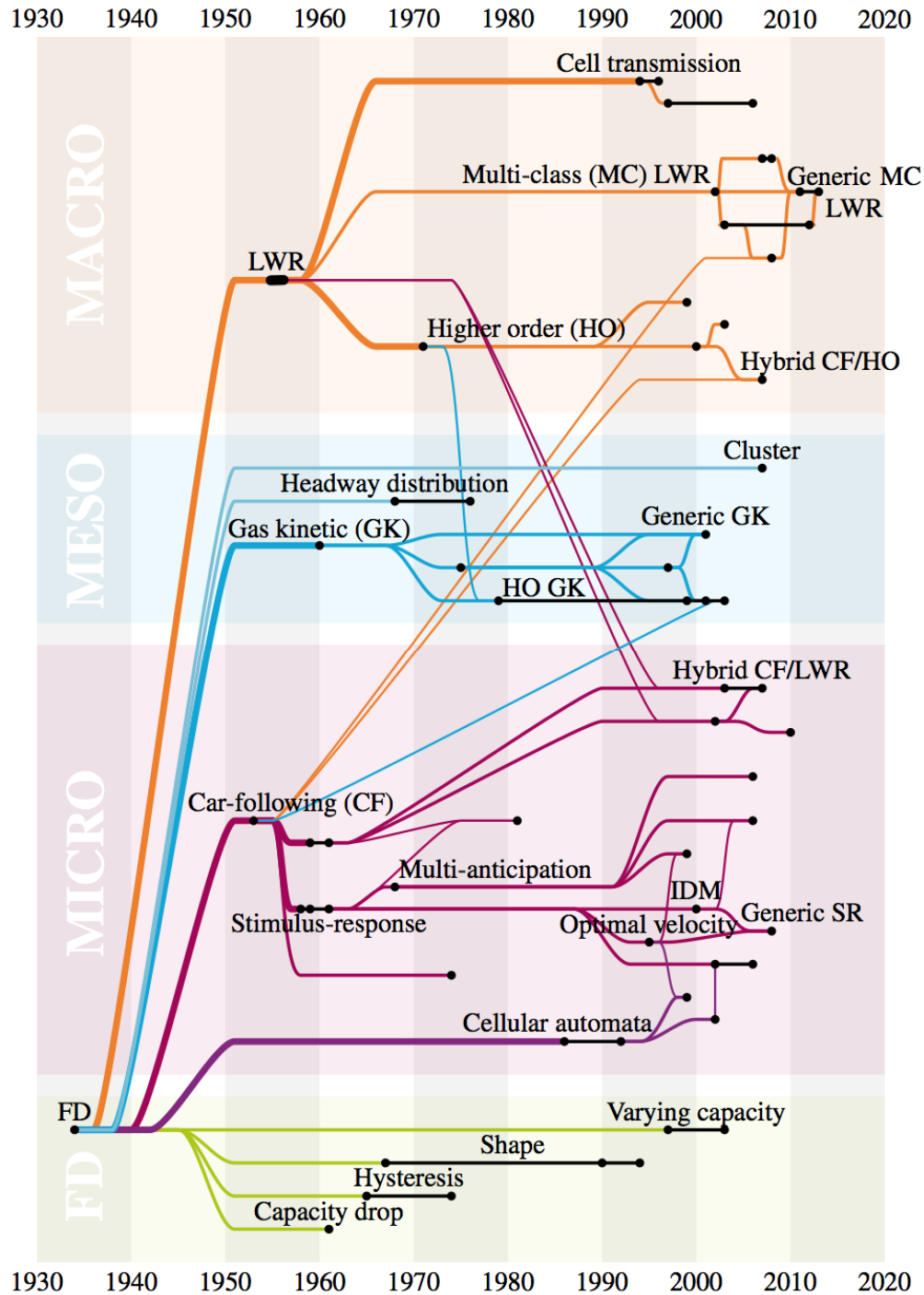
FIGURE 1 Genealogy of traffic flow models. Black dots indicate models, black lines between dots indicate that the same (or a very similar) model has been proposed multiple times, and colored lines indicate descent. A full (and much larger) version of the genealogy can be found in van Wageningen-Kessels (*63, 75*).
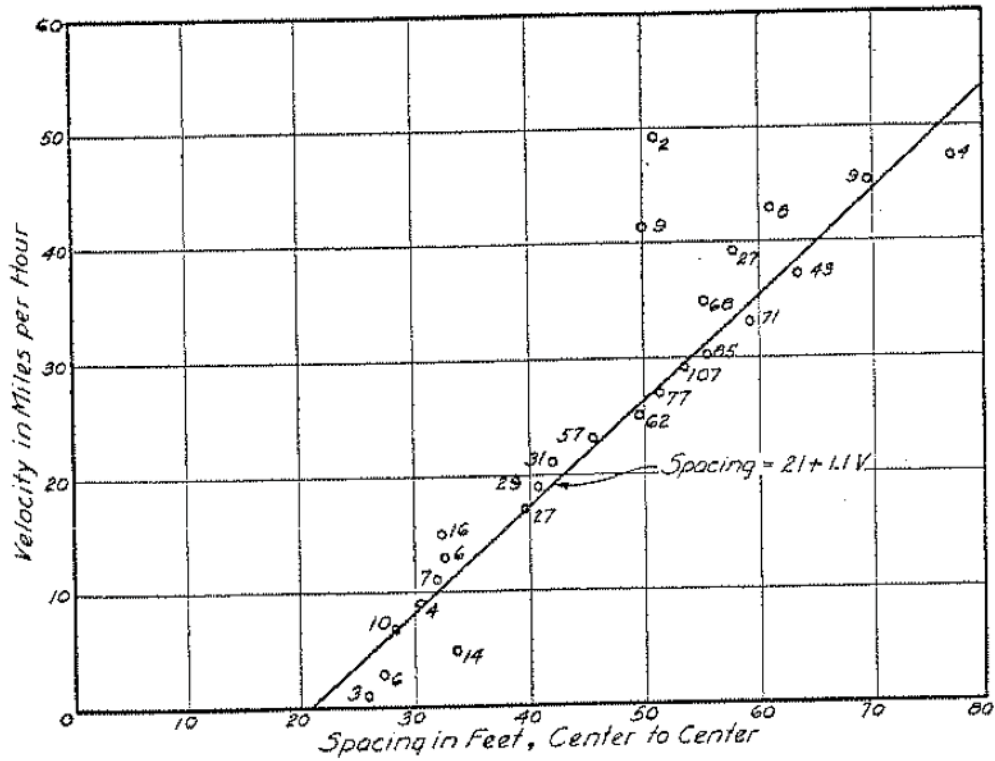
**FIGURE 2 Greenshields' original fundamental diagram (1934), showing a
linear relation between spacing and speed (*1*).**
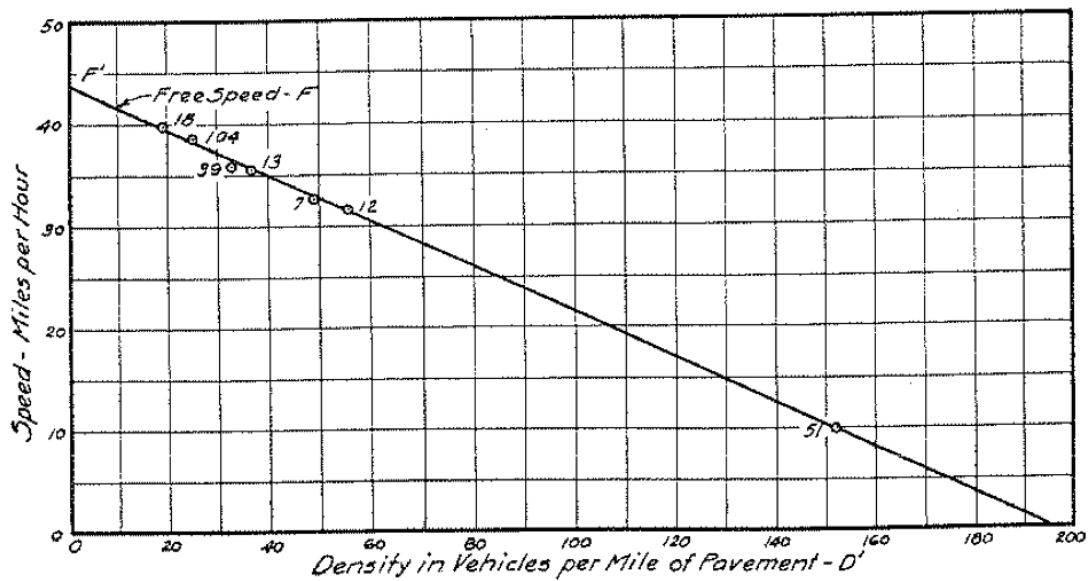
**FIGURE 3 Greenshields' fundamental diagram (1935), showing a
linear relation between density and speed (*4*).**

Shape of the Fundamental Diagram

Since its first introduction the shape of the fundamental diagram has been much debated. Table 1 shows some of the proposed shapes (*4–7*). It also shows an alternative representation of the fundamental diagram, relating the density to the flow: the number of vehicles per time unit. Del Castillo (*8*) recently introduced a set of requirements for the fundamental diagram. Of the fundamental diagrams in Table 2, the ones by Greenshields, Smulders and Daganzo, satisfy the criteria. However, it is argued that they do not represent scatter in observed density–flow (or density–speed) plots well enough.

Scatter in the Fundamental Diagram

Scatter in observed density–flow plots (Figure 4) is partly introduced by the measurement method and the aggregation of data. The remaining scatter is explained and modeled in different ways. In 1961, Edie (*9*) proposed a fundamental diagram with a capacity drop. The capacity drop models that the outflow out of a congested area is lower than the flow just before breakdown.

**TABLE 1 Different shapes of fundamental diagrams,
in density–flow and in density–speed plane.**
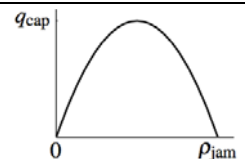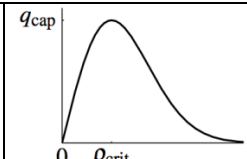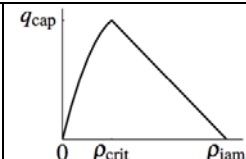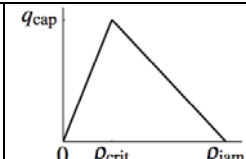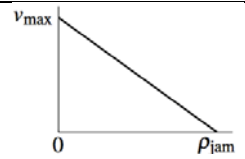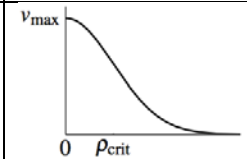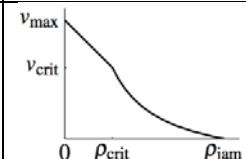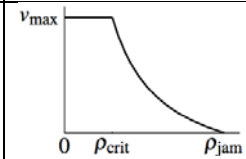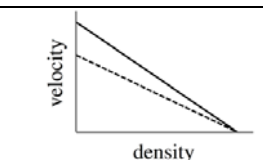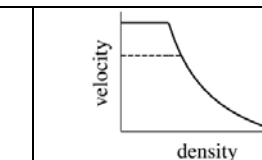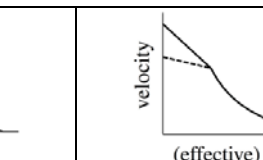
Density–flow				
Density–speed				
Shape	Parabolic	Bell	Parabolic–linear	Bilinear
Author	Greenshields	Drake	Smulders	Daganzo
Year	1934	1967	1990	1994
Reference	*4*	*5*	*6*	*7*

TABLE 2 Fundamental Diagrams of Multiclass Kinematic Wave Models

(Effective) Density–Speed			
Reference multiclass	Benzoni-Gavage and Colombo (*56*)	Logghe and Immers (*59*)	Chanut and Buisson (*13*); Van Wageningen-Kessels et al. (*61*)
Author mixed class	Greenshields (*4*)	Daganzo (*7*)	Smulders (*6*)

NOTE: Solid line = cars; broken line = trucks.
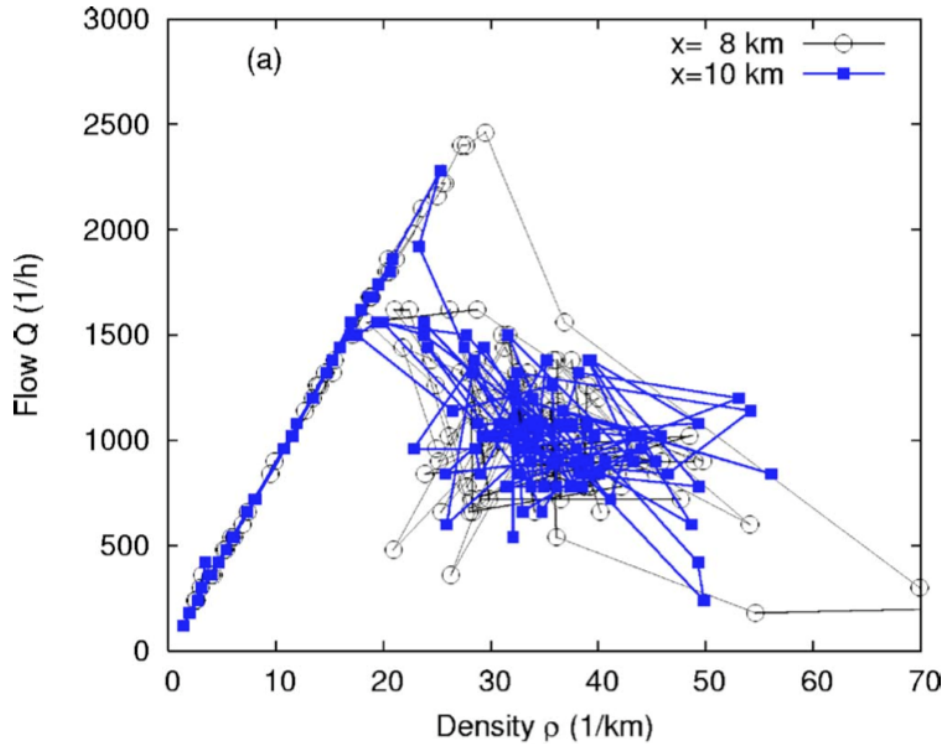
FIGURE 4 Scatter in an observed density–flow plot (*76*).

Using the graphs in Figure 5, Edie showed that a fundamental diagram with capacity drop better represents scattered data. A few years later, in 1965, Newell (*10*) introduced the concept of hysteresis: in congestion, when accelerating the density–speed relation is different from the relation when decelerating. Almost a decade later, Treiterer and Myers (*11*) showed that hysteresis could explain much of the observed scatter (Figure 6). In 1997, Kerner and Rehborn (*12*) take a different approach by proposing another nonunique relation between density and flow. They argue that in congestion, traffic may be in any state in the gray area in Figure 7. Finally, in 2003, Chanut and Buisson (*13*) propose a three-dimensional fundamental diagram. In this fundamental diagram the density of cars is taken into account separately from the density of trucks. Therefore, with the same total number of vehicles, a larger share of trucks leads to lower speeds (Figure 8).

MICROSCOPIC TRAFFIC FLOW MODELS

The three other families in the model tree include dynamics. They describe how traffic states evolve over time. The microscopic model family is the oldest of those families. Microscopic models describe and trace the behavior of individual vehicles and have evolved into car-following models, including three branches and one separate branch including cellular-automata models.

FIG. 4

$q = 17.2\,k\,\ln(228/k)$

k (cars/mile)

(a)

FIG. 6

Congested Flow
$q = 14.5\,k\,\ln(250/k)$

Non-Congested Flow
$q = 90\,u\,\ln(46/u)$

k (cars/mile)
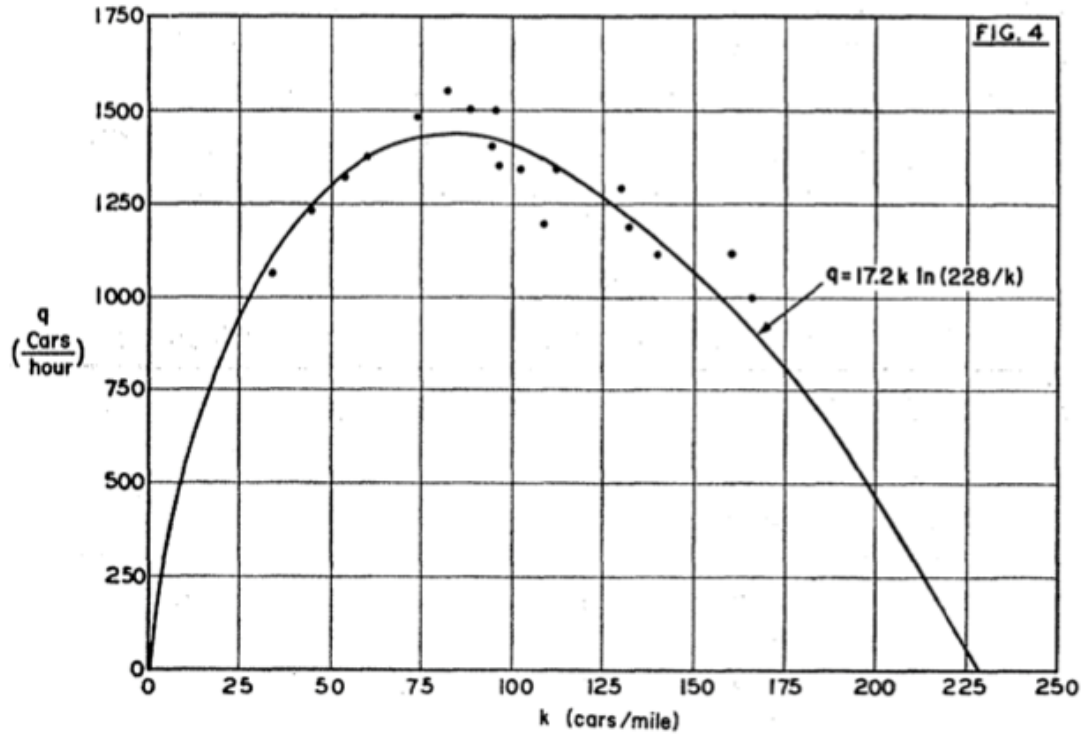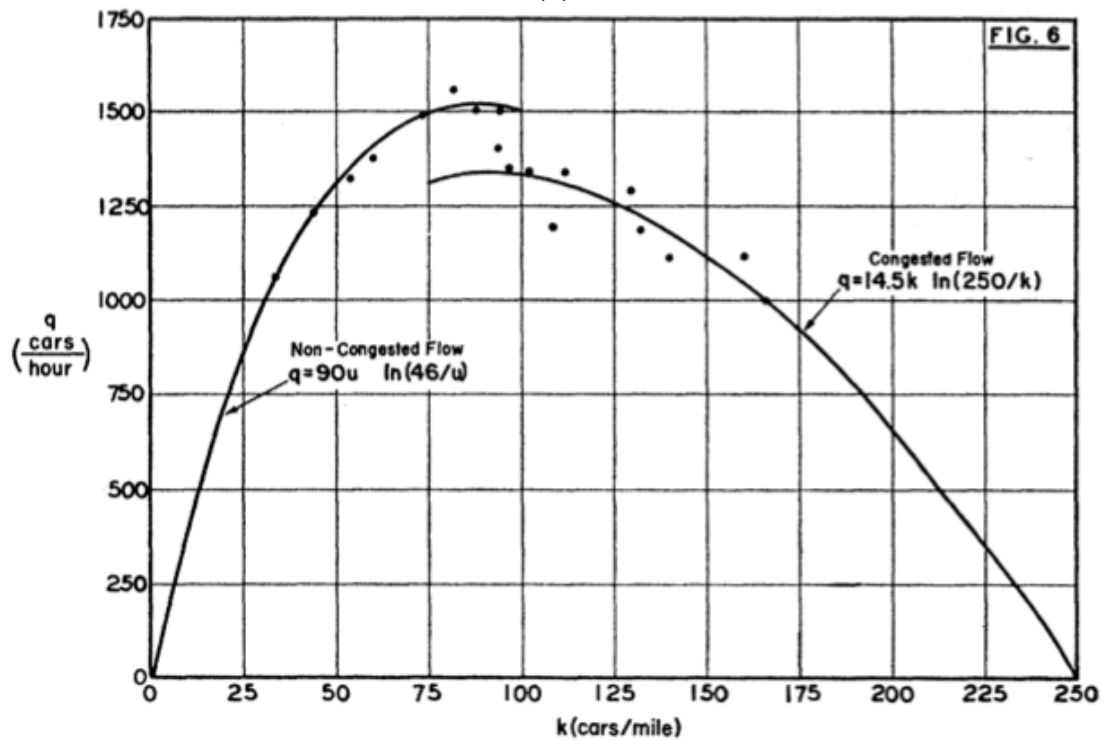
(b)

FIGURE 5 Fundamental diagram (*a*) without and (*b*) with capacity drop. The graph shows a better fit with the data of the fundamental diagram with capacity drop (*9*).
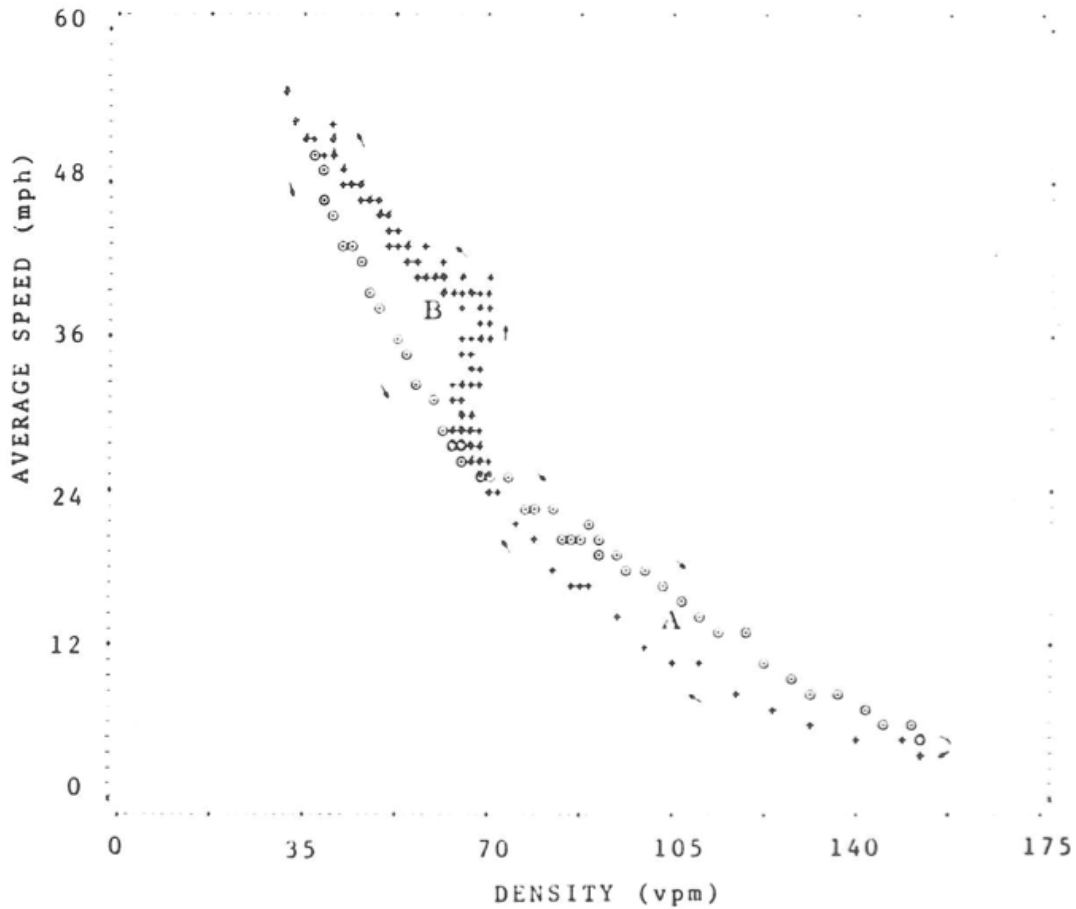
FIGURE 6 Observed densities and speeds showing the hysteresis phenomenon. At relatively low densities, speeds are higher when accelerating (diamonds) than when decelerating (circles), at relatively high densities, it is the other way around (*11*).
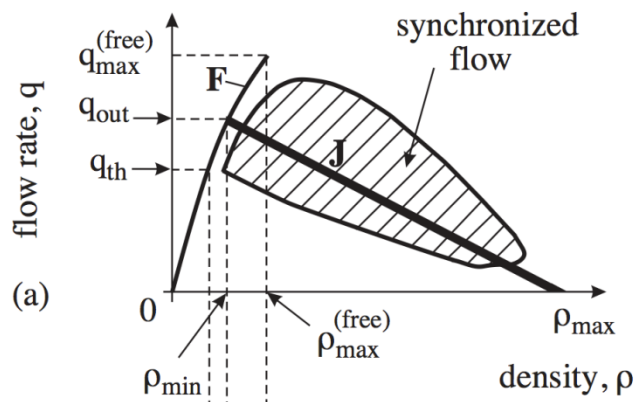
FIGURE 7 Fundamental diagram with infinitely many admissible states in the congestion branch (shaded area) (*77*). For detailed explanation of the labels, see Kerner (*77*).
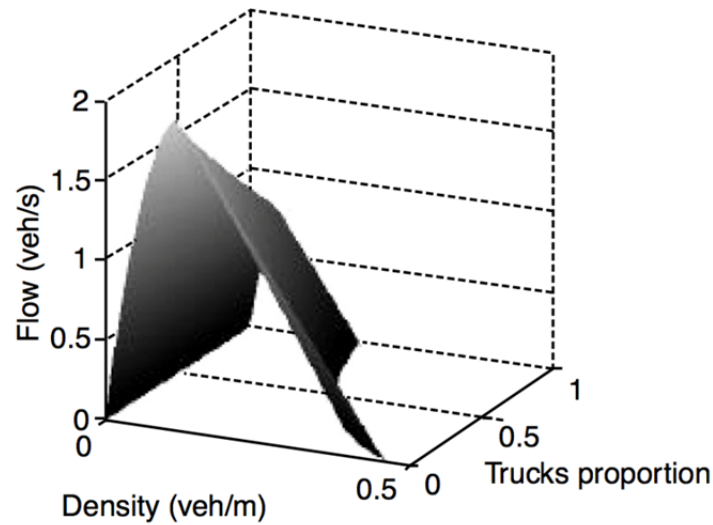
**FIGURE 8 Three-dimensional fundamental diagram where a high
trucks proportion leads to lower speeds and flows (*13*).**

Safe-Distance Models

The earliest car-following model was a safe-distance model and was introduced by Pipes in 1953
(*2*). In his model, vehicles adjust their speed according to a safe distance to their leader, as
illustrated in Figure 9. Safe-distance car-following models were refined by Gipps in 1981 by
introducing two regimes (*14*). In one regime the speed is limited by the vehicle or the (legal)
speed limit and in the other regime the speed is reduced because the drivers keeps a safe distance
to the leading vehicle.

A revival of safe-distance models took place in the last decade, starting by Newell with a
simplification of his 1961 car-following model (*15, 16*). This simplified car-following model has
been shown to be equivalent to certain models in the cellular-automata branch and in the
kinematic wave branch (*17, 18*). The equivalence is used to develop hybrid models combining
properties of microscopic and macroscopic models (*19, 20*).

Stimulus–Response Models

The second branch of car-following models consists of stimulus–response models. The model
tree shows a rapid development of these models in around 1960 (*21–24*). The authors propose
that acceleration of drivers can be modeled as a reaction to three stimuli:

1. Own current speed,
2. Distance to leader, and
3. Relative speed with respect to leader.

A lot of effort has been put into calibrating and validating stimulus–response models.
However, in 1999 Brackstone and McDonald (*25*) concluded that the models were used less
frequently because of contradictory findings on parameter values. Nevertheless, new stimulus–
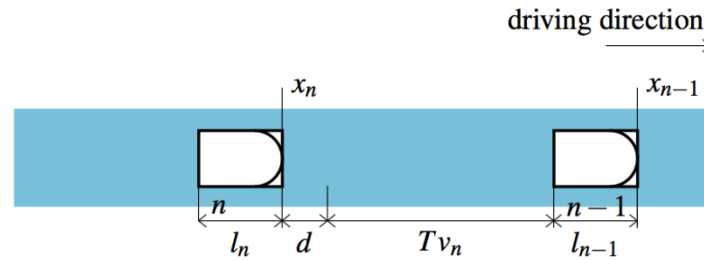
FIGURE 9 Variables and parameters in Pipes' safe-distance model. The position x_n of the nth vehicle is determined the position x_{n-1} of its leader and the safe distance between them. The safe distance is a constant distance determined by the distance at standstill d, the vehicle length l_{n-1} and a variable safe stopping distance Tv_n with T being safe time headway and v_n the speed.

response models have been developed since, including the optimal velocity model (*26*) and the intelligent driver model (*27*). Again, it is argued that it is often difficult, if at all possible, to find good parameter values (*28*). Wilson and Ward argue that researchers should focus on a small subset of stimulus–response models with good qualitative properties. Wilson also proposes a framework to assess the models with respect to qualitative properties (*29*).

Action Point Models

Action point models form the third, and last, branch of car-following models. They were first introduced by Wiedemann in 1974 (*30*). For these models, it is assumed that drivers only react if the change is large enough for them to be perceived. In contrast to other car-following models, this implies that driving behavior is only influenced by other vehicles if headways are small and if changes in relative velocity or headways are large enough to be perceived.

Cellular-Automata Models

Cellular-automata models are usually categorized in the microscopic model family, as a branch separate from the car-following models. In cellular-automata models, the movement of individual vehicles is described and traced, just like in other microscopic models. In contrast to car-following models, space and sometimes time is discretized as well. The first model in this branch stems from 1986 (*31*) but the model introduced in 1992 by Nagel and Schreckenberg (*32*) is regarded as the prototype cellular-automata model. The road is discretized into cells and in each time step each vehicle is advanced zero, one, or more cells, according to a certain algorithm. Some of the most popular cellular-automata models are compared in Knospe et al. (*33*).

MESOSCOPIC MODELS

Mesoscopic models fill the gap between microscopic models that model and trace the behavior of individual vehicles and macroscopic models that describe traffic as a continuum flow. Mesoscopic models describe vehicle movements in aggregate terms such as probability distributions. However, behavioral rules are defined for individual vehicles. The family of

mesoscopic models includes headway distribution models (*34, 35*) and cluster models (*36*). However, the oldest and most extended and popular branch within this family consists of gas–kinetic traffic flow models.

Gas–kinetic traffic flow models were first introduced in the early 1960s (*37, 38*). It describes traffic flow in a way similar to how gas is modeled in gas–kinetic models. The movements of vehicles (or molecules in a gas) are not modeled individually. Instead, distributions of density and speeds are used to calculate and lead to expected densities and speeds. A first revival of the branch took place in the mid- and late 1970s with an improved model (*39*) and a continuum gas–kinetic model (*40*). A second revival of gas–kinetic traffic flow models took place from the mid-1990s. The older models were extended and generalized (*41, 42*) and more continuum models were derived (*43–46*).

MACROSCOPIC MODELS

The fourth and last family in the model tree consists of macroscopic models. They describe traffic as if it were a continuum flow. Only aggregated variables such as (average) density, (average) flow, and (average) speed are considered. The family consists of two major branches: kinematic wave models and higher-order models. In order to include differences between types of vehicles (e.g., passenger cars and trucks), multiclass versions of both types of macroscopic models are developed as well.

Kinematic Wave Models

The prototype macroscopic model is a kinematic wave model introduced in the mid-1950s by Lighthill (*3*) and, independently, Richards (*47*). This model, also known as the LWR model, has received much attention and critique. The main critique is that vehicles are assumed to attain new speeds immediately after a change in the density. This implies infinite acceleration or deceleration. The issue has mainly been dealt with in higher-order macroscopic models (see next section), but also by relatively recent variants of the LWR model including bounded acceleration (*48, 49*). In the original LWR model, the transition from free-flow to congestion regime (breakdown) always happens at the same density and without capacity drop. This is considered as a second major drawback. It was addressed by introducing lane changes (*50, 51*) and by introducing breakdown probabilities (*52*).

LWR models are often used for simulations studies as they are relatively simple and computations can be done fast. Therefore, space and time are discretized into spatial cells of typically 200 m long and time steps of 0.5 s to several seconds. Densities in each cell are computed using the old densities and the flow into and out of the cell each time step. This approach is used in the cell transmission model introduced by Daganzo in 1994 (*7*) and the Godunov scheme (*53*). More advanced and accurate simulation methods have been introduced in the past few years (*18, 54*).

Furthermore, since 2001, many multiclass kinematic wave models have been proposed (*13, 55–62*). They address the issue of breakdown taking place at various densities place by introducing multiple vehicle classes. This model approach also allows for different speeds and other distinctive features for each class. As discussed in the section on fundamental diagrams, multiclass models can reproduce scattered fundamental diagrams. Multiclass models often

include different fundamental diagrams for different classes (Table 2). Furthermore, the speed does not depend on the total number of vehicles per time unit (density) but most models apply an "effective density" to which some classes contribute more than other classes. For example, trucks are supposed to have a higher impact on traffic flow than passenger cars. Therefore, relatively few trucks can create a breakdown, while many passenger cars are needed to do the same. Multiclass kinematic wave models were generalized in the Fastlane model (*61*, *63*), which can also be used to assess multiclass kinematic wave models (*63*, *64*).

Higher-Order Models

Higher-order models form the other main branch in the family of macroscopic traffic flow models. They were first introduced by Payne in 1971 (*65*). Higher order models include an equation to account for the acceleration and deceleration towards the equilibrium speed prescribed by the fundamental relation. This way, they address the issue of infinite acceleration–deceleration in the LWR model. However, also this type of models received much critique. In 1995, Daganzo initiated an ongoing discussion on whether or not higher order models are flawed because they are not anisotropic and on whether traffic flow models ought to be anisotropic (*66*, *67*). The most important implication of a traffic flow model that is not anisotropic is that, in the model and the simulation, vehicles do not only react on their leader but also on their follower which results in vehicles driving backward in certain situations. Since the start of this discussion, many anisotropic models have been developed (*68–70*), including a multiclass higher-order model (*71*).

Other recent models in the higher-order branch include the generalized higher-order model by Lebacque et al. (*72*) and a hybrid model that couples a higher-order model with a microscopic version of it (*73*, *74*).

DISCUSSION AND OUTLOOK

The model tree is used to identify recent trends and provide outlooks for the future.

Trends

We identify four main trends in the model tree.

1. Certain branches converge to a generalized model. Del Castillo develops a framework that includes most fundamental diagrams (*8*); many car-following models are generalized in Wilson's model (*29*); Hoogendoorn and Bovy generalize gas–kinetic models (*42*); a generalized multiclass kinematic wave model is proposed by Van Wageningen-Kessels et al. (*61*, *63*); and a generalized higher-order model is proposed by Lebacque et al. (*72*).
2. The LWR model is extended and adapted to better reproduce observations. Zhang proposes a model that includes hysteresis (*68*); Lebacque includes bounded acceleration and deceleration (*48*); and multi-class models are introduced by Wong and Wong (*55*) and many other authors thereafter.
3. Multiclass versions of different types of models are introduced. Hoogendoorn introduces a multiclass gas–kinetic model (*44*); a multiclass higher order model is introduced by

Bagnerini and Rascle (*71*); and, again, multiclass kinematic wave models are introduced by Wong and Wong (*55*) and many other authors thereafter.

4. Hybrid models are introduced to combine the advantages of both microscopic and macroscopic models. Bourrel and Lesort (*19*) and Leclercq (*20*) apply the LWR model for hybridization and a higher-order model is combined with a car-following model by Moutari and Rascle (*74*).

Outlook

From the model tree, we see that the cellular-automata and the mesoscopic model families do not receive much research attention recently. Cellular-automata models are used in simulations, but less often than microscopic and macroscopic models. Mesoscopic models are often hard to discretize and are therefore seldom applied in simulation tools. Therefore, we expect that future traffic flow modeling and simulation will focus on new and improved car-following and macroscopic models. Especially for the macroscopic models and simulation tools, good fundamental diagrams will be needed as well.

Furthermore, we expect the other trends discussed above to set in. The development of generalized models as described in the first trend is valuable to assess models and to select qualitatively appropriate models. Future developments include even more generalized models and assessment of existing and new models. This way, it can be prevented that qualitatively inferior models, which inevitably lead to quantitatively poor results, are applied in simulations. Furthermore, it is prevented that resources are spend in quantitatively calibrating models that will give qualitatively undesirable results.

Microscopic models and simulation tools predict traffic in more detail than macroscopic models. Therefore, they are well-suited for adaptive cruise control and similar applications where it is necessary to predict the behavior of individual vehicles. However, in many applications the details are less important and fast computations achieved with macroscopic models are necessary. This includes dynamic traffic management for large areas and evacuation optimization. For these applications more realistic macroscopic models as described in the second and third trend are valuable. Finally, some applications require on the one hand detail and accuracy in a small area and on the other hand fast computations to make predictions over a longer time horizon. These applications benefit from the fourth trend in which hybrid models are developed. Detailed predictions can be made, for example for a small urban area, and the less detailed prediction for the larger surrounding area allow for fast computations.

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Brief History of Traffic Simulation

Edward B. Lieberman
KLD Associates, Inc.

This paper presents a brief history of the development of traffic simulation from the 1950s to the present time, largely from an autobiographical perspective. Since I participated in some of the early developments and had personal exposure to those pioneers who preceded me, I am hopeful that this perspective can provide insights that a chronological literature survey, alone, could not provide. General-purpose digital computers became available in 1952. A small number of researchers at universities which had access to these early computers became interested in simulation technology and developed software applied to individual intersections and short freeway sections. Other researchers recognized the need to represent traffic flow in analytical terms and developed formulations which could be utilized by simulation modelers. In the 1960s and 1970s, as computers became more plentiful and of greater power, FHWA, NCHRP, and other national research agencies, supported the development of useful network simulation models. As a result, the technology's value in the field of traffic operations and control became apparent to an increasing number of practitioners. In the 1980s, simulation models that integrated traffic operations with traffic assignment were introduced; these attracted transportation planners who were seeking more effective, equilibrium-based tools. The continuing development of personal computer (PC) technology has fostered the development of regional simulation-based multimode models which are now routinely applied by practitioners worldwide. The pressing need to manage transportation systems to be increasingly productive and efficient in an environment of increasing demand will require simulation-based tools well into the future.

INTRODUCTION

Traffic simulation-based models describing all modes of transportation are now applied routinely by practitioners and researchers to analyze facilities ranging from individual intersections to extensive regional networks of some 50,000 links. The ability of simulation models to reliably detail the dynamic traffic environment and to be integrated with a range of other analytical models used by traffic engineers, transportation planners, and system designers, provides professionals with powerful tools. The widespread use of such models is reflected in the hundreds of papers presented at 93rd Annual Meeting of the Transportation Research Board in 2012 that discussed simulation models.

The emergence of traffic simulation parallels the emergence development of digital computers; the first developments in both technologies occurred some 60 years ago in the United States and in Europe; later developments originated in Asia. To provide an historical perspective, this paper presents a chronological account which identifies the "prime movers" and events, with an acknowledged bias to those who contributed in the United States. The development of simulation models did not take place in a vacuum: there were many relevant and supportive contributions by innovators in related fields who are likewise identified. Since the author participated in the simulation activity, several anecdotal tales derived from personal communication will be included to present a picture of the professional environment of each historical period.

THE FIRST DECADE: 1950s

As the decade began, the only digital computers available were special-purpose computers, most designed for the military. In the United States, the dominant player in the design and manufacture of digital computers during this decade was the IBM Corporation. The IBM 701, known as the Defense Calculator while in development, made its debut in 1952 as IBM's first commercial scientific computer. It provided a total memory of 2,048 words of 36 bits each with a memory cycle time of 12 microseconds. A multiplication or division operation required 38 cycles (456 microseconds). A year later, the IBM 650 Magnetic Drum Data-Processing Machine was introduced; almost 2,000 systems were produced over 10 years. Its rotating drum memory provided up to 4,000 words of memory, each consisting of 10 digits or five characters. The IBM 704 computer, which followed in 1955 and was dubbed a "super-computer," included core memory (RAM) of 4,096 36-bit words, three index memories, could execute up to 4,000 operations per second, and provided a floating-point (hardware) unit. The 704, which was not compatible with the 701, sold 123 systems over 5 years. None of these computers had an operating system or a high-level language compiler. Programming was implemented using a numerical machine language or assembler; FORTRAN for the IBM 704 was released in 1956. The UNIVAC computer, a rotating drum machine, was introduced in 1956 to the commercial market. The IBM 709, introduced in 1958, had 32,768 words of 36-bit memory and could execute 42,000 add or subtract instructions per second. An optional hardware emulator executed legacy IBM 704 programs on the IBM 709. A transistorized version, named the IBM 7090, was introduced the following year. An upgraded version, the IBM 7094, was first installed in September 1962. IBSYS, an IBM-supplied operating system, was included, as was a "Floating-point Assembler Program."

It is seen that early simulation model developers of this period had to deal with an adverse computing environment. Not only were computers in limited supply and computer time very costly, software developers had to deal with severe computer storage and programming constraints. To illustrate this environment, I relate the experience of Jim Kell (as told to me) during his final year as a graduate student at University of California–Berkeley. He chose as his master's thesis the development of a simulation model to analyze traffic flow at two intersections controlled with stop signs. During that year, he taught himself to program the IBM 701 computer, and collected and analyzed field data to design and calibrate his model. Finally, near the end of the school year, he reserved time on the computer to generate the results. As that day dawned, he entered the computer lab and was greeted by an empty space where the computer had been. Upon inquiry, he was told that the computer was just shipped out that morning and would be replaced by an IBM 704 computer. Knowing that the two computers were not compatible, Jim rushed to the loading dock to find the 701 on the truck about to be driven away. Fortunately, Jim was a large man who was able to persuade the dock workers to move the computer off the truck and back into the lab, whereupon he was able to complete his thesis (*1*, *2*).

Possibly the first simulation program in the United States was developed by Harry H. Goode of University of Michigan (*3*). Goode was a professor of Electrical and Industrial Engineering and an expert on computers. His work attracted the attention of a graduate student at University of California–Los Angeles (UCLA) named Daniel Gerlough which resulted in his 1955 dissertation (*4*, *5*, *6*, *6a*) and launched a pioneering career in traffic simulation and flow theory. In fact, it was Gerlough who proposed that the Highway Research Board create a committee on traffic flow theory (Committee No. 9) (*7*). One of the best-known results obtained

from simulation in this decade was that by F. V. Webster on delay at signalized intersections (*8*) which took the form of the classical equation documented in the monograph by Webster and Cobbe in 1966 (*9*).

While the limited availability of computing equipment restricted the development of simulation software in the 1950s, theoretical developments were taking place which would profoundly promote the development and use of traffic simulation in the future. It should be noted that the profession of transportation engineering was itself emerging during this decade and that most of the pioneers migrated from other disciplines: operations research; physics; civil, electrical, and computing engineering; aerospace; and economics and mathematics. Examples include John Nash who formulated the Nash Equilibrium in 1950 (*10, 11*), established the foundation for John Wardrop's equilibrium laws in 1952 (*12*) which forms the basis for traffic assignment and the present application of simulation-based network modeling (*13*); fluid flow analogies of traffic flow developed by Lighthill and Witham in 1955 (*14*) and by Richards in 1956 (*15*) (LWR theory) which form the basis for most macroscopic simulation models; car-following theoretical development which forms the core of microscopic simulation models was pursued by many researchers including R. E. Chandler, Robert Herman, E. W. Montroll, R. B. Potts, R. W. Rothery, and D. C. Gazis (*16–19*); and statistical modeling of traffic flow (*20*). The growing interest in traffic flow theory led to the organization of the first International Symposium on the Theory of Traffic Flow, held in 1959 in Detroit, Michigan, which was sponsored by GM. While only one simulation model was presented (*21*), several papers addressed simulation concepts (*22*), thereby establishing the close relationship between simulation modeling and traffic flow theory.

SIMULATION AS AN EMERGING TOOL: 1960s

This decade ushered in major improvements and affordability in computer technology and in programming ease. Other vendors joined IBM and UNIVAC, including Bendix, Hewlett-Packard, Control Data, Digital Equipment, and Data General; the latter two introduced the concept of the minicomputer. New high-level languages were developed, including COBOL, ALGOL, PL/1, and BASIC. Of particular interest was the development of simulation languages such as the General Purpose Simulation System (GPSS) in 1961 (*23*); SIMSCRIPT, a FORTRAN-based language in 1963; and SIMULA, an object-oriented superset of ALGOL in Norway, which inspired the later development of C++.

The efforts of researchers in the fields of traffic flow theory and transportation planning continued to lay the groundwork for simulation development. The second international symposium on the theory of road traffic flow in 1963 (*23a*) had a separate section on area traffic control and simulation which included a description of the work performed by Wagner and Gerlough (see below). The third symposium in 1965 (*23b*) presented papers on the subject of traffic assignment, as an adjunct of traffic flow theory. An important development was establishing the relationship between "car hopping" and traffic flow theory, which set the stage for mesoscopic simulation models and those employing computer automata procedures (*23c*).

When the Washington, D.C., District Department of Traffic (DCDOT) took delivery of a minicomputer, none of the engineers at DCDOT had experience with computers (as related to me). Finally, after trying to decide what to do with it, someone suggested that they sponsor the development of a traffic simulation model to evaluate proposed signal timings. This was done;

Planning Research Corp. with a proposed team of Fred Wagner (engineer), Dan Gerlough (simulation design), and Jesse Katz (programmer) won the competition. The resulting product, which had to be designed for the DCDOT minicomputer as a contractual requirement, was a network simulation model named, TRANS (*24*). The constraints imposed by the relatively small computer significantly limited the model design: there was no car-following or lane-change logic, vehicles hopped from one cell to the next (each lane was subdivided into cells) at a constant speed until a queue was reached, and a constant simulation time-step of 2 s was applied for all vehicle movements. Nevertheless, the model worked and demonstrated the potential of traffic simulation as a viable tool for evaluating control systems and network designs. The model was applied in three NCHRP projects (*25–27*) and was one of the first to employ a mesoscopic representation and a cellular-automata technique to move vehicles (although those terms were not used at the time). Unfortunately, the compromises in model design required to meet the contractual requirements led to criticisms as an outcome of validation studies conducted.

A new application of simulation technology appeared towards the end of the decade in the form of the TRANSYT signal optimization model (*28, 29*). Here, the traffic flow model, in the form of a cycle-based macroscopic simulation model (which took the form of a statistical histogram acted upon by a platoon dispersion formulation) was embedded as a component of a signal timing iterative procedure, rather than as a stand-alone evaluation tool. This application, which is still applied worldwide in various versions, expanded the application of traffic simulation and was a forerunner of modern developments.

While the research community's interest in simulation increased over the decade, most practitioners were either oblivious or dubious of the value of simulation, a posture that extended into the 1980s. The 1965 *Highway Capacity Manual* (HCM) (*30*) made no mention of the potential application of simulation as an analytical tool. One prominent practitioner who was an exception and who made many innovative contributions to the profession, particularly in the field of urban traffic operations, was Henry Barnes (*31*). He was probably best known for "Barnes' Dance" where traffic signals at intersections that serviced heavy pedestrian traffic had an extended phase of all-red indications for all approaches which permitted pedestrians to safely cross in all directions. He was also credited with the concept of semi-actuated control and the pedestrian pushbutton to call a signal phase. At the time (1968) I became interested in Traffic Engineering, and in simulation, he was Commissioner of Traffic in New York City.

My friend and former classmate, Lou Pignataro (*32*), arranged a meeting with him where I described the technology and offered to demonstrate the value of simulation, pro bono. Barnes immediately recognized the potential value of simulation and identified a problematic signalized interchange in the Bronx that experienced extreme congestion during the p.m. peak period; this congestion in the interchange caused queues on the exit ramps from the Whitestone Parkway to extend onto the freeway—a condition that resulted in many collisions. This effort resulted in the DAFT model (*33*), coded in the GPSS/360 block language released to the public by IBM, which was used iteratively as a design tool to incrementally improve the signal policy when installed at the interchange. As a result of the improvements in signal timing, traffic congestion which had extended to 8 p.m. originally dissipated at 6:15 p.m. and the queues on the exit ramps no longer spilled back on the freeway. While the demonstration was a success, there was no following activity as Barnes suffered a heart attack about a month after our meeting.

At about that time, the FHWA launched a research and development project entitled Urban Traffic Control System (UTCS). One activity was the development, calibration, and validation of an urban network microscopic traffic simulation model to be named, UTCS-1. The

intended use of this model was to evaluate traffic signal timing policies to be developed under this project. The technical representative for FHWA was Guido Radelat who developed a simulation model of bus operations along arterials, named SUB, as his dissertation (*34*). This was a one of the first hybrid models, which represented the background traffic macroscopically while moving bus vehicles as a mesoscopic process.

The UTCS-1 model was coded in FORTRAN which made it computer-independent and scalable. While the original contract called for a network size of 25 intersections, UTCS-1 (and its successor, NETSIM) were capable of simulating much larger networks, limited only by computer size. The model used a 1-s time-step with a resolution of 0.1 s and included car-following and queuing and lane-change logic; the model assigned driver behavioral characteristics stochastically and accommodated many vehicle types as well as pedestrian–vehicle interaction effects. Traffic data for calibration and for validation were collected using timelapse photography from an aerial platform (helicopter) and recorded on 70-mm film. The model was completed, documented (*35, 36*) and applied to several networks to demonstrate its utility (*37*). The developer team of Peat Marwick Mitchell and General Applied Science Laboratories was headed by Dick Worrall and me, with technical oversight by Jim Kell, and with important contributions by others. The support provided by FHWA provided the impetus for further simulation development which continues to the present time.

THE MATURATION OF SIMULATION DEVELOPMENT
AND APPLICATION: 1970s

Computer systems became more powerful (more RAM and faster processors) and more plentiful, making them accessible to more organizations and spurring interest in computer-based tools such as simulation. The UNIX operating system was developed as well as the C programming language; structured programming standards were developed to increase the reliability of software while reducing its cost. Companies such as Atari, Commodore, Tandy, Data General, and Apple were formed to produce small computers; Intel was formed to produce microprocessors; and Microsoft was formed to produce software. These latter developments had no immediate impact on simulation modeling, but would revolutionize the computing environment for simulation-based models in coming decades.

Advances continued in traffic flow theory and were compiled in a handbook (*38*). After a lag of almost 20 years, Wardrop's Laws were expressed as mathematical algorithms (*39*) and in software, which opened a new frontier for traffic simulation models. The LWR theory was further refined by Pete Payne (*40*) and later realized as a macroscopic freeway simulation model.

The success of UTCS-1 prompted FHWA to add more features: simulation of bus operations and adaptive control, calculation of vehicle emissions and fuel consumption, and expanded output capabilities. These extensions continued throughout the decade and into the next. The source code was distributed and researchers across the country gained experience and exposure to simulation (e.g., *41–44*). The agency extended simulation model development to freeways with the INTRAS model (*45*). With a view of extending the scope of simulation to larger, regional networks, the agency sponsored the development of the "hybrid" TRAFLO system (*46–48*) which was an integration of individual mesoscopic and macroscopic models for simulating traffic over a general network of freeways and surface roads and incorporated the Sang Nguyen algorithm for static equilibrium assignment which permitted demand data to be entered as origin–

destination (O-D) volumes. Another hybrid model integrated a microscopic urban model with a mesoscopic freeway model (*48a*). In contrast, FHWA supported the very detailed microscopic TEXAS simulation model which was designed to examine safety aspects at individual intersections (*49*). This model has been refined and extended many times over the years.

Towards the end of the decade, the development of simulation models of traffic flow on two-lane rural roads was begun in the United States, Europe, and Australia. This activity was preceded by research in traffic flow and in formulating the performance of vehicles on grades to capture the behavior of platoon formation (*50*). Another development that was to have a major impact on the application of simulation models was the publication of the original papers on dynamic traffic assignment (*50a*, *50b*).

THE EMERGENCE OF THE PC AND FURTHER DEVELOPMENT OF INTEGRATED SIMULATION MODELS: 1980s

The IBM PC was introduced in August 1981 and sold 100,000 computers by year-end. Thirteen years later, there were 100 million PCs worldwide running Microsoft's MS-DOS. In 1982, the Compaq Corp. released their PC-compatible portable computer. The first PC with a hard drive was released in early 1983. The PC had little influence on simulation modeling until 1985 when Intel released the 80386 DX processor, which could address up to 4 GB of RAM. Compaq Corp. released the first PC with this processor. FORTRAN compilers for the PC meant that mainframe software could be ported to the PC. High-performance graphical processors were also being developed along with software that could bind with high-level programming languages. The C++ language was introduced in 1983.

At mid-decade, the practitioner community had a limited acceptance of simulation technology. For example, the 1985 HCM (*51*) does not contain the word "simulation" in its index, although the procedures in Chapter 8: Rural Roads, reflect in part the results of microscopic simulation analysis. The vast majority of consultants are small firms whose budgets precluded the procurement of large computer systems. The subsequent PC revolution was to have a major impact upon the acceptance of traffic simulation by practitioners. FHWA led the way by porting the NETSIM model to a PC (*52*) and by sponsoring the development of animation software to display simulated vehicle movements on PC screens (*53*). By now, most schools had included simulation courses as part of their curricula. Over the following years, practitioners discovered that simulation software, provided free of charge by FHWA (*54*, *55*) (which offered training courses), operated on affordable PCs and became an essential part of their services.

This decade also witnessed the availability of simulation models designed for rural roads. These included the VTI model from Sweden (*56*), the TRARR model from Australia (*56*), and the TWOPAS (*58*) and ROADSIM (*59*) models from the United States; all these models are microscopic. While developed on mainframe computers, all were ported to the PC. FHWA sponsored the development of the FRESIM freeway microscopic simulation model, a refinement and extension of INTRAS for the PC (*59a*).

Development of integrated simulation-based models which incorporated both operational and planning components intensified. Among the first to appear came from the United Kingdom in the form of the CONTRAM model (*60*) closely followed by the SATURN model (*61*). From Canada came the INTEGRATION mesoscopic simulation model as the dissertation of Michel

Van Aerde in 1983 (*62*); working with Sam Yagar, the model was refined (it became microscopic) and extended (*63–65*). The INTEGRATION model has been periodically extended and applied since then and is supported at VTI since Van Aerde's death in 1999. The development of large-scale integrated simulation-based models designed for the PC were begun in Europe and released in the following decade.

Research in traffic flow theory continued to support the growth in the number and functionality of simulation models (*66–74*). In addition, increasing attention became focused on the accuracy and reliability of simulation models (*75*), an emphasis that was intensified over the ensuing years.

AN EXPLOSION OF SIMULATION R&D AND RISING PC COMPUTING POWER: 1990s

This decade witnessed the continued evolution of the integrated simulation model as the dominant medium in network modeling: for multiple modes of traffic operations and for transportation planning. All simulation software has now targeted the PC computer. Even the TRANSIMS development which was originally designed for parallel processing (*76*) was eventually ported to the PC. In 1993 the multitasking Windows NT 3.1 was released along with the first Pentium chip-set with a speed of 66 MHz; in 1998 a Pentium at 333MHz was released.

The trend toward integrated simulation models continued. The FHWA sponsored the development of CORSIM by integrating the urban NETSIM and freeway FRESIM microscopic models (*77, 78*). Since then, CORSIM has enjoyed continuing support and has been expanded to include rural roads, diamond interchanges and other features. In addition, several universities formed "breeding grounds" for simulation-based software products that have been further developed by organizations in the private sector; others were developed solely by private organizations. All commercial simulation-based products are now marketed worldwide. Some of the more prominent packages include

- Aimsun: Transport Simulation Systems (TSS);
- CUBE: Citilabs;
- Dynameq: INRO;
- MITSIMLab: MIT;
- PARAMICS: Quadstone;
- Simtraffic: Trafficware;
- Transmodeler: Caliper; and
- VISSIM–VISUM: PTV.

All these products provide microscopic or mesoscopic simulation models and most provide the option of macroscopic simulation modeling as well. Dynamic traffic assignment based on equilibrium theory and route choice models are included. All provide user interfaces, graphical (and animation) displays, and a wide range of data formats for displaying the analysis results. Many provide application programmer interfaces (APIs) so that skilled users can customize these packages, using high-level programming languages, to suit their needs. These integrated packages generally consider many traffic modes including pedestrian simulation models. While many were not widely available until the present millennium, the basic

development effort occurred during the 1990s when PC technology permitted. All operate on PC equipment or on UNIX workstations and can be applied to regional networks of 10,000+ links.

Other large-scale network simulation-based models emerged from sponsored research activities, including DYNASMART (*79*), TRANSIMS (*80, 82*), and HUTSIM (*81*); the first uses a mesoscopic representation of traffic, the second employs a "vehicle hopping," cellular-automaton process, while the third is microscopic. All models are currently supported, have been extended over time, and are available for use.

This decade also witnessed advances in research which influenced simulation modeling going forward. Carlos Deganzo (*83, 84*) developed the cell transmission model (CTM) based on LWR theory to provide a macroscopic simulation treatment. The CTM has been investigated by many researchers and extended (*85*). Given the wide variety of simulation-based models available at the end of the decade, attention focused on the selection procedures of a model for a specific project (*86, 87*) and on the calibration and validation of selected simulation models (*88–91*). These activities would continue to the present time.

FURTHER EXPANSION OF SIMULATION-BASED SYSTEMS AND NEW APPLICATION PROTOCOLS: 2000+

Desktop computer speeds and RAM capacity continued to improve while costs continued to drop. The Intel dual and quad Core chipsets were launched in 2006 and are used by Apple computers, as well. Simulation software developers were no longer constrained by hardware limitations and were able to expand their products subject only to market constraints and by developments in network theory.

The FHWA sponsored the Next Generation Simulation (NGSIM) project in 2004 as a public–private partnership which prevails to this day (*92*). The project developed core simulation algorithms which were introduced into many commercial and public software products and an empirical database of vehicle trajectories along I-80, US-101 (a freeway), and Lankershim Boulevard, a surface artery that included four signalized intersections. These data sets, which include geometrics and control settings, are available without charge to those engaged in research worldwide and are proving to be a long-lived legacy of the project. These data are not only an outstanding resource for model developers; they have also prompted valuable research in data analysis (*93*).

Advances in simulation led to the development of more efficient software for implementing dynamic network loading models in support of dynamic traffic assignment algorithms. In particular, the introduction of the link transmission model by Yperman (*94*) in 2007 paved the way for additional developments (*95, 96*) which enabled computing times to decline. These lower computing times, along with new operating systems that support parallel processing, enhanced the development of network software that could be deployed on-line as traffic management systems (*97–99*). The emphasis on developing vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and infrastructure-to-vehicle (I2V) communication and management architectures involves the online deployment of simulation-based models.

There were over 500 papers presented at the 2012 TRB meeting that involved traffic simulation. All modes of travel were represented, with many papers addressing various combinations of travel modes interacting in the same environment. This testifies to the interest in, and need for simulation development. While simulation is now a mature technology, it

continues to evolve to meet society's needs as the demand for travel services increase while the expansion of the physical infrastructure is severely constrained.

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Evolution of the TEXAS Model for Intersection Traffic Simulation Animation and Traffic Flow Theory Milestones

THOMAS W. (TOM) RIOUX
Rioux Engineering, Austin, Texas;
Consultant to Harmonia Holdings Group, LLC

The Traffic EXperimental and Analytical Simulation Model for Intersection Traffic (TEXAS Model) was developed by the Center for Transportation Research at the University of Texas at Austin beginning in the late 1960s under the leadership of Dr. Clyde E. Lee. Dr. Thomas W. Rioux was leader of the team of graduate students that developed the TEXAS Model and has been upgrading the TEXAS Model since its initial development. The TEXAS Model is being enhanced to include connected vehicle messages by Harmonia Holdings Group and Rioux to be a test bed for connected vehicle applications. The TEXAS Model source code is available for use by the public under the GNU General Public License as published by the Free Software Foundation. The TEXAS Model source code for the standard version may be downloaded from http://groups.yahoo.com/neo/groups/TEXAS_Model while the version with Connected Vehicle applications may be downloaded from http://www.etexascode.org. This paper chronicles the evolution of the TEXAS Model simulation animation from the early 1970s through 2008 and the early traffic flow theory concepts of triangular acceleration, triangular deceleration, equations of motion, car following, intersection conflict checking, intersection conflict avoidance, sight distance restriction checking, lane changing, and crashes.

INTRODUCTION

Microscopic traffic simulation involves defining the movement of individual driver–vehicle units through a roadway system in response to driver desires and control, other driver–vehicle units in the system, and the absence or presence of traffic control. A driver–vehicle unit is a vehicle with specified characteristics (such as type of vehicle, length, maximum acceleration, maximum speed, etc.) controlled by a driver with specified characteristics (such as driver type, reaction time, desired speed, etc.) that has an intersection origin leg and lane and a destination leg. Every driver–vehicle unit in the system is processed every small time-step increment (generally 1 s or less) wherein each individual driver makes many decisions (change lanes, slow down, speed up, stop, turn, avoid crash, etc.), vehicle detectors and signal controllers are simulated, and many measures of effectiveness (MOEs) are gathered and reported.

Clyde E. Lee was the faculty member who, in the late 1960s, conceived the idea of applying the University of Texas at Austin's (UT) new Control Data Corporation (CDC) 1604 mainframe digital computer for simulating traffic flow through an intersection. He initiated the first development efforts and supervised several ensuing research projects that culminated in the TEXAS Model (a name suggested by Guido Radelat of the FHWA Turner–Fairbank Highway Research Center) being initially released in 1977. Lee continued supervising research projects that enhanced or used the TEXAS Model until his retirement from UT in 1999. The TEXAS Model was developed by the Center for Highway Research and later the Center for Transportation Research (CTR) at UT using FORTRAN and mainframe computers. Initial

funding for the development efforts was provided by the Texas Department of Transportation (DOT) in cooperation with the FHWA with later funding by the FHWA and the UT College of Engineering.

Tom Rioux developed an interactive graphics system (*a*) to display and manipulate a finite elements model mesh during the 1969–1970 school year and (*b*) to display the theoretical and observed dynamic forces between the tires and pavement of a moving truck allowing the spring constants and damping coefficients to be modified during the 1970–1971 school year at UT using the CDC 250 Display System.

The original TEXAS Model simulated a single intersection with no control, yield-sign control, less-than-all-way stop-sign control, all-way stop-sign control, pretimed signal control, semiactuated–signal control, or full-actuated–signal control using time-step increments between 0.5 and 1.5 s, inclusive, for a total of 4,500 s (1.25 h). The geometry included up to six legs with up to six inbound and six outbound lanes per leg; up to 1,000 ft straight lanes that could be blocked at the near end, far end, or in the middle; specification of movements allowed to be made from each inbound lane; specification of movements allowed to be accepted for each outbound lane; sight distance restrictions; detailed intersection path geometry using arcs of a circle and tangent sections; and the calculation of potential points of geometric conflicts between intersection paths. The traffic stream was stochastically generated using constant, Erlang, Gamma, lognormal, negative exponential, shifted negative exponential, and uniform distributions for headways with user-specified parameters; the normal distribution for desired speeds; and discrete percentages for turn movements, lane assignments, and other percentage-based parameters. For each inbound leg, the user specified the hourly volume, the headway distribution name and any parameters, the mean and 85th percentile speed, and the percentage of each vehicle class in the traffic stream. For each vehicle class (10 provided with a maximum of 15), the user specified the percentage of each driver class (three provided with a maximum of five).The model included intersection conflict checking; sight-distance restriction checking; cooperative lane changing using a cosine curve for the lateral position; car following using the Gazis–Herman–Rothery model with user-specified values for lambda (power for relative position), mu (power for speed), and alpha (constant); jerk-rate-driven equations of motion; triangular acceleration; triangular deceleration; and crashes with the driver–vehicle unit in front. MOEs included

1. Total delay (actual travel time minus the time to travel the same distance at the time-averaged desired speed);
2. Queue delay (time from initially joining the end of the queue of driver–vehicle units at the stop line until crossing the stop line);
3. Stopped delay (time stopped from initially joining the end of the queue of driver–vehicle units at the stop line until crossing the stop line);
4. Delay below a user-specified speed such as 10 mph;
5. Vehicle-miles of travel;
6. Travel time;
7. Volume;
8. Time and space mean speed;
9. Turn percentages;
10. Maximum and average queue length in 20-ft vehicles; and
11. Number of crashes.

The MOEs could be printed per driver–vehicle unit and were summarized per lane or movement, per inbound leg, and for the entire intersection.

Initial model development effort began in 1968. Many students, faculty, and staff at UT have been involved in the development and use of the TEXAS Model:

- James W. Thomas, a graduate student in Civil Engineering at the time, began defining the concepts and techniques for modeling traffic flow through an intersection.
- Roger S. Walker, a graduate student in Electrical Engineering at the time, wrote some of the earliest CDC 1604 computer code for the TEXAS Model. His work included the development of the COordinated Logic Entity Attribute Simulation Environment (COLEASE) program which provided extremely efficient storage of model data and implemented an efficient means for processing logical binary networks. He was assisted by Dennis Banks.
- Thomas W. *Tom+Rioux, a graduate student in Civil Engineering at the time, started work on the project in 1971 and followed up on Walker's initial work and became the leader of the team that developed the TEXAS Model into a viable tool for practical use in traffic engineering and research using the CDC 6600 computer system until the TEXAS Model was released in 1977 (Rioux 1973 TexITE; Rioux 1973 thesis; Fett 1974 thesis; Rioux 1977 dissertation; Rioux et al. 1977 TRB TRR 644; Lee et al. 1977 184-1; Lee et. al. 1977 184-2; Lee et al. 1977 184-3; and Lee et al. 1978 184-4F). Rioux was the primary person who developed the field data analog-to-digital processing software that was used for model validation, DISFIT, GEOPRO, SIMPRO, the CDC 250 Display System version of DISPRO, SIMSTA, REMOVEC, REPLACEC, and gdvsim. He also participated in the development of DVPRO, the Intergraph UNIX X Windows version of DISPRO, the Java version of geoplot, and the Java version of dispro. In 1973, Rioux developed an animation on the CDC 250 Display System that was used during initial development efforts. Field measurements of queue delay using specifically designed recording devices were used to calibrate and validate the TEXAS Model at a four-leg intersection with pretimed-signal control in Austin, Texas.
- Charlie R. Copeland, Jr., an undergraduate and then a graduate student in Civil Engineering at the time, was part of the original development team and was the primary person who developed DVPRO and EMPRO. He also participated in the development of the field data analog-to-digital processing software, DISFIT, GDVDATA, GDVCONV, SIMDATA, SIMCONV, and SIMPRO.
- Robert F. "Bobby" Inman, an undergraduate student in Mechanical Engineering at the time, was part of the original development team and was the primary person who developed the field data collection hardware, GDVDATA, GDVCONV, SIMDATA, SIMCONV, DISPRE, and the DOS version of DISPRO. He also led the development effort of the Texas Diamond and NEMA traffic signal controller simulators within SIMPRO. Harold Dalrymple assisted him in the development of the field data collection hardware.
- Ivar Fett, a graduate student in Civil Engineering at the time, was the person who collected and analyzed the field data and developed the original lane changing geometry and decision models, developed the initial all-way-stop sign control logic, and developed the initial pre-timed signal control logic for SIMPRO. He participated in the development of the car-following logic for SIMPRO.
- William P. Bulloch, a graduate student in Civil Engineering at the time, developed the initial acceleration, deceleration, and car-following models for SIMPRO.

- Elia King Jordan, a graduate student in Civil Engineering at the time, developed the initial version of DVPRO.
- Glenn E. Grayson, a graduate student in Civil Engineering at the time, assisted in the development of the actuated signal control logic for SIMPRO and supervised the field data collection and analysis which was used to validate the TEXAS Model.
- Vivek S. Savur, a graduate student in Civil Engineering at the time, assisted in the field data collection and analysis and assisted in the development of GEOPRO.
- Scott Carter, a graduate student in Civil Engineering at the time, was the primary person that developed the Intergraph UNIX X Windows version of DISPRO.
- Moboluwaji "Bolu" Sanu, a graduate student in Electrical and Computing Engineering at the time, was the primary person who developed the Java versions of geoplot and dispro. He later participated in the Small Business Innovative Research Projects performed by Rioux Engineering (Rioux 2004 DTRS57-04-C-10007; Rioux 2008 DTRT57-06-C- 10016).
- Zhonghui Ning participated in the development of gdvsim in the Small Business Innovative Research Projects performed by Rioux Engineering (Rioux 2004 DTRS57-04- C-10007; Rioux 2008 DTRT57-06-C-10016).

Many research projects have used the TEXAS Model and their results are documented elsewhere. The original software programs proved to be a very robust and logically sound platform upon which numerous evolutionary enhancements, revisions, and new features were subsequently added through additional projects at CTR and Rioux Engineering as the TEXAS Model migrated from batch mode on a mainframe computer to interactive mode on modern microcomputers, including the following:

- 1977/12/01 V1.00, initial release.
- 1983/08/01 V2.00, Emissions Processor added (Lee et. al. 1983 250).
- 1985/11/01 V2.50, converted to run on the DOS operating system on a microcomputer using 16-bit FORTRAN compilers, user-friendly interface added, and DOS animation added (Lee et. al. 1985 361).
- 1989/01/01 V3.00, diamond interchange geometry and Texas DOT Figure 3, 4, 6, and 7 dual-ring actuated diamond signal controller added (Lee et. al. 1989 443).
- 1992/01/31 V3.10, replicate runs added, wide or narrow output selection added, left-turn pull-out option added, hesitation factor added, maximum number of loop detectors per lane was increased from three to six, blocked lane processing modified, intersection conflict avoidance added, and driver–vehicle unit delay for unsignalized lanes modified.
- 1992/03/25 V3.11, intersection conflict avoidance error fixed, lane change errors fixed, and look ahead algorithms modified.
- 1992/12/15 V3.12, converted to run on the Unix operating system on a workstation, Headway Distribution Fitting Processor added, Geometry Plotting Processor added, Simulation Statistics Processor added, UNIX X Window animation added, free u-turns at diamond interchange added, Dallas diamond signal controller phase numbering added, NEMA TS 1-1989 signal controller with volume–density operation added, replicate runs for specified number of runs added, replicate runs to specified statistical tolerance added, spreadsheet macros developed, car following modified, and many small enhancements to numerous algorithms (Rioux et. al. 1993 1258).
- 1993/11/23 V3.20, car following modified and NEMA controller errors fixed.

- 1994/05/10 V3.21, lane change error fixed.
- 1994/06/07 V3.22, NEMA and Texas diamond controller errors fixed.
- 1996/02/28 V3.23, car-following logic modified.
- 1998/09/21 V3.24, utility programs from80d.exe and to80d.exe added and Y2K-compliant modifications made.
- 2000/08/03 V3.25, Java animation added.
- 2003/08/29 V4.00, compiled using 32-bit FORTRAN compilers and initial vehicle messages added.
- 2005/08/12 V5.00, Java user interface added; Geometry Plotting Processor converted to Java; source code released under GNU General Public License as published by the Free Software Foundation; increased number of driver types to nine; increased number of vehicle types to 99; classify detector added; modified logical binary networks to use type LOGICAL variables; added vehicle message system (VMS) messages for special driver– vehicle units— forced go time and duration, forced stop location and duration, and forced run red signal time and duration; changed minimum time-step increment to 0.01 s; converted all REAL variables to double precision; added VMS message types—driver DMS, driver IVDMS, and vehicle IVDMS; added VMS messages—accelerate or decelerate to speed *xx* using normal acceleration or deceleration, accelerate or decelerate to speed *xx* using maximum vehicle acceleration or deceleration, stop at the intersection stop line, stop at location *xx*, stop immediately using maximum vehicle deceleration, stop immediately using crash deceleration, change lanes to the left, change lanes to the right, forced go, and forced run the red signal; add VMS message— start time, active time, location (lane or intersection path and beginning and ending positions), driver–vehicle unit number (0 = all), and reaction time distributions and parameters; Surrogate Safety Assessment Methodology (SSAM) file support added; Linux version developed (Rioux 2004 DTRS57-04-C-10007 and Rioux 2005 DTFH61-03-C-00138).
- 2008/07/31 V6.00, all user interface software made Section 508 compliant; built-in help and tool tips added; displaying the sight distance restrictions added; displaying the detector geometry and activity added; Java application developed to automate the running of the TEXAS Model; total simulation time extended to 9999.99 s (2.777775 h); lane length extended to 4,000 ft; Java application to display statistics from one run or replicate runs developed; stop on crash using crash deceleration and remain stopped option added; crashes between driver–vehicle units on different intersection paths added; automated the running of SSAM; attach and display orthorectified image file added; updated the NEMA traffic signal controller simulator to NEMA TS 2-2003; pedestrians added as they affect the operation and timing of the NEMA and hardware-in-the-loop traffic signal controllers; pedestrian signal operation added to animation; caused other driver–vehicle units to react to a crash; dilemma zone statistics added; time-varying traffic for two or more periods added; hardware-in-the-loop traffic signal controller added; additional vehicle attributes added to articulate vehicles; distracted driver VMS message added; an optional lane change before or after the intersection to move from behind a slower driver– vehicle unit added; and simulation of bicycles, emergency driver–vehicle units, and rail driver– vehicle units added (Rioux et. al. 2008 DTRT57-06-C-10016-F).
- 2010, Small Business Innovative Research (SBIR) project Topic 10.1-FH3 "Simulating Signal Phase and Timing with an Intersection Collision Avoidance Traffic Model" adding SAE J2735 Basic Safety Message (BSM), Signal Phase and Timing Message (SPAT), and Map Data Message (MAP) awarded to Harmonia Holdings Group, LLC., Blacksburg, Virginia; Phase I completed; Phase II in progress.

- 2011, SBIR project Topic 11.1-FH2 "Augmenting Inductive Loop Vehicle Sensor Data with SPAT and GrID (MAP) via Data Fusion" adding National Transportation Communications for ITS Protocol (NTCIP) 1202 vehicle detector, traffic signal controller parameter, and traffic signal display messages awarded to Harmonia Holdings Group, LLC., Blacksburg, Virginia; Phase I completed; Phase II in progress.

EVOLUTION OF THE TEXAS MODEL SIMULATION ANIMATION

1970s

In 1973, Rioux developed an animation on the CDC 250 Display System that was used during initial development efforts (Rioux 1977 dissertation, and Lee et. al. 1977 184-1). The CDC 250 Display System (see Figure 1) was channel connected to a CDC 6600 mainframe system which was the fastest computer in the world when purchased, had a vector refresh display, a 4,095-word display buffer, a 60-times-per-second refresh rate, a 1,024 by 1,024 first quadrant coordinate system, a light pen, and a standard keyboard entry device. An analog line could be drawn from any coordinate to any other coordinate, horizontal text could be placed at any coordinate, and the system would return the address of the object in the display buffer that the light pen touched thus the software had to keep track of the location in the display buffer of objects that could be triggered by the light pen. Computer code was directly added to the TEXAS Model simulation source code to display the animation thus the user could pause the animation but could not reverse the animation. Each driver–vehicle unit was updated on the screen each time step increment, was individually characterized, had blinking left- and right-turn

FIGURE 1 CDC 250 display system.

signals, and had brake lights on the rear bumper. To make the animation movie, a 16-mm single-frame movie camera was mounted on a tripod, a photocell was attached to the lower right corner of the screen, the animation was updated one time–step increment, a flash of light was produced in the lower right corner of the screen to take one frame of movie film, and the process continued taking 3 h to produce 3 min of film. This animation can be viewed at http://www.youtube.com /watch?v=1z4WIeIOfbw.

1980s

In 1985, Robert F. "Bobby" Inman developed the DOS version of the animation named DISPRO (Lee et. al. 1985 361). The simulation model produced a file with records for each driver–vehicle unit for each time-step increment. A preprocessor program DISPRE read this data and reformatted and processed the data to make it easier to animate. The animation program DISPRO read the data from the preprocessor program DISPRE, took direct control of a display monitor turning on and off individual pixels on the color screen, and took input from the keyboard and function keys. The animation could be paused and go backward and forward in single step, slow, or fast mode. Vehicles appeared as a series of dots making up the edge of the vehicles and again had blinking left- and right-turn signals and brake lights on the rear bumper. The lane edges and stop lines were drawn as lines and traffic signal indications were displayed near the stop line. For development purposes, the traffic signal controller timers and states as well as detector actuations were displayed. This animation can be viewed at http://www.youtube.com/watch?v=S0utMJ9fZls.

1990s

In 1992, Scott Carter and Rioux developed the X Windows version of the animation named DISPRO on an Intergraph Corporation RISC-processor-based Unix workstation (Rioux et. al. 1993 1258). The animation program DISPRO read the data from the preprocessor program DISPRE, opened one control X Window, opened one to four intersection X Windows so the user could compare two or more different runs, and took input from the keyboard and mouse. Each X Window could be separately panned, zoomed, sized, and moved around the screen. The animation could be paused and go backward and forward in single step, slow, or fast mode.

Vehicles appeared as lines making up the edge of the vehicles and again had blinking left- and right-turn signals and brake lights on the rear bumper. The lane edges and stop lines were drawn as lines and traffic signal indications were displayed beyond the stop line as green, yellow, or red arrows or squares. This animation can be viewed at http://www.youtube.com/watch?v=PcU6W caOAcE.

2000s

In 2000, Moboluwaji "Bolu" Sanu and Rioux developed the proof of concept version of the Java animation (Rioux 2005 DTFH61-03-C-00138). In 2005, Sanu and Rioux developed the Java version of the animation (Rioux 2004 DTRS57-04-C-10007 and Rioux 2005 DTFH61-03-C-00138). The animation program runs on any computer with the Java Runtime Environment (JRE) or the Java Development Kit (JDK) which is a free download from http://www.oracle.com /technetwork/java/index.html. The animation program texasdis.jar reads the data from the preprocessor program DISPRE, opens one control window, opens one to two intersection

windows so the user can compare two different runs, and takes input from the keyboard and mouse. Each window can be separately panned, zoomed, sized, and moved around the screen. The animation can be paused, restarted, and go forward or backward in single step, slow, or variable speed fast mode. The user can enter the start time for the animation.

Optionally, the user can enable Presentation Mode so that it would restart at the end rather than stopping at the end. Vehicles appear as filled shapes with angled front ends, a blue windshield, blinking left- and right-turn signals, and brake lights on the rear bumper. The TEXAS Model had been upgraded to have articulated vehicles and these are drawn to scale. The lane edges and stop lines are drawn as lines and traffic signal indications are displayed beyond the stop line as green, yellow, or red arrows or squares. The user can optionally

1. Display the driver–vehicle unit number,
2. Change the vehicle color by vehicle class,
3. View turn signals,
4. View brake lights,
5. Identify vehicles blocked by a major collision,
6. Identify vehicles involved in a major collision,
7. Identify emergency vehicles running calls,
8. View vehicles reacting to emergency vehicles running calls,
9. View vehicles reacting to VMS messages,
10. View an attached image file,
11. View pedestrian activity if there is a NEMA traffic signal controller with pedestrians,
12. View vehicle detector activity (vehicle front bumper crossing the front edge, vehicle rear bumper crossing the rear edge, and vehicle within or spanning the detector),
13. View sight distance restriction locations,
14. View user-defined arcs of circles, and
15. View user-defined lines.
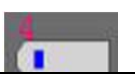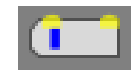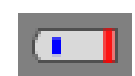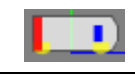
This animation can be viewed at http://www.youtube.com /watch?v=oah6nCGKwig. Table 1 describes some of the vehicle animation features of the Java animation.

TEXAS MODEL TRAFFIC FLOW THEORY

The TEXAS Model defines the Perception, Identification, Judgment, and Reaction Time (PIJR) as a user-specified parameter for each driver class in seconds. Typical values are 0.5 for aggressive drivers, 1.0 for average drivers, and 1.5 for slow drivers. Throughout the remainder of this document, several functions and constants are used as follows:

$$\begin{aligned}
\text{ABS(A)} &= \text{the absolute value A} \\
\text{ACOS(A)} &= \text{the arccosine of A} \\
\text{COS(A)} &= \text{the cosine of Ad} \\
\text{DT} &= \text{the time step increment in seconds} \\
\text{Max(A,B)} &= \text{the maximum value of A and B} \\
\text{PI} &= \text{the value for PI}
\end{aligned}$$

TABLE 1 Java Animation Features

1	Display the driver–vehicle unit number	
2	Change the vehicle color by vehicle class	
3	View turn signals: if the vehicle is making a u-turn or a left turn then blinking yellow turn signals are displayed near the front bumper and near the rear bumper on the left side of the vehicle	
	View turn signals: if the vehicle is making a right turn then blinking yellow turn signals are displayed near the front bumper and near the rear bumper on the right side of the vehicle	
4	View brake lights: if the vehicle's new deceleration rate is less than or equal to DECBRK or the vehicle's new speed is equal to zero then a red bar is displayed near the rear bumper of the vehicle	
5	Identify vehicles blocked by a major collision: if the vehicle is blocked by a major collision then the vehicle color is displayed in orange	
6	Identify vehicles involved in a major collision: if the vehicle is involved in a major collision then the vehicle color is displayed in red	
7	Identify emergency vehicles running calls: if the vehicle is an emergency vehicle then a flashing red rectangle is displayed behind the windshield of the vehicle representing a "light bar" seen on most fire, EMS, and police vehicles	
8	View vehicles reacting to emergency vehicles running calls: if the vehicle is reacting to an emergency vehicle then a "E" is displayed behind the windshield of the vehicle	
9	View vehicles reacting to VMS messages: if the vehicle is reacting to a VMS message then a "V" is displayed behind the windshield of the vehicle	
11	View pedestrian activity if there is a NEMA traffic signal controller with pedestrians: the status of the pedestrian signal and detector is displayed for each phase	
12	View vehicle detector activity: vehicle front bumper crossing the front edge	
	View vehicle detector activity: vehicle rear bumper crossing the rear edge	
	View vehicle detector activity: vehicle within or spanning the detector	

Triangular Acceleration

An investigation of existing acceleration models was undertaken in the early 1970s by Lee and Rioux and it was found that the uniform acceleration model did not match observed behavior accurately when considered on a microscopic scale. Using a Chi-squared goodness-of-fit test, a best-fit uniform acceleration model was calculated and the results plotted (see Figure 2 below) along with observed data points (Beakey 1938 HRB). This figure illustrates that the uniform acceleration model computes velocities which are too low during initial acceleration and which result in the driver–vehicle unit's reaching desired velocity much sooner than it should. A linear acceleration model which hypothesizes use of maximum acceleration when vehicular velocity is zero, zero acceleration at desired velocity, and a linear variation of acceleration over time was investigated. Comparisons of this model with observed data (see Figure 2) indicate excellent agreement. This model also compared favorably with the nonuniform acceleration theory (Drew 1968 TFT&C) used in describing the maximum available acceleration for the driver–vehicle unit.

This work lead to the development of the triangular acceleration model used in the TEXAS Model. The author will use the term "jerk rate" to describe the rate of change of acceleration or deceleration over time and is usually in units of feet per second per second per second. Starting from a stopped condition, a driver–vehicle unit will use a maximum positive jerk rate until it reaches the maximum acceleration then the driver–vehicle unit will use a negative jerk rate until the acceleration is zero at the driver–vehicle unit's desired speed. The maximum acceleration is defined by the driver–vehicle unit's desired speed and the maximum acceleration for the driver–vehicle unit.
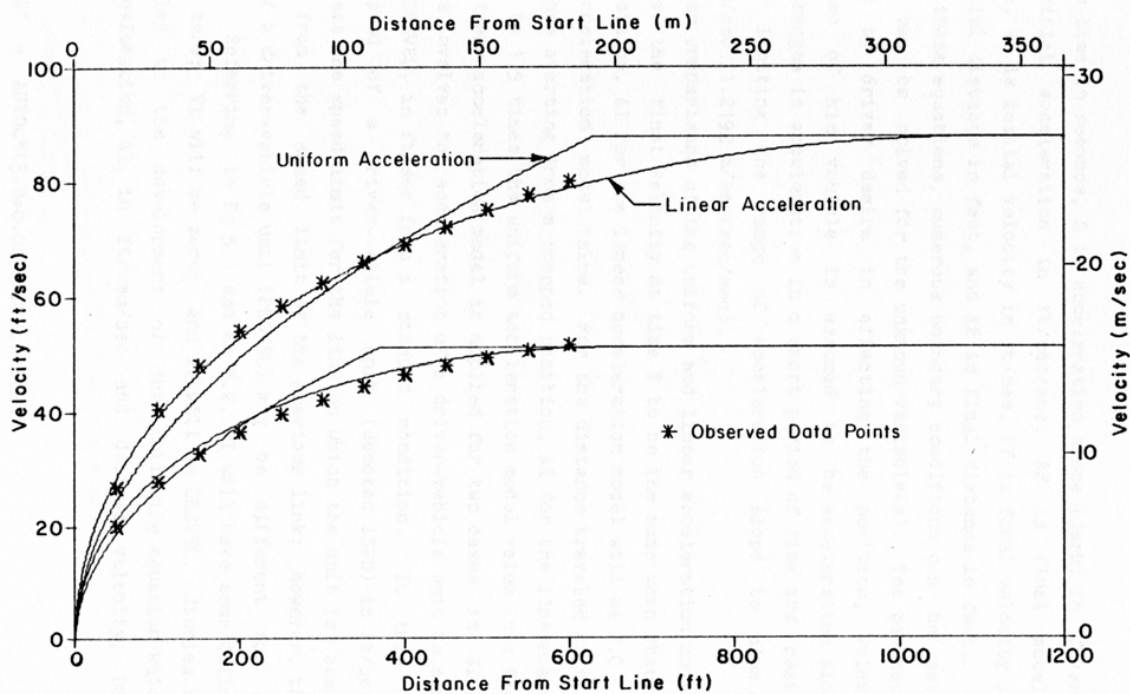
FIGURE 2 Uniform versus linear acceleration and observed data.

Triangular Deceleration

An investigation of existing deceleration models was also undertaken in the early 1970s by Lee and Rioux and it was found that the uniform deceleration model did not match observed behavior accurately when considered on a microscopic scale. Using a Chi-squared goodness-of- fit test, a best-fit uniform deceleration model was calculated and the results plotted (see Figure 3 below) along with observed data points (Beakey 1938 HRB). This figure illustrates that the uniform deceleration model yields a higher velocity during the first part of the deceleration maneuver and, as the velocity approaches zero, produces values that are lower than observed values. A linear deceleration model which hypothesizes use of a zero initial deceleration, maximum deceleration at the instant the driver–vehicle unit stops, and a linear variation of deceleration over time was investigated. Comparisons of this model with observed data (see Figure 3) indicate excellent agreement.

This work led to the development of the triangular deceleration model used in the TEXAS Model. Starting from a moving condition, a driver–vehicle unit will use a maximum negative jerk rate until it reaches the maximum deceleration when the driver–vehicle unit stops. The maximum deceleration is defined by the driver–vehicle unit's current speed and the maximum deceleration for the driver–vehicle unit. If a driver–vehicle unit is to decelerate to a stop, the time to stop and then the distance to stop is calculated each time step increment using current speed, current acceleration–deceleration, and current maximum deceleration. A deceleration to a stop is initiated when the driver–vehicle unit's distance to the location for a stop becomes less than or equal to the distance to stop.
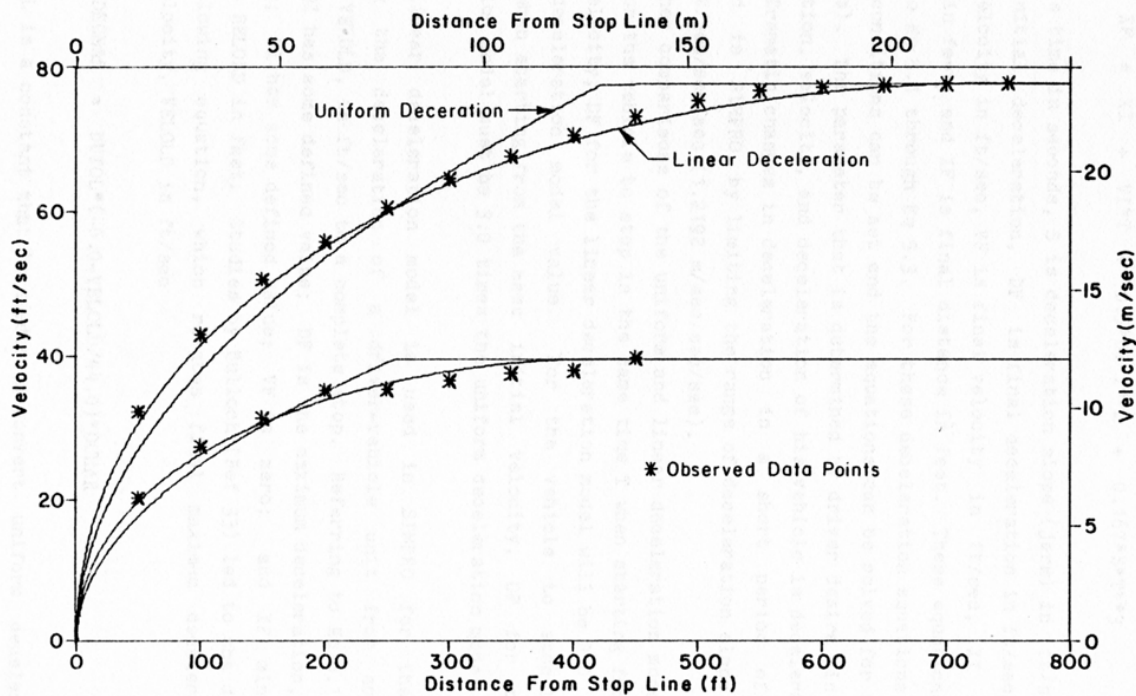
FIGURE 3 Uniform versus linear deceleration and observed data.

Equations of Motion

With the development of the triangular acceleration and triangular deceleration models, it was clear that the equations of motion had to include jerk rate as follows:

$$AN = AO + J * DT$$

$$VN = VO + AO * DT + 1/2 * J * DT^2$$

$$PN = PO + VO * DT + 1/2 * AO * DT^2 + 1/6 * J * DT^3$$

where

<div style="padding-left:3em">

AN = acceleration/deceleration new in ft/s/s;
AO = acceleration/deceleration old in ft/s/s;
DT = time step increment in seconds;
J = jerk rate in ft/s/s/s;
PN= front bumper position new in feet;
PO= front bumper position old in feet;
VN = velocity new in ft/s; and
VO = velocity old in ft/s.

</div>

In the TEXAS Model, only the jerk rate is possibly changed each time step increment and limits are placed on the maximum positive and negative values for jerk rate. Only in collisions are extremely large values of jerk rate used to stop a driver–vehicle unit in about 3 to 6 ft.

Car Following

An investigation of existing car-following models was undertaken in the early 1970s by Lee and Rioux and the noninteger, microscopic, generalized Gazis-Herman-Rothery (GHR) car-following model (Gazis et. al. 1960 OR and May et. al. 1967 HRR 199) was selected because of its superiority and flexibility. If there is no previous driver–vehicle unit (no driver–vehicle unit ahead of the current driver–vehicle unit) then it cannot car follow and thus other logic is used. If the previous driver–vehicle unit is stopped then it cannot car follow and thus other logic is used. The GHR model equation is as follows:

<div style="padding-left:2em">

RelPos = PVPos – PO
RelVel = PVVel – VO
AN = $CarEqA * VO^{CarEqM}/RelPos^{CarEqL} * RelVel$

</div>

where

<div style="padding-left:3em">

AN = current driver–vehicle unit acceleration/deceleration new in ft/s/s;
CarEqA = user-specified GHR model alpha parameter (min = 1, def = 4,000, max = 10,000);
CarEqL = user-specified GHR model lambda parameter (min = 2.3, def = 2.8, max = 4.0)

</div>

CarEqM = user-specified GHR model mu parameter (min = 0.6, def = 0.8, max = 1.0);
PO = current driver–vehicle unit front bumper current position old in feet;
PVPos = previous driver–vehicle unit rear bumper position in feet;
PVVel = previous driver–vehicle unit velocity in ft/s;
RelPos = relative position in feet;
RelVel = relative velocity in ft/s; and
VO = current driver–vehicle unit velocity old in ft/s.

The acceleration–deceleration new AN is not allowed to exceed the maximum deceleration for the vehicle. The jerk rate to go from the current driver–vehicle unit acceleration–deceleration old AO to the current driver–vehicle unit acceleration–deceleration new AN is not allowed to exceed the maximum jerk rate. A conservative car-following distance is defined as follows:

$$RelVel = PVVel - VO$$

$$CarDis = (1.7 * PVVel + 4 * RelVel^2) / DrivChar$$

where

CarDis = car-following distance in feet;
DrivChar = user-specified driver characteristic (<1 = slow, 1 = average, >1 = aggressive, min. = 0.5, and max. = 1.0);
PVVel = previous driver–vehicle unit velocity in ft/s;
RelVel = relative velocity in ft/s;
VO = current driver–vehicle unit velocity old in ft/s.

If the relative velocity RelVel is greater than or equal to zero (the previous driver–vehicle unit is going faster than the current driver–vehicle unit) and the relative position RelPos is greater than some minimum value then the driver–vehicle unit is allowed to accelerate to its desired speed.

If the relative position of the vehicle RelPos is less than or equal to zero then emergency braking is applied. If the relative position of the vehicle RelPos is greater than the 1.2 times the car-following distance CarDis then the driver–vehicle unit is allowed to accelerate to its desired speed.

If the previous driver–vehicle unit is decelerating then calculate where it will stop and calculate the deceleration to stop behind the driver–vehicle unit ahead when it stops and if this deceleration is less than the car-following deceleration then use it.

If the traffic signal changed from green to yellow and the current driver–vehicle unit decides to stop on yellow then calculate a deceleration to a stop at the stop line. If the traffic signal is yellow and the driver–vehicle unit previously decided to stop on yellow then continue a deceleration to a stop at the stop line.

Intersection Conflict Checking and Intersection Conflict Avoidance

Intersection conflict checking (ICC) and intersection conflict avoidance (ICA) are essential algorithms for microscopic traffic simulation. ICC is the algorithm that determines whether a

driver–vehicle unit, seeking the right to enter the intersection, has a predicted time–space trajectory through the intersection that does not conflict with the predicted time–space trajectory through the intersection of all other driver–vehicle units that have the right to enter the intersection. ICA is the algorithm used to simulate the behavior of driver–vehicle units that have the right to enter the intersection and try to maintain a nonconflict time–space trajectory through the intersection with the predicted time–space trajectory through the intersection of other driver–vehicle units that have the right to enter the intersection. Certain driver–vehicle units automatically gain the right to enter the intersection when there are no major collisions within the system: driver–vehicle units on an uncontrolled lane at a sign-controlled or signal-controlled intersection, driver–vehicle units going straight or right on intersection paths that do not change lanes within the intersection when the signal displays circular green, and all driver–vehicle units on signalized lanes when the signal displays protected green for their movement. Typical applications of ICC and ICA include a left-turning driver–vehicle unit crossing opposing leg straight through driver–vehicle units. The TEXAS Model included the ICC algorithm in Version 1.00 released 12/01/1977, added the ICA algorithm in Version 3.10 released 01/31/1992, and enhanced both algorithms in subsequent versions. The functionality and effectiveness of these algorithms has been verified extensively over the years by evaluation of the animation and analysis of the corresponding summary statistics from many, varied simulations.

The TEXAS Model Geometry Processor (GEOPRO) calculates intersection paths starting at the coordinate for the middle of the stop line for an inbound lane, ending at the coordinate for the middle of the entry line for a diamond interchange internal inbound or outbound lane, tangent to the inbound lane, tangent to the outbound lane, and using the largest radius circular arc when needed. The user defines the turn movements that can be made from an inbound lane and the turn movements that can be accepted by an outbound lane. An intersection path consists of four segments in sequence. Each segment may or may not be used in the intersection path and is tangent at each end. The first segment is a tangent section, the second segment is an arc of a circle, the third segment is an arc of a circle, and the fourth segment is a tangent section. After calculating the geometry for all intersection paths, GEOPRO calculates the geometric conflicts between intersection paths including dual left-turn side swipes (the intersection paths come within a user- specified distance but do not cross) and merges into the outbound lane. Finally, GEOPRO creates a list of geometric conflicts ordered by the distance from the beginning of the intersection path down the intersection path centerline to the point of geometric conflict. Data for each geometric conflict include the intersection path information and the conflict angle.

For each intersection path involved in a geometric conflict, the TEXAS Model Simulation Processor (SIMPRO) maintains a linked list of driver–vehicle units whose rear bumper plus a time safety zone has not crossed the point of geometric conflict. When a driver–vehicle unit gains the right to enter the intersection, SIMPRO adds the driver–vehicle unit to the end of the linked list for each geometric conflict for the driver–vehicle unit's intersection path. When a driver–vehicle unit is denied the right to enter the intersection, such as when a driver–vehicle unit decides to stop on a yellow signal indication, SIMPRO removes the driver–vehicle unit from the linked list for each geometric conflict for the driver–vehicle unit's intersection path. As the rear bumper plus a time safety zone crosses the point of geometric conflict, SIMPRO removes the driver–vehicle unit from the linked list for the geometric conflict for the driver–vehicle unit's intersection path.

To process the intersection conflicts for ICC for a driver–vehicle unit on an inbound lane or diamond interchange internal inbound lane that has not gained the right to enter the

intersection, SIMPRO first checks whether there are any geometric conflicts for the driver–vehicle unit's intersection path and if there are none, then intersection conflicts are clear. Next, SIMPRO processes each geometric conflict for the driver–vehicle unit's intersection path in distance order. If a geometric conflict does not have a driver–vehicle unit whose rear bumper plus a time safety zone has not crossed the point of geometric conflict, then the geometric conflict is clear and the next geometric conflict is tested, else this geometric conflict is processed. In this discussion, "I", "me", or "my" refers to the driver–vehicle unit being processed while "he", "him", or "his" refers to the next driver–vehicle unit whose rear bumper plus a time safety zone has not crossed the point of geometric conflict. The time for my front bumper to arrive at the geometric conflict (TCM), velocity at the geometric conflict for me (VCM), acceleration at the geometric conflict for me (ACM), and jerk rate at the geometric conflict for me (SCM) are predicted using my current distance to the geometric conflict, velocity, acceleration, jerk rate, driver characteristics, vehicle characteristics, speed limit for my intersection path, and information about any lead driver–vehicle unit that must be car-followed. The time for his front bumper to arrive at the geometric conflict (TCH), velocity at the geometric conflict for him (VCH), acceleration at the geometric conflict for him (ACH), and jerk rate at the geometric conflict for him (SCH) are predicted using his current distance to the geometric conflict, velocity, acceleration, jerk rate, driver characteristics, vehicle characteristics, speed limit for his intersection path, and information about any lead driver–vehicle unit that must be car-followed. A mini-simulation is used by SIMPRO to determine the time it takes the driver–vehicle unit to traverse the specified distance assuming that the driver–vehicle unit can accelerate to its desired speed or speed limit of its intersection path or car follow any lead driver–vehicle unit. The lead driver–vehicle unit, if any, is assumed to continue its current jerk rate. The velocity, acceleration, and jerk rate of the driver–vehicle unit when it has traversed the specified distance is also calculated. For ICC and ICA purposes, the lead gap is the space between my rear bumper and his front bumper when I go ahead of him through the geometric conflict whereas the lag gap is the space between his rear bumper and my front bumper when I go behind him through the geometric conflict.

SIMPRO then calculates the time for the front safety zone for him (TFZ) and the time for the rear safety zone for him (TRZ) will arrive at the geometric conflict (see the top diagram in Figure 4) using the following equations:

$$\text{ERRJUD} = \text{if TCH} > 5 \text{ then max}(0.0, \text{PIJR}*(\text{TCH}-5.0)/7.0), \text{ else } 0;$$
$$\text{TPASSM} = \text{LVAPM/VCM};$$
$$\text{TPASCM} = \text{DISCLM/VCM} \quad \text{TPASSH} = \text{LVAPH/VCH} \quad \text{TPASCH} = \text{DISCLH/VCH};$$
$$\text{TFZ} = \text{TCH} - \text{TPASSM} - \text{TPASCM} - (\text{TLEAD} - \text{APIJR}) - \text{PIJR} - \text{ERRJUD}/2;$$
$$\text{TRZ} = \text{TCH} + \text{TPASSH} + \text{TPASCH} + (\text{TLAG} - \text{APIJR}) + \text{PIJR} + \text{ERRJUD}/2$$
$$+ \text{TPASCM}$$

where

APIJR = average PIJR time for all driver–vehicle units in the entire traffic stream in seconds (calculated by the TEXAS Model DVPRO);
DISCLH = safety distance for him for merge into the same outbound lane in feet;
DISCLM = safety distance for me for merge into the same outbound lane in feet;
ERRJUD = error in judgment in seconds for TCH values greater than 5;
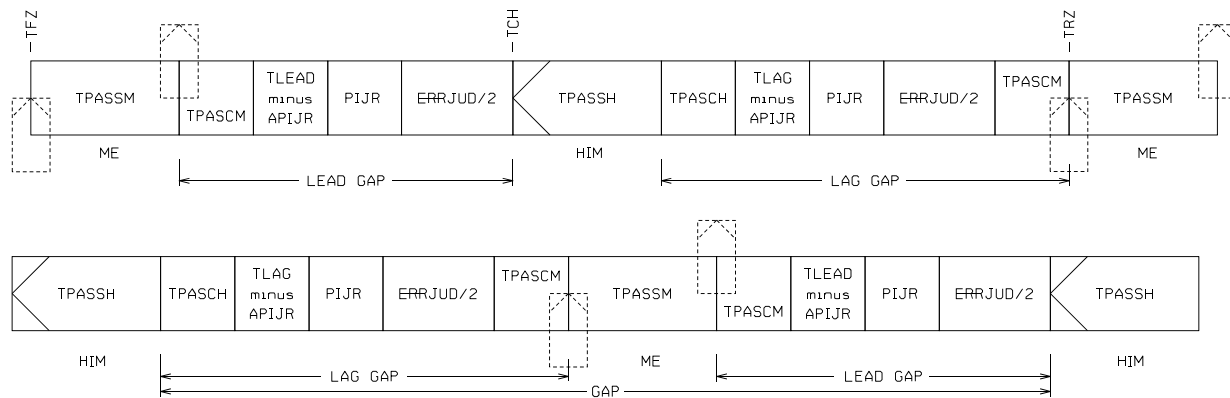
FIGURE 4 TEXAS Model intersection conflict checking gap calculations.

LVAPH = length of vehicle along the intersection path for him at his current position in feet;

LVAPM = length of vehicle along the intersection path for me at my current position in feet;

PIJR = Perception, identification, judgment, and reaction time for the current driver–vehicle unit in seconds;

TCH = time for his front bumper to arrive at the geometric conflict in seconds;

TFZ = the time for the front safety zone for him in seconds;

TLAG = user-defined lag time gap for ICC in seconds (min = 0.5, def = 0.8, max = 3.0);

TLEAD = user-defined lead time gap for ICC in seconds (min = 0.5, def = 0.8, max = 3.0);

TPASCH = time for his driver–vehicle unit to pass through the geometric conflict because of a merge into the same outbound lane in seconds (0, if no merge);

TPASCM = time for my driver–vehicle unit to pass through the geometric conflict because of a merge into the same outbound lane in seconds (0, if no merge);

TPASSH = time for his driver–vehicle unit to pass through the geometric conflict in seconds;

TPASSM = time for my driver–vehicle unit to pass through the geometric conflict in seconds;

TRZ = time for the rear safety zone for him in second;

VCH = velocity at the geometric conflict for him in ft/s; and

VCM = velocity at the geometric conflict for me in ft/s.

The time period from TFZ until TRZ is blocked for me by his driver–vehicle unit. See the bottom diagram in Figure 4 to look at the time sequences from a gap perspective. If I can go safely in front of him (TCM is less than TFZ) or I can go safely behind him (TCM is greater than TRZ), then there is no conflict with his driver–vehicle unit at this geometric conflict. If I am blocked by his driver–vehicle unit at this geometric conflict (TCM is greater than or equal to TFZ and TCM is less than or equal to TRZ), then there is a conflict with his driver–vehicle unit at this geometric conflict. If there is a conflict, then the ICC process is completed with a conflict found.

If there is no conflict, I go behind him (TCM is greater than TFZ), and there is another driver–vehicle unit whose rear bumper plus a time safety zone has not crossed the point of geometric conflict, then I check the next driver–vehicle unit whose rear bumper plus a time safety zone has not crossed the point of geometric conflict. If there is no conflict and I go before him (TCM is less than or equal to TFZ), then I check the next geometric conflict for his intersection path because if I can go before him, then I can go before all other driver–vehicle units behind him. If all geometric conflicts for his intersection path have been checked and there are no conflicts, then the ICC process is completed with no conflict found. There are many special cases accommodated within the actual code when the geometric conflict is a merge, when there is a major collision somewhere within the system, when the other driver–vehicle unit is stopped and blocked by a major collision, when there is an emergency driver–vehicle unit in the system, or when a driver–vehicle unit is currently processing a forced go or forced run the red signal VMS message.

ICA is the algorithm used to simulate the behavior of driver–vehicle units that have the right to enter the intersection and try to maintain a nonconflict time–space trajectory through the intersection with the predicted time–space trajectory through the intersection of other driver–vehicle units that have the right to enter the intersection. The linked list of driver–vehicle units whose rear bumper plus a time safety zone has not crossed the point of geometric conflict as described for ICC is also used for ICA. The jerk rate used for ICA (SLPCON) is initialized to 0.0.

To process the intersection conflicts for ICA for a driver–vehicle unit on an inbound lane or diamond interchange internal inbound lane that has gained the right to enter the intersection or a driver–vehicle unit that is within the intersection, SIMPRO uses a similar process as described for ICC. TCM, TCH, TFZ, TRZ, and the other variables are calculated in the same manner and the same tests are performed to determine whether there is a conflict. The difference between the ICC and ICA process is the action that is taken when a conflict is found. A variable TIM is calculated based upon TCH, the turn movement for my intersection path, the turn movement for his intersection path, and whether there is a new green signal setting for me. TIM gives priority to a straight driver–vehicle unit over a turning driver–vehicle unit when they are both predicted to arrive at the geometric conflict at approximately the same time. If my turning movement is straight and his turning movement is straight, then TIM is set to TCH. If my turning movement is straight and his turning movement is left or right, then if I have a new green signal setting, then set TIM to TCH – 1.0, else set TIM to TCH + 1.5. If my turning movement is left or right and his turning movement is straight, then set TIM to TCH – 1.5. If my turning movement is left or right and his turning movement is left or right, then set TIM to TCH. Finally, if I am not an emergency driver–vehicle unit and he is an emergency driver–vehicle unit, then set TIM to TCH – 5.0. The jerk rate SLPTCM required for me to travel from my current position to the geometric conflict in time TCM starting with my current velocity and acceleration is calculated. This jerk rate represents the average value from the prediction process. If I have already passed the geometric conflict (TCM is less than or equal to 0.0), then nothing is done for this geometric conflict and the next driver–vehicle unit or the next geometric conflict is processed.

The following logic is used when I am trying to go in front of him (TCM is less than or equal to TIM) therefore I try to accelerate to avoid the conflict. If the front safety zone for him has already arrived at the geometric conflict (TFZ is less than or equal to 0.0), then I should accelerate as fast as possible (set SLPTFZ to six times the critical jerk rate CRISLP). If the front safety zone for him has not already arrived at the geometric conflict (TFZ is greater than

0.0), then I should accelerate to go in front of him (set SLPTFZ to the jerk rate required for me to travel from my current position to the geometric conflict in time TFZ starting with my current velocity and acceleration). A temporary jerk rate SLPTMP is set to the maximum of (SLPTFZ – SLPTCM) and 0.0. If I need to accelerate more than normal (SLPTMP is greater than 0.0), and there is no driver–vehicle unit ahead that I must car follow, and the temporary jerk rate is greater than the jerk rate used for ICA (SLPTMP is greater than SLPCON), then set SLPCON to SLPTMP. If I need to accelerate more than normal (SLPTMP is greater than 0.0), and there is a driver–vehicle unit ahead that I must car follow, and my speed is less than my desired speed, and the distance between me and the driver–vehicle unit ahead that I must car follow is greater than the car following distance, and the temporary jerk rate is greater than the jerk rate used for ICA (SLPTMP is greater than SLPCON), then set SLPCON to SLPTMP. The next driver–vehicle unit or the next geometric conflict is processed. This procedure will find the maximum positive jerk rate needed to accelerate to go in front of any driver–vehicle unit where a conflict has been found.

The following logic is used when I am trying to go behind him (TCM is greater than TIM) therefore I try to decelerate to avoid the conflict. If his rear safety zone has not reached the geometric conflict (TRZ is greater than 0.0), then I should decelerate to go behind him (set SLPTRZ to the jerk rate required for me to travel from my current position to the geometric conflict in time TRZ starting with my current velocity and acceleration). A temporary jerk rate SLPTMP is set to the minimum of 4.5 × (SLPTFZ – SLPTCM) and 0.0. If I need to decelerate more than normal (SLPTMP is less than 0.0), then set SLPCON to SLPTMP and the ICA checking process is completed. This procedure will find the negative jerk rate needed to decelerate to go behind the first driver–vehicle unit where a conflict has been found. If SLPCON is not set to SLPTMP, then the next driver–vehicle unit or the next geometric conflict is processed.

If the jerk rate used for ICA has been set (SLPCON is not equal to 0.0), then SLPCON is added to the jerk rate calculated for this driver–vehicle unit (SLPNEW) if it is the critical value. There are many special cases accommodated within the actual code when the geometric conflict is a merge, when there is a major collision somewhere within the system, when the other driver–vehicle unit is stopped and blocked by a major collision, when there is an emergency driver–vehicle unit in the system, or when a driver–vehicle unit is currently processing a forced go or forced run the red signal VMS message.

Sight-Distance Restriction Checking

The user defines the coordinates of all critical points needed to locate sight obstructions in the intersection area and the TEXAS Model Geometry Processor (GEOPRO) calculates the distance that is visible between pairs of inbound approaches for every 25-ft increment along each inbound approach. The TEXAS Model Simulation Processor (SIMPRO) checks sight distance restrictions. Each driver–vehicle unit on an inbound approach assumes that it must stop at the stop line until it gains the right to enter the intersection. If the inbound lane is stop sign controlled or signal controlled, the assumption is made that sight distance restrictions are not critical and therefore do not need to be checked. If adequate sight distance is not available to a unit stopped at the stop line, this will not be detected in SIMPRO.

For driver–vehicle units on inbound lanes to an uncontrolled intersection, if there are units stopped at a stop line waiting to enter the intersection and the inbound driver–vehicle unit

being examined is not stopped at the stop line, the approaching driver–vehicle unit will continue to decelerate to a stop at the stop line without checking sight distance restrictions again until it is stopped at the stop line or until there are no driver–vehicle units stopped at the stop line. This procedure eliminates unnecessary computations and gives the right of way to other driver–vehicle units already stopped at the stop line when the intersection is uncontrolled. If there are no sight-distance restrictions for driver–vehicle units on an inbound approach then intersection conflicts are checked (see the ICC discussion above). If (*a*) a driver–vehicle unit is on an uncontrolled lane approaching a yield-sign–controlled, (*b*) the driver–vehicle unit is stopped at the stop line, or (*c*) the intersection path of the driver–vehicle unit has no geometric intersection conflicts then it is assumes that there are no sight-distance restrictions.

The maximum time from the end of the inbound lane that the driver–vehicle unit is permitted to begin checking sight-distance restrictions, so that it may decide to proceed to ICC if sight-distance restrictions are clear, is initially set to 3 s for all intersections. This prohibition prevents the driver–vehicle unit from gaining the right to enter the intersection when it is relatively far away from the intersection and thereby unnecessarily affecting the behavior of driver–vehicle units on other inbound approaches. If the inbound lane is an uncontrolled lane approaching a yield-sign–controlled intersection, the time is increased by 2 s plus the time for the lead safety zone for ICC. This longer time allows driver–vehicle units on the uncontrolled lanes to gain the right to enter the intersection ahead of other driver–vehicle units on the yield-sign-controlled lanes. If the intersection is uncontrolled then the time is reduced to 2 s.

In SIMPRO, the time required for the driver–vehicle unit being checked to travel to the end of the lane is predicted. If this predicted time is greater than the maximum time from the end of the lane that the driver–vehicle unit may decide to proceed to ICC then the driver–vehicle unit cannot clear its sight distance restrictions and it must check again in the next time-step increment.

The order in which sight-distance restrictions are checked by SIMPRO is determined by the sequence in which intersection conflicts might occur. The sight-distance restriction associated with the longest travel time to an intersection conflict is checked first then other sight-distance restrictions are checked in descending order of travel time to the intersection conflict. This order of checking facilitates early detection of an opportunity to pass in front of a driver–vehicle unit approaching on a sight-restricted lane. Checking continues until all inbound approaches which have possible sight-distance restrictions with the subject inbound approach are cleared.

To check sight-distance restrictions in SIMPRO, the time required for a fictitious driver–vehicle unit, traveling at the speed limit of the approach, to travel from a position that is just visible on the inbound approach to the point of intersection conflict is predicted. Next, the time required for the driver–vehicle unit being examined to travel to the point of intersection conflict is predicted. This prediction assumes that the driver–vehicle unit under examination has gained the right to enter the intersection and that it may accelerate to its desired speed. If the unit being checked may not safely pass through the point of intersection conflict ahead of the fictitious driver–vehicle unit then it may not clear its sight-distance restrictions and it must check again in the next time-step increment, otherwise, it clears the sight-distance restriction and continues checking other sight-distance restrictions.

This procedure ensures that a driver–vehicle unit may safely enter the intersection even if a driver–vehicle unit were to appear from behind the sight-distance restriction just after the decision to enter the intersection was made.

Lane Changing

An investigation of lane-changing models was undertaken in the early 1970s by Lee and Ivar Fett (Fett 1974 thesis). Fett collected and analyzed the field data, developed the original lead and lag-gap acceptance decision models, and used a cosine curve for the lateral position for a lane change.

Rioux developed the concept of distinguishing between two types of lane changes: (*a*) the forced lane change wherein the currently occupied lane does not provide an intersection path to the driver–vehicle unit's desired outbound approach and (*b*) the optional lane change wherein less delay can be expected by changing to an adjacent lane which also connects to the driver–vehicle unit's desired outbound approach. Later, Rioux added cooperative lane changing and a lane change to get from behind a slower vehicle.

When a lane change is forced, a check is made to determine whether an alternate lane is geometrically available adjacent to the current position of the driver–vehicle unit being examined and is continuous to the intersection ahead. In the case of the alternate lane not being accessible from the current position, but available ahead, one of the two following conditions exists: (*a*) there is a lead driver–vehicle unit in the alternate lane ahead in which case the driver–vehicle unit sets the lane change jerk rate to car follow the lead driver–vehicle unit in the alternate lane or (*b*) there is not a lead driver–vehicle unit in the alternate lane ahead in which case the lane change jerk rate is set to stop the driver–vehicle unit at the end of the alternate lane. If the end of the alternate lane has already been passed by the driver–vehicle unit when the check for an available alternate lane is made then the driver–vehicle unit is forced to choose one of the available intersection paths leading from the currently occupied lane and abandon the original destination. Otherwise, the driver–vehicle unit checks for an acceptable gap for lane changing.

When a lane change is optional, SIMPRO delays further lane-change checking until the driver–vehicle unit is dedicated to an intersection path. If there are no lane alternates adjacent to the current lane then the lane change status flag is set to no longer consider a lane change. If the driver–vehicle unit is the first unit in the current lane and its intersection path does not change lanes within the intersection then the lane change status flag is set to no longer consider a lane change. The expected delay is then computed for the driver–vehicle unit's current lane as well as for its alternate lanes. If less delay can be expected if the driver–vehicle unit changes into one of the alternate lanes then that lane is checked for the presence of an acceptable lead gap and an acceptable lag gap otherwise the process is repeated the next time step increment. If there is an acceptable lead gap and an acceptable lag gap then the driver–vehicle unit is logged out of the current lane, logged into the new lane, and the lane change is initiated.

When the lead gap or the lag gap is not acceptable, the driver–vehicle unit tries to maneuver itself to make the gaps acceptable the next time step increment by accelerating, decelerating, or asking the lag driver–vehicle unit to car follow the current driver–vehicle unit to increase the lag gap (this is cooperative lane changing).

SIMPRO keeps track of the lateral position for the lane change old LatPosOld in feet which starts at the value for the total lateral distance for a lane change in feet TLDIST and decreases to zero when the lane change maneuver is completed. The lateral position of the lane change is computed using a cosine curve. Each time step increment, the current position on the cosine curve XOLD and the new position on the cosine curve XNEW are calculated as follows:

XTOT = 3.5 * VO / (DrivChar * VehChar)

TLDIST = 1/2 * LanWidOrg + 1/2 * LanWidNew

XOLD = XTOT * ACOS [2 * ABS(LatPosOld) / TLDIST – 1] / PI

XNEW = XOLD + VO * DT + 1/2 * AO * Power (DT,2) + 1/6 * JN * Power (DT,3)

where

AO =	current driver–vehicle unit acceleration/deceleration old in ft/s/s;
DrivChar =	user-specified driver characteristic (<1 = slow, 1 = average, >1 = aggressive, min. = 0.5, max. = 1.5);
JN =	current driver–vehicle unit jerk rate new in ft/s/s/s;
LanWidNew =	new lane width in feet;
LanWidOrg =	original lane width in feet;
LatPosOld =	lateral position for the lane change old in feet;
TLDIST =	total lateral distance for a lane change in feet;
VehChar =	user-specified vehicle characteristic (<1.0 = sluggish, 1 = average, >1 = responsive, min. = 0.5, max. = 1.5);
VO =	current driver–vehicle unit velocity old in ft/s;
XNEW =	new position on the cosine curve in feet;
XOLD =	current position on the cosine curve in feet; and
XTOT =	total length of the lane change in feet.

   If the new position on the cosine curve XNEW is greater than 95% of the total length of the lane change XTOT then the lane change is completed. The lateral position for the lane change new LatPosNew is calculated and stored as follows:

LatPosNew = 1/2 * TLDIST * [1 + COS(PI * XNEW / XTOT)]

where

LatPosNew = lateral position for the lane change new in feet.

   If lateral position for the lane change new LatPosNew is less than 0.3 ft then the lane change is completed. Note that if the driver–vehicle unit speeds up then the total length of the lane change XTOT increases which causes the lane change to lengthen.
   In 2008, Thomas W. Rioux extended the maximum lane length from 1,000 to 4,000 ft (Rioux et. al. 2008 DTRT57-06-C-10016-F). This enhancement caused an additional optional lane change to be added before or after the intersection to move a driver–vehicle unit from behind a slower driver–vehicle unit. If the adjacent lane did not have an intersection path to the driver–vehicle unit's desired outbound approach, a lane change that would temporarily use the adjacent lane, pass the slower moving driver–vehicle unit, and lane change back into the original lane was performed if possible.

Crashes

If the front bumper position of the driver–vehicle unit (lag driver–vehicle unit) is greater than the rear bumper position of the driver–vehicle unit ahead (lead driver–vehicle unit) then there is a crash. These were called "clear zone intrusions". A message giving the details of the lead driver–vehicle unit and the lag driver–vehicle unit involved in the "clear zone intrusion" was output and the "clear zone intrusions" were counted. The lag driver–vehicle unit defied physics by placing itself 3 feet behind the lead driver–vehicle unit traveling at the speed of the lead driver–vehicle unit and with zero acceleration–deceleration and jerk rate and the traffic simulation continued normally. Only crashes between a lead driver–vehicle unit and a lag driver–vehicle unit were detected.

In 2008, Thomas W. Rioux added the option to stop a driver–vehicle unit involved in a "major" crash using crash deceleration and remain stopped for the remainder of the simulation (Rioux et al. 2008 DTRT57-06-C-10016-F). This involved defining a "major" crash.

Additionally, a crash between driver–vehicle units on different intersection paths was detected. Finally, code was added to cause other driver–vehicle units to react to driver–vehicle units involved in a "major" crash by slowing down as they passed near a crash if the driver–vehicle unit was not blocked by the "major" crash. After the driver–vehicle unit stopped because it was blocked by the "major" crash and a stochastically generated response time had elapsed, the driver–vehicle unit could possibly reverse a lane change maneuver if the driver–vehicle unit was still in the original lane or choosing a different intersection path to a possibly different desired outbound approach.

CONCLUSION

This paper chronicles the evolution of the TEXAS Model which was developed by the CTR UT at Austin beginning in the late 1960s. Topics include the TEXAS Model simulation animation from the early 1970s through 2008 and the early traffic flow theory concepts of triangular acceleration, triangular deceleration, equations of motion, car following, intersection conflict checking, intersection conflict avoidance, sight-distance restriction checking, lane changing, and crashes. The TEXAS Model is being enhanced to include Connected Vehicle messages by Harmonia Holdings Group and Rioux to be a test bed for Connected Vehicle applications.

The TEXAS Model source code is available for use by the public under the GNU General Public License as published by the Free Software Foundation. The source code for the TEXAS Model may be downloaded from http://groups.yahoo.com/neo/groups/TEXAS_Model (standard version) and http://www.etexascode.org (version with messaging).

The TEXAS Model Animations may be watched from YouTube (or search YouTube for "TEXAS Model for Intersection Traffic Animation"):

     1970s: http://www.youtube.com/watch?v=1z4WIeIOfbw
     1980s: http://www.youtube.com/watch?v=S0utMJ9fZls
     1990s: http://www.youtube.com/watch?v=PcU6WcaOAcE
     2000s: http://www.youtube.com/watch?v=oah6nCGKwig

     Most of the references may be downloaded from Files at

- http://groups.yahoo.com/neo/groups/TEXAS_Model_Documentation1:
  – 00000000_READ_ME.TXT,
  – 00000001_TEXAS_Model_Development_History.txt,
  – 19730126_TexITE.zip 19730500_Rioux_thesis.zip, z01, and z02,
  – 19740500_Fett_thesis.zip19770000_TRB_TRR_644.zip,
  – 19771200_CTR_Research_Report_184-1.zip, z01, z02, z03, z04, and z05,
  – 19771200_CTR_Research_Report_184-2.zip, z01, z02, z03, z04, z05, z06, and z07,
  – 19770700_CTR_Research_Report_184-3.zip and z01;
- http://groups.yahoo.com/neo/groups/TEXAS_Model_Documentation2:
  – 19771200_Rioux_dissertation.zip, z01, z02, z03, z04, z05, z06, z07, z08, z09, and z10,
  – 19780700_CTR_Research_Report_184-4F.zip,
  – 19801100_Torres_Evaluation_of_TEXAS_Model.zip,
  – 19830800_CTR_Research_Report_250-1.zip, z01, z02, z03, z04, z05, z06, and z07;
- http://groups.yahoo.com/neo/groups/TEXAS_Model_Documentation3:
  – 19851100_CTR_Research_Report_361-1F.zip and z01,
  – 19890100_CTR_Research_Report_443-1F.zip, z01, z02, z03, and z04,
  – 19910800_CTR_TEXAS_Model_Version_3_0_Documentation.zip, z01, z02, and z03,
  – 19930100_CTR_Research_Report_1258-1F.pdf ,
  – 19931100_CTR_TEXAS_Model_Version_3_20_Documentation.zip, z01, and z02 ,
  – 20040824_RiouxEngineering_DTRS57-04-C-10007_report.pdf ,
  – 20050800_CTR_DTFH61-03-C-00138.pdf,
  – 20080731_RiouxEngineering_DTRT57-06-C-10016_report.pdf,
  – 20100110 TRB Intersection Conflict Checking and Avoidance.pdf (not accepted),
  – 20120122 TRB Simulating Crashes and Creating SSAM Files.pdf,
  – 20120122 TRB Simulating Crashes and Creating SSAM Files.ppt,
  – Evolution_of_Animation_of_the_TEXAS_Model.ppt,
  – TEXAS_Model_for_Intersection_Traffic.ppt,
  – TEXAS_Model_for_Intersection_Traffic_Section_508.ppt, and
  – TEXAS_Model_Online_Documentation.htm.

ACKNOWLEDGMENTS

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History of VISSIM's Development

PETER VORTISCH
Karlsruhe Institute of Technology

In this paper I give my personal view on the development of VISSIM, which is probably the most widely used commercial traffic simulation tool in practice and in academia (counting the number of TRB papers using VISSIM). I joined the simulation group headed by Rainer Wiedemann at Karlsruhe University in 1985 as a student assistant and have taken part in VISSIM's development in several roles from this point on, including leading the VISSIM development at PTV for about 10 years and now heading the same institute at the university where the whole thing started. But the success of VISSIM definitely was a team effort, and there were at least two other key players involved: Martin Fellendorf, now a professor at the University of Graz, who had the idea of making VISSIM a commercial product and driving its international presence, and Lukas Kautzsch, who was never interested in getting academically visible, but contributed most significantly to both the software and the modeling side. I am writing this paper because I am probably the person who was involved over the longest timespan.

This report will end in 2009, not because VISSIM's development would come to an end here, but because on one hand I wanted to keep a 5-year distance to the current product in order to avoid the impression of marketing and on the other hand because I left the VISSIM development team in 2010 to go back to the university institute from which VISSIM originated.

ACADEMIC ROOTS

In Germany, traffic microsimulation started when Rainer Wiedemann, an associate professor at the Institute for Transport Studies at the University of Karlsruhe (lead by Wilhelm Leutzbach), wrote a thesis about "The Simulation of Traffic Flow" in 1974 (*1*) (Figure 1). The thesis was in German and never really published in English in its full version. He introduced the psycho-physical car-following model later known as "Wiedemann 74" and implemented it in Algol on the university's mainframe computer, at this time still using punched Hollerith cards. The idea of the action point model was not originally by Wiedemann, he took it from earlier work of Todosiev et al. (*2*), but his contribution was making it an operative research tool by implementing it on a computer. He called the software "INTAC" (for "interaction" of vehicles) and simply numbered the model versions over the years. INTAC described car following on a single lane.

After this start, a series of PhD dissertations extended the model, e.g., Udo Sparmann developed a first lane changing model for German freeways (*3*) and Ulrich Brannolte developed a model for rural roads (*4*). But the big step towards VISSIM came in 1983 with the PhD thesis of Hans Hubschneider (*5*) (Figure 2). He implemented the existing models and some new models for signal control and public transport in SIMULA-67, a very early object-oriented programming language, and designed a simulation tool that allowed the user to compose an arbitrary network from predefined building blocks without the need of programming. Instead, there was a network description language introduced, already similar to the VISSIM's network file description text file (up to VISSIM 5.40, now it is XML). He called the software tool MISSION, an acronym for

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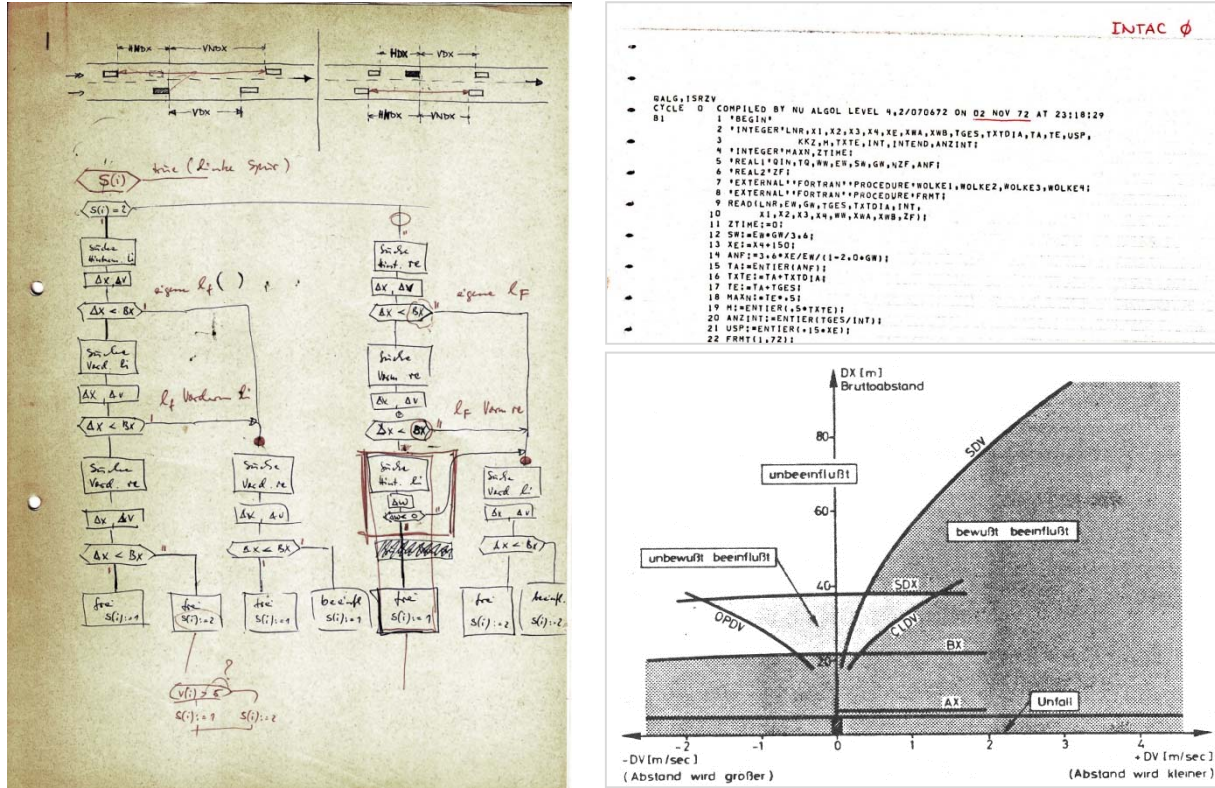
**FIGURE 1 Flowchart sketch by Rainer Wiedemann, an early implementation from 1972
and the dv-dx-diagram from Wiedemann's original work, 1974.**
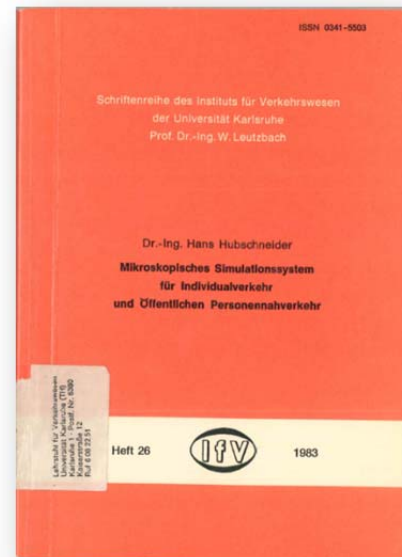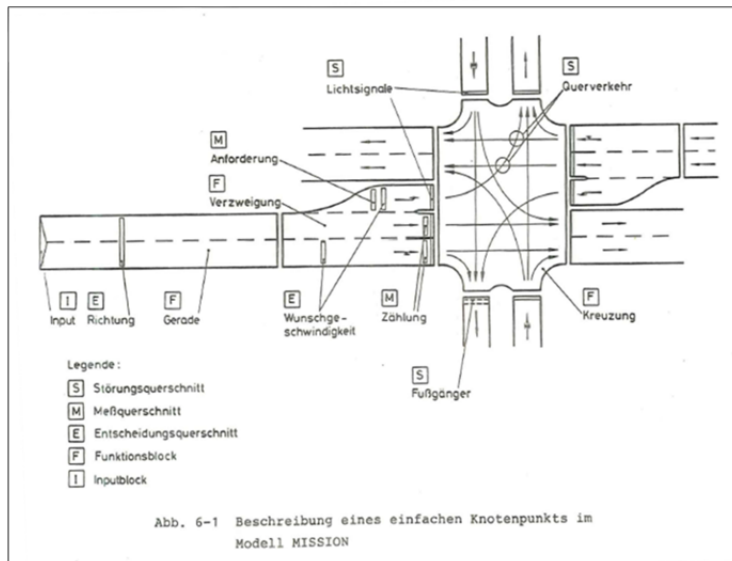
**FIGURE 2 Hans Hubschneider's PhD thesis from 1983 showing
the concept of road network building blocks.**

Mikroskopische Simulation von Individualverkehr und Oeffentlichem Nahverkehr (microscopic simulation of urban private and public transportation).

The availability of MISSION triggered a series of research projects for the Karlsruhe Institute, each contributing to the further development of software and behavior models. Computers made improvements as well, and the time of the PC had come. So it was a natural move for MISSION to migrate from the mainframe to a PC. Since the programming language Simula had disappeared (actually being too far ahead of time), the first PC implementation was done in Modula-2, a programming language designed as the successor of Pascal, but actually did not make it in the end. Our first PC implementation in 1988 was able to simulate about 50 vehicles in real time with simulation time steps of one second on a PC running an 80286 processor.

In those early days the focus of model development was on the operative-driving level, i.e., car following and lane changing. Getting real data was much more effort at that time than today, having no video cameras, no radar sensors in the vehicles, etc. Wiedemann's calibration was mainly done using measurements from loop detectors on the Autobahn A5 close to Karlsruhe, where the institute had a series of pretty close double loops for traffic flow research purposes. But since simulation originated from traffic flow theory, model development already included the idea of calibration and validation. Sometimes, model extension was done pretty straight forward and a bit naïve; when we needed a four-lane freeway simulation for a project but had only a model for three lanes, we just mechanically extended the software to four lanes, hoping the lane changing rules would hold. A research project to actually validating the four-lane model was done not before several years later.

Another source of input to simulation development came with the raise of traffic telematics. We took part in the PROMETHEUS and DRIVE research programs of the European Union (1987–1995) and used microsimulation to evaluate future intelligent transportation systems (ITS) like ACC or even convoy driving. The modeling task at that time was mainly implementing the ITS functionality into the simulation, and calibration and validation were a bit lost. The typical results of our simulations were some clouds of speed–flow points moving up or down due to the impact of the ITS system (something that has not much changed in the last 20 years).

GETTING COMMERCIAL

With a PC implementation of traffic flow simulation available, one could think about applications outside the university. Vehicle actuated signal control became popular at the same time, and Martin Fellendorf could interest Siemens in simulation as a new tool to support traffic engineers designing the signal logic. With this potential customer in mind, PTV took over MISSION as a basis for a commercial product in 1990. (PTV had been founded some years before by the same Hans Hubschneider who developed MISSION in his PhD thesis.) The first thing we did then was re-implement the models in C to build a stronger software platform. That was the moment when MISSION became VISSIM.

On the model side, the focus was now inner-urban traffic around a single intersection with vehicle actuated signals. Saturation flow became the most important calibration value, and we tweaked the cars acceleration behavior (to unrealistic high accelerations) to compensate for the too-long reaction times due to the large simulation time step of one second. Another necessary step was a multianticipative car-following model, first for only two vehicles ahead,

later for a user defined number of leading vehicles. The behavior logic was to compute the reaction to all leading vehicles independently and then realize the minimum acceleration from all these interactions.

To make simulation a tool for a signal control engineer, we had to add two new features on the software side: a graphical network editor and a description language for signal control logic. At PTV we worked a lot with students at that time, and so these features like many others were developed by computer science students as part of their master theses. In 1992, we had a graphical user interface under MS-DOS, but soon moved to the Windows platform and finally released the official VISSIM 1.0 in 1993, although VISSIM was commercially available since 1991 already (Figure 3). From 1994 on, VISSIM was included in Siemens' software suite for traffic engineers under the name SIMULA.

The following years until 1997 were mainly focused on more functionality for signal control engineers. With VAP ("Vehicle Actuated Programming") we introduced a signal control logic programming language, something like BASIC with signal specific commands. In this context, we made a design decision not to integrate signal control in VISSIM directly but to provide an interface to external (software-in-the-loop) signal control. Even our own control language VAP is implemented as separate software and interfaced to VISSIM. We never worked towards a standard with this interface, but since VISSIM was pretty much alone in the market at that time, many signal control vendors simply adopted the interface to be able to test their control logic with VISSIM.

The focus at that time was still on simulating a single intersection, but VISSIM never had a technical restriction concerning the network size; actually it does not even have the notion of an intersection since everything is modeled as a network of links and connectors. The simulated networks started to grow slowly, and even if it was only to model the surrounding intersections of the one for which the signal control was designed. The vehicles in VISSIM got their directions where to drive from what we called turning decisions, i.e., a point in the network where cars get a direction randomly assigned with defined probabilities. That is no longer sufficient, when it matters if the right-turning vehicles at one intersection will be the left turners at the next. So in 1995 VISSIM introduced the concept of routes as series of links in the network that vehicles want to follow. One challenge was to provide a comfortable user interface for the definition of routes, and another was to model the mandatory lane changes necessary to follow the route. This
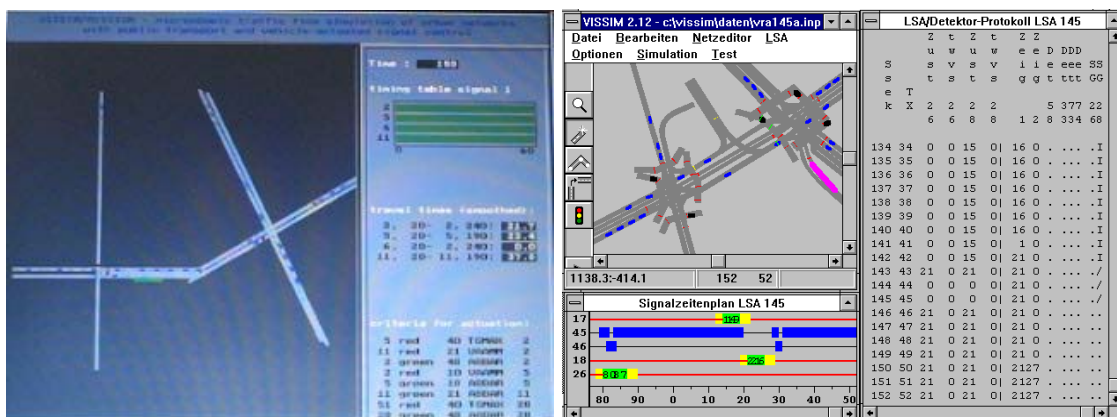
**FIGURE 3 Screenshot of MS-DOS version of VISSIM 1992 and an early
Windows version, 1995.**

was the point where the first elements of tactical driving were introduced, an area of continued research and improvement till today.

Another requirement induced by actuated signal control was the modeling of transit. In Germany signal control was very often traffic actuated because of transit priority, so the simulation had to include transit vehicles like busses and trams. Therefore VISSIM pretty early included functionality to define transit lines with line routes, stops and timetables.

THE "ADVANCE" PROJECT

The next major step for VISSIM was triggered by a new lead customer: Volkswagen. Pollutant emissions had become a major concern, and Volkswagen needed a tool to study vehicle emissions in an urban area. In 1997, they approached PTV, and together we designed an ambitious project that we called the "ADVANCE" project. Volkswagen already had a model to compute vehicle emissions from the current speed and load of an engine, and this model was to be integrated in VISSIM. On the technical side this meant that VISSIM had to handle a lot of new vehicle characteristics, and on the user side user-defined vehicle fleets and vehicle type specific evaluations were necessary. Therefore we introduced user defined vehicle types and the concept of vehicle classes as sets of vehicle types. The challenge on the modeling side was that emission computation needed much more precise accelerations than we had with VISSIM's 1-s time–step. The solution was that we made the time–step user defined, aiming at a resolution of .1 s for a good reproduction of accelerations. Changing the time step might sound like a minor problem, but this one second was often implicitly hardcoded in places in VISSIM so that to identify and change all these places meant going through every part of the software.

The model of emission production in the engine and of the reduction of emissions in the catalytic converter needed as an input the temperatures of engine and converter. The temperature depends on how long the vehicle was running and how much power the engine has produced so far. Even worse, it a car parks for a while, the temperature drops again. Therefore it was not enough to simulate some links in the road network, but the simulation of the whole trips of the vehicles over a day was necessary. What we wanted to reach in the ADVANCE project was the simulation of 1 day of traffic for the whole city of Braunschweig, a medium-sized city in Germany near Volkswagen's headquarters with about 250,000 inhabitants.

To generate the travel demand, we used an existing macroscopic transport demand model and disaggregated the demand down to individual trips based on activity chains. The result was microscopic trip chains for 1 day with a temporal resolution of 1 s and a spatial resolution of 75 travel analysis zones. Of course, the routes for all these trips could not be modeled manually, so this was the point when we needed a route-choice model in VISSIM. In a 2-day workshop together with some Volkswagen researchers we developed a route-choice model based on iterated simulations. Drivers would experience travel times and decide in the next iteration for a route based on these travel times. What we actually did was to reinvent the concept of dynamic assignment, because at that time none of us were aware of the existing theory or the DTA projects in the United States. A year later in 2000, I attended the MIT summer school and finally learned about all the already-existing concepts.

So the ADVANCE project motivated several substantial developments in VISSIM, and we were lucky that we had a lead customer who not only supported the development financially but also allowed us to provide the new functionality within the standard VISSIM product to other

customers. We wrote a TRB paper about the project (*6*), but unfortunately we did not follow the path of an integrated microscopic demand generation and flow simulation, a topic that has been intensively studied in past years.

GOING INTERNATIONAL

In the middle of the 1990s we had a stable product for traffic engineers and a good presence in the German market, especially through the connection to Siemens. It was time to go to other markets. Compared to the market for travel demand modeling software, the simulation market was already at that time rather international, i.e., the relevant commercial products did not reflect a specific national planning philosophy as this was the case with travel-demand models. Besides language support for the user interface and the manual, it looked easy to go to the U.S. market. For the U.S. market we found a partner in Innovative Transportation Concepts, a small consulting company founded by Thomas Bauer from Germany and Jim Dale from Texas. Beginning in 1995, they used VISSIM in their projects and acted as resellers for VISSIM. For us developers in Germany, their input on local requirements was essential for really adapting VISSIM to the U.S. market. For example, they provided the first NEMA signal controller for VISSIM.

Freeway traffic on German Autobahn is different than on U.S. freeways and probably most freeway driving behavior in the world. For U.S. freeways, we modified the lane selection and lane change behavior and calibrated VISSIM using some freeway measurement data. We published a short TRB paper about this calibration (*7*), which did not make it into the TRR journal, but is still the most cited VISSIM paper so far with 140 citations in Google Scholar. The reason is probably not that the paper contains valuable information but that it was used as a kind of standard reference for VISSIM in the absence of a more original VISSIM description. [Today most authors use the VISSIM chapter in Jaume Barcelo's book on traffic flow simulation (*8*) as a reference.]

To be more flexible when calibrating freeway traffic, we added a slightly different version of Wiedemann's car-following model and made more of its parameters available in the user interface. The new Wiedemann model was the result of some private research Rainer Wiedemann did after his retirement. Compared to the original Wiedemann-74 (W-74) model the model we called Wiedemann-99 (W-99) added less stochastic noise and was simpler, e.g., the action threshold for a driver changing from free driving to approaching was now defined by a fixed time-to-collision, whereas before it had used a root function of the speed difference. One problem of Wiedemann-99 was that there has never been a publication about it; instead we got the information from Rainer Wiedemann in the form of some printed pages of basic programming code. So one of the often-asked questions in the hotline from academic users was if we can provide a reference for W-99, and we could not. The other problem was that users were not sure which of the two models to choose. For some years there was a recommendation around to use W-74 for urban traffic and W-99 for freeways, but actually it is difficult to justify that by the model itself.

Another important market for traffic simulation was the U.K. market. The United Kingdom had a strong tradition in using models in transportation planning and was relatively open to the use of traffic flow simulation as well. In 2000, we released VISSIM 3.0, a version that finally brought many small improvements for the normal users after some years with a

strong focus on the ADVANCE project and dynamic assignment. And it was the first VISSIM with the ability to model left-handed driving. Since VISSIM's network model consisted of links and connectors and was agnostic to "intersections" or "road" concepts, left-handed traffic required very little modifications. The most effort actually was caused by the adaptation of the user interface. The breakthrough in the U.K. market finally was that Transport for London established VISSIM as their standard modeling tool for road traffic control.

The next step in internationalization with a strong impact on model development was bringing VISSIM to Asia, especially to India. Whereas traffic in western countries is organized in lanes, or at least can be modeled that way, the heterogeneous traffic on Indian streets is definitely not lane based. To model capacities on such roads, the software must be able to represent the mix of very different two-, three-, and four-wheelers, and to allow a continuous lateral movement within the road or lanes. VISSIM so far had a lane-based architecture, i.e., the road network was represented by links with a defined number of lanes, and the behavior model included a lane-changing model that discretely decided on which lane a driver wanted to drive. There was no lateral position on the lane and no model to control it. But in 2001, long before we had the first user in India, we took part in a research project about capacities of biking lanes for the German *Highway Capacity Manual*. Within this project we had developed the prototype of a continuous lateral movement to model the driving behavior of bikes. This included the extension of the network architecture so that we could position vehicles anywhere laterally on lanes and a model to determine this lateral position. Our simple idea was that the driver wants to keep a speed-dependent lateral safety distance and chooses the lateral position with the highest time-to-collision in driving direction. For Indian traffic, we reactivated this model in 2006 and added some tactical aspects like lateral sorting upstream of intersections. With the help of local academic and commercial partners we calibrated this model so that VISSIM could be used for capacity analysis under heterogeneous traffic conditions. An overview of this work is given by Vortisch and Gopalakrishnan (*9*), in a paper for an Indian conference.

PEDESTRIANS

The last major development effort that I want to report in this paper was the inclusion of a realistic pedestrian behavior model in VISSIM. Pedestrians were available in very early versions of VISSIM because they were needed to, e.g., reduce the capacity of turning traffic at intersections. These early pedestrians have been nothing else than strangely shaped small vehicles with a very simple "driving" behavior. They could not be used for studies of pedestrian movement or pedestrian capacity analysis.

Around 2005 pedestrian simulation became a topic of interest in the world of road traffic flow simulation. So far, pedestrian simulation was mainly used in specialized tools for planning of train stations, for evacuation planning or for animation in movies, but not in combination with car traffic. But suddenly three of the commercial simulation tools talked about integrating pedestrian and vehicular traffic. We analyzed the available models and soon started to talk to Dirk Helbing, a professor at ETH Zurich, who had invented the so called social-force-model for pedestrian movement (*10*). We agreed to build a little prototype in which his pedestrian model was connected to VISSIM using an interface for external movement models, to be able to show something at the next VISSIM user meeting. On our side this meant another extension of the network model, because pedestrians move on areas, not links. In 2006 we were able to show the

first Helbing pedestrians in VISSIM. Around that time we could hire Tobias Kretz, who had just finished his PhD on pedestrian simulation and was well connected in the pedestrian modeling community.

It took another 2 years of development before we finally released pedestrian simulation as a module in VISSIM 5.10 in 2008. Much of the time was spent on the user interface for pedestrian areas, obstacles, stairs, etc., and for pedestrian specific evaluations. Many aspects of pedestrian modeling were similar to what we had for vehicles, e.g., definition of routes, but they were still different enough to require separate treatment. On the modeling side, the interaction of vehicles and pedestrians and the connection of transit vehicles and pedestrians as their passengers were the main areas of work. At the end the pedestrian part in VISSIM had grown pretty large, and there was a potential market in the pedestrian-only simulation, so that PTV marketing decided in 2011 to have a pedestrian-only version of VISSIM under the separate product name VISWALK.

CONCLUSION

In retrospect, the success of VISSIM was supported in different phases of its lifetime by different opportunities. As most commercial simulation tools VISSIM had academic roots, so that PTV had a good basis to build on. But the crucial step is to have someone like Martin Fellendorf at the right point in time with the idea to make a commercial product from this academic research tool. In the first years as a product, VISSIM's development was guided by strong lead users with their own visions what they want to achieve with simulation. Later, when the user base had grown larger, the role of product management became more important to balance the uncountable requests for feature improvements from the existing users and the exploitation of new application fields for new users. And in the time I surveyed, a close connection to the research community was helpful, both by keeping VISSIM visible in the academic world and by listening to upcoming new ideas.

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APPENDIX: EARLY CONTRIBUTORS, IN ORDER OF VISSIM APPEARANCE

| Rainer Wiedemann | Hans Hubschneider | Peter Vortisch | Martin Fellendorf | Lukas Kautzsch |

Evolution of SUMO's Simulation Model

Michael Behrisch
Laura Bieker
Jakob Erdmann
Melanie Knocke
Daniel Krajzewicz
Peter Wagner
Institute of Transportation Systems
German Aerospace Centre (DLR)

This text gives a short account on DLR's open source microsimulation tool SUMO. It does so mostly by reporting some of the applications cases that had been performed with the help of SUMO. These application cases show that SUMO is a very versatile, timely, and mature research tool which nevertheless is continuously developed further.

A SHORT ACCOUNT OF SUMO

Arguably the first microsimulation model that made it into a journal article was the one introduced by Reuschel in 1950 (*1*). Ever since, a continuous string of new microscopic traffic flow models has been invented (*2–4*). Today, still new models are invented or older ones are improved, and there seems to be no end in sight to this process. Also, since the late of the 1980s, first implementations of such models into microsimulation packages have been reported. The first tools have mainly being used to help with the design and optimization of traffic signals at intersections, but today even large scale simulations are to be performed by such tools. Of course, when going truly large scale, simplification of the underlying dynamics is needed, which is often done with so-called queueing models. An example of this is the MATSim project (*5*).

The implementation of the microscopic traffic simulation SUMO (*6, 7*) started in 2001 as a cooperation project between the DLR and the Centre for Parallel Computing at the University of Cologne. SUMO was from the beginning designed as an open-source project. The major reason for supplying an open-source tool was the observation that many similar applications were built as an intermediate tool needed to evaluate a developed traffic management application or a model of traffic. After closing such a project, the used traffic simulation was usually abandoned. Having a common test bed makes the implementation of an owned evaluation system unnecessary, saving time and allowing concentration on the application, not on the evaluation system. Additionally, it was assumed that the usage of a common test bed increases the comparability of different traffic management applications. Since 2002, SUMO has been used within many of the projects the German Aerospace Centre participated in. The authors admit that in addition that a lot has been learned about traffic and traffic flow by writing and testing the software.

The initial purpose of the simulation was to deliver travel times of a synthetic population of the city of Cologne. The major requirement was therefore to simulate large urban areas as fast as possible. Although SUMO has been used for other purposes, the requirement for a fast simulation of large networks had a strong influence on the design of the simulation suite; a more-

detailed explanation is given in section 3.3. The available hardware was heterogeneous, including desktop computers running the MSWindows operating system, as well as Linux and even Solaris systems. This dictated a strong focus on portability. Now, the SUMO can be run under all major operating systems, including the named ones and additionally MacOS.

Originally, just one microscopic traffic flow was built into SUMO that was the model of Krauß (*8*). This model bears a strong similarity with the Gipps model (*9*), however, it has been radically designed for simplicity. Meanwhile, SUMO hosts a small number of well-known traffic simulation models, like the Intelligent Driver Model (IDM), the Wiedemann model, one of Kerner's three phase models, and a few lesser-known experimental models.

But making software available as open source matters only if there are groups interested in such software. Meanwhile, SUMO is routinely being used in a considerable number of internal projects as well as by a worldwide community. In Krajzewicz (*10*), the evaluation of 362 papers that cite or at least mention SUMO is given. It shows that the number of such publications increases, almost continuously, as visualized in Figure 1. From this analysis, it is known that the majority of the research with SUMO is done within "sole projects", such as masters' theses. But on the other hand, long-term single users are known as well as organizations, mainly universities, which start to use SUMO for teaching purposes.

SOFTWARE DESIGN AND MODEL DEVELOPMENT

Models like the Gipps and IDM are constructed as car-following models. To make them useable for the simulation of traffic flow in a realistic environment (urban or motorway), they need to be extended by more complex tasks. In the following sections the intersection and the lane changing model, respectively, will be discussed. Together with car following, these three form the heart of the microscopic simulation.

However, this is not all. To run a microscopic simulation, not only the behavior of all traffic participants must be defined, the participants and their environment must be defined as well. In other words, the simulation road network including traffic lights, the traffic demand and also the fleet composition must be declared. Modeling the scenario is a task left to the end user
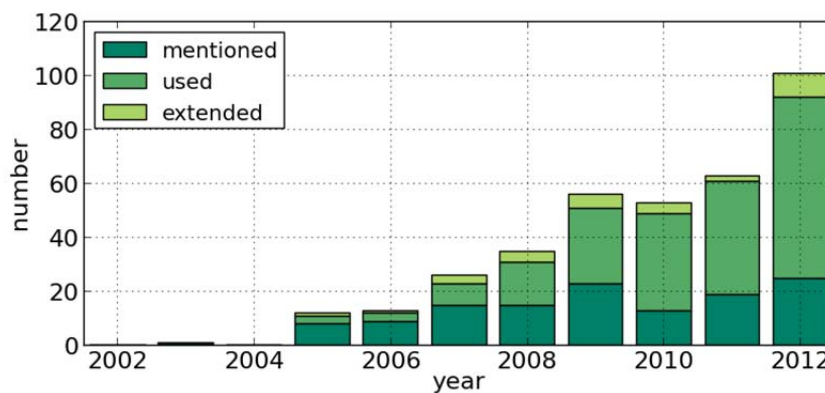
FIGURE 1 The development of the publications that cite SUMO, classified by the role of SUMO within the research.

and it is by no means trivial. To aid and empower the user, SUMO is designed as a suite of applications to support these preparatory tasks. An overview over these supporting applications is given in section 2.3.

Finally, there are a number of simulation tasks which require dynamic control of a running simulation. In section 2.4, the TraCI API of SUMO is described which allows client programs written in different programming languages to control a running SUMO simulation. Usage examples for this type of control are given in section 3.3.

Intersection Model

The behavior of vehicles when approaching and crossing an intersection is of immense importance when simulating traffic microscopically in urban environments. Here, vehicles need to avoid collision with any vehicle that crosses their path. This requires dealing with a number of different schemes for intersection control that are found in reality such as priority intersections, right-before-left rules, and traffic lights. In contrast to car-following models where the ego vehicle typically has no influence on the behavior of its leader vehicle, a vehicle passing an intersection can assume that its presence on the intersection will cause oncoming vehicles to adapt their behavior. For this reason, the intersection model in SUMO is considerably more complex than any of the car-following models. The complexity of intersection models in generally is also the reason why this part of the simulation architecture cannot be as easily exchanged as the car-following model.

During the evolution of SUMO the model has experienced a growing increase in complexity. In the beginning, the model only answered the question whether a vehicle should pass an intersection and this vehicle would then instantly continue driving on the other side of the intersection, seemingly "jumping" across. In later stages of the model, the driving dynamics on the junction were also modeled. This prompted considerations such as the stopping position of left-turning vehicles within the intersection while waiting for a gap in oncoming traffic. Another aspect where the complexity of the model has grown is the acceptance of safe-time gaps when crossing an intersection without having the priority. In older versions of the model, vehicles would not enter an intersection if it meant that other vehicles had to adapt their speed at all. In the current versions, a concept of impatience is implemented where vehicles may enter the junction even if it means that vehicles with priority have to slow down a bit.

For the future evolution of the intersection model it would be desirable to increase the modularity to allow research on alternative models. This might be achievable by dividing the intersection model into smaller parts with well-defined interfaces.

Lane-Changing Model

Another core component of the vehicle dynamics is the lane-changing behavior. This is needed to simulate behavior on multilane roads which occur frequently in urban environments and on motorways. Vehicles change their lane for multiple reasons including mandatory as well as optional maneuvers. The lane-changing model in SUMO currently recognizes four reasons for lane changing:

- Strategic (another lane must be used to continue the current route);
- Cooperative (the vehicle would like to clear the lane for another vehicle);

- Speed gain (the vehicle speed up its travel by changing to a faster lane); and
- Keep right (the vehicle should keep the left lanes clear for faster vehicles).

The lane-changing model not only governs the "motivation" for changing lanes, it is also responsible for adapting vehicle speeds to allow lane-changing maneuvers to take place. This is of immense importance in dense traffic flow because the vehicles need to maintain safe distances to all vehicles on the target lane to avoid collisions later on. Achieving safe distances often require speed changes by the ego vehicle as well as by vehicles on the target lane. Among the questions that typically need to be answered by the lane-change model is whether a blocking vehicle on the target lane should be overtaken or whether it is better to slow down and take this vehicle as the leader.

Due to the different motivations for lane-changing and the large number of traffic situations that must be dealt with (in regard to urgency of lane changing and occupancy of the target lane) the lane-changing model in SUMO is arguably even more complex than the intersection model. Nevertheless, the model is already compartmentalized from the rest of the simulation and different lane-changing models can be selected. The enormous impact of the lane-changing model on simulation behavior could be seen recently when a new model was implemented in SUMO. Motorway scenarios that experienced strong congestion using the older model exhibited freely-flowing traffic when run again with the new model. One important aspect that was changed was the way how vehicles ensure the success of strategic lane changes and the avoidance of deadlocks when two vehicles need to change in opposite directions and thus block each other. An example of this situation to be avoided can be seen in Figure 2.

For the future it is planned to increase the configurability of the implemented lane-changing models by exposing more calibration variables to the end user.

Applications for Scenario Modeling

One of the first major applications was the simulation of large cities, mainly the city of Cologne for supplying travel times to a demand model based on a synthetic population model that was developed in parallel. Quite early, the need to extend available road network representations by simulation-specific information, such as proper right-of-way representations, simulation-specific representations of traffic lights, etc., became obvious. As this information was not given within the
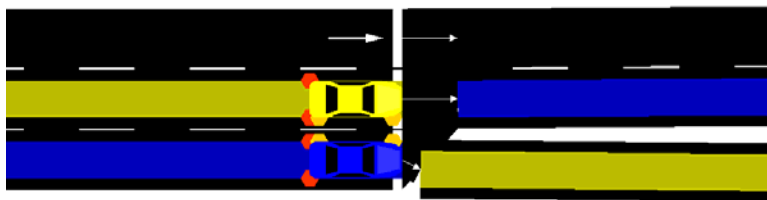
FIGURE 2 Deadlock on a motorway. Two vehicles need to change in opposite directions and block each other's path. In reality, drivers may even change their route to avoid blocking the motorway.

available digital road networks, heuristics for computing them had to be implemented. This computation has to be performed only once for every "imported" road network and as it may take some minutes for large road networks, it was decided to embed it into a dedicated application, not directly into the simulation.

Similar constraints and assumptions about simulation usage apply for the computation of vehicle routes. In most cases, the simulation is used to evaluate some kind of a system that changes the behavior of traffic by changing infrastructure elements, such as traffic lights or by changing the behavior of vehicles. The simulation is used to compare the performance of traffic with such a change against the initial (original) behavior. Usually, the same demand is used to simulate both variants. For larger scenarios, the demand is usually imported from O-D matrices and a traffic assignment is performed. This is usually very time-consuming, since it requires running the same simulation (with a changed set of routes) over and over again until equilibrium is reached. Therefore, the computation of routes is not performed within the simulation either, but by an additional application. This application is responsible for computing routes using travel times obtained from the traffic simulation.

Summarizing, to run a SUMO simulation the user must prepare at least a simulation network file and a demand definition file in a specific XML format. SUMO's approach is to support this work by providing additional tools with a certain purpose. Overall, the suite supplies the following applications:

- **NETCONVERT:** Imports digital road networks in commonly used formats such as OpenStreetMap, VISUM, Vissim, Shapefile, OpenDrive and many more. Information missing in the source networks such as traffic light plans and lane-to-lane connectivity are supplemented heuristically. Road networks can be modified in various ways (i.e., by removing edges, adding more traffic lights).
- **OD2TRIPS:** Disaggregates O-D matrices into individual vehicles departing at specific points in time.
- **DUAROUTER:** Computes fastest paths based on given travel times and implements route choice models for route alternatives. When iterating simulation and routing this can be used to compute the Dynamic User Assignment.
- **DFROUTER:** Computes routes matching given detector flow measurements.
- **JTRROUTER:** Computes routes matching given junction turn ratios.
- **TOOLS:** More than 40 additional applications to process simulation output, prepare input files, compare networks, etc.

The tools allow using a large variety of available data to set up simulation scenarios. Nonetheless, we observe that some user needs are not covered properly, yet. This mainly concerns the generation of a demand for a given area. For instance, when using the JTRROUTER on large areas where only turning ratios at intersections are given, then the routes generated have unrealistic loops. The DFROUTER can only be applied on highway networks, and the O-D matrices that are usually used by DUAROUTER are not always available. Two attempts are followed to close the gap, supporting complete simulation scenarios and the implementation of further tools that estimate a demand for a given area.

TraCI

In many use cases for microscopic traffic simulation, the behavior of the simulation must be adjusted dynamically while the simulation is running. A typical example is the simulation of applications based on vehicular communication (V2X). These V2X applications as well as the communication are not part of SUMO but are controlled and provided by external programs. However, they use information from the simulation such as the proximity of vehicles and they influence the simulation dynamically, i.e., by altering vehicle speeds or routes. The same holds true for the development of new traffic control algorithms in general, like ramp metering, traffic signal controls algorithms, or freeway applications.

To allow for these use cases, SUMO provides the **Tra**ffic**C**ontrol**I**nterface (TraCI) which allows client programs to retrieve information and to influence the simulation over a network socket. To use this functionality, libraries are provided in various programming languages which can be used to write control programs for the simulation. Among the currently supported languages are python, C++, and Java. Exemplary functions from the python library are

- `traci.vehicle.getSpeed(vehID)` and
- `traci.vehicle.setRoute(vehID, edgeList)`

The socket interface is well documented and the Java libraries are maintained outside the DLR. Likewise, Matlab libraries for TraCI are currently being developed outside the DLR and expected to be included in the next release of SUMO.

SELECTED SUMO CASE STUDIES

This section will describe more detailed some of the case studies that have been done with SUMO. Some of the scenarios can be found on SUMO's homepage (*7*).

Comparison of Intersection Control Algorithms

In Oertel and Wagner (*11*), a case study can be found that demonstrates how such a comparison works. There, a new traffic control algorithm named delay-based control was tested against an idealized fixed-time control and against a standard traffic-actuated control that worked with loop detectors. Albeit the intersection used was a highly abstracted (but fairly generic) one with four arms and two phases, the simulation tested a whole range of demands (in fact all possible ones). This is done as follows. From the range of demands (e.g. 100, 200,…, 1,000 vehicles per hour) pick a pair (q_1, q_2) and compute for this pair the optimum fixed cycle parameters, i.e. the cycle length and the green times. Run a simulation with this set-up which works as the base scenario, and then run two additional simulations with the same demand, but with a different control strategy. Now, the three simulations can be compared with each other, leading to a fair comparison. Note, that the delay-based control runs with input via vehicle-to-infrastructure communication, so there is a dependency on the equipment rate as well, which can measured via simulation. A typical result is shown in Figure 3.
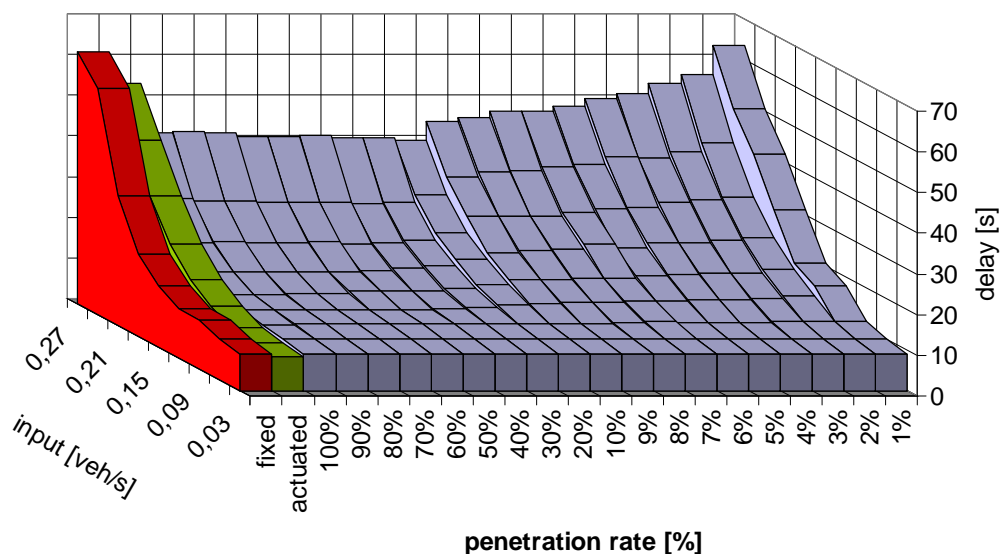
**FIGURE 3 Average delay times of the fixed-time control (red), the
traffic-actuated control (green), and the delay-based control (grey) as
function of ratio of equipped vehicles and traffic flow.**

Recently in Erdmann (*12*), this approach has been extended by using a combination of
GLOSA (green light optimal speed advisory) and a dynamic programming approach to create an
intersection control strategy that minimize energy consumption at a single intersection.

Emission Modeling

The computations of vehicular emissions and of fuel consumption were first targeted in 2008, in
the scope of the iTETRIS project, cofunded by the European Commission (*13*). The task was to
extend SUMO by according models to determine whether the developed V2X applications
besides improving traffic flow also reduce the environmental impact of traffic. The resulting
model should have computed the pollutants CO, CO_2, NO_x, HC, and PM_x as well as fuel
consumption. Additionally, a noise model had been implemented that will not be discussed here.
Please note, that SUMO hosts emission models only. No attempt has been made to work on the
effect of such emissions, i.e., to have an immission model.

The model should have worked on a "microscopic scale" for different reasons. The first
is SUMO's microscopic nature, aggregating the simulation state into a kind of macroscopic
states as required by inventory models would add an unnecessary error. The second is grounded
in the major scope of most investigations, namely vehicular communications. As usually only a
fraction of the vehicles is assumed to be equipped with such a technology, the emission model
should allow to investigate the emissions of both equipped and unequipped vehicles, and to
compare them against each other. But this is only possible, if each vehicle can be accessed
individually. The third reason is the granularity of the effects of the investigated applications.
Some of them affect the acceleration behavior of single vehicles rather than changing the

macroscopic state of traffic. The accelerations are but one of the major factors influencing the amount of emitted pollutants. As a result, a model was assumed to be needed that takes into account the acceleration behavior of vehicles.

After evaluating 15 emission models, the decision to use the inventory model HBEFA (at that time available in version 2.1) as the input for an own model was taken (*14*). HBEFA is a macroscopic inventory model and covers a large part of nowadays' vehicle fleet (for European countries such as Germany or Austria). HBEFA does not include information about the influence of a vehicle's acceleration on emissions. This was substituted by using the influence of the road slope on emissions that is given in HBEFA. To integrate the HBEFA into SUMO, the tables have been fitted with a function $e(v,a) = c_0 + b_1va + c_1v + c_2v^2 + c_3v^3$. During a simulation run, SUMO inserts in any time-step the current speed and acceleration into this expression to compute the amount of emissions produced. To ease the set-up of scenarios by avoiding the need to explicitly give the distribution of vehicle emission classes on vehicles, the obtained coefficient sets (for 93 vehicle classes) were classified using a clustering algorithm. Finally, three different classification schemes for heavy duty vehicles and two for light vehicles were chosen. Incrementing the number of clusters does not significantly increase the quality of the fit as could be measured by, e.g., the residual sum of squares.

The implementation of the emission model allowed benchmarking the emission behavior of the applications developed in iTETRIS. In addition, some research has been performed that used the ability to compute emissions. The first of those to name is "emission-based routing". Results are reported where a traffic assignment used the amount of emitted pollutants instead of the travel time for the road network's edge weights. Further tests of similar kind but have shown unstable behavior of such an emission-based assignment processed. Digging deeper, it turned out that such an assignment lacks a unique user equilibrium solution. This is due to the effect that the energy consumption of vehicles has a minimum at speeds around 60 km/h. It can be shown, that this carries over to a link performance function whose cost function (energy) is dependent on demand, but now with a nonmonotonous link performance function; for small and large demands, the energy consumption is big, while it is minimal in between. This may be an explanation of the observed instabilities.

European laws force real-world traffic management to cope with vehicular emissions by enforcing thresholds for pollutant concentrations (EC-Directive 2001/81/EC). Some cities instantiate certain traffic management actions that aim at reducing the amount of emitted pollutants.

Now, given a certain city, what could be the best traffic management action to be instantiated? The combination of a microscopic emission model and a fast traffic simulation allows answering such questions, including the change in traffic participants' behavior due to changed travel times or restricted areas. In Vergés (*15*), three emission reduction actions have been investigated: a speed reduction to 30km/h in living areas, a permissive environment zone, and a restrictive environment zone. This research was the first one that used the emission model PHEMlight which allows distinguishing EURO-Norms.

Emission modeling in SUMO is itself not yet finished. Within the COLOMBO project, the emission model PHEMlight was implemented and embedded into SUMO. It uses data obtained by resampling the emissions computed by PHEM (*16*), an instantaneous emissions model that is used for the development of HBEFA as well as of COPERT, an inventory emissions model. The inclusion of this second model was done by extending the available emission classes by the ones PHEMlight includes and deciding which model to use internally,

depending on the emission class of the vehicle to compute emissions for. Within the project AMITRAN, also cofunded by the European Commission, SUMO is extended by a third emission model, derived from HBEFA v3.1. It uses new methods for fitting the used function to data and new vehicle classification schemes. In SUMO's vehicular emissions modeling capabilities, the influences of the load of a vehicle on its emissions as well as cold-start emissions are not yet regarded.

After having gained some initial insights into the work with emission models, we would like to state that neither the complexity of modeling emissions nor their implementation in software are the crucial points of such investigations. Rather than that the interpretation of such fine-grained results for which proper presentation or aggregation has to be found as well as a wise set up of scenarios cause the major problems. Additionally, when looking at acceleration-dependent emission behavior, the correct acceleration behavior of the used car-following model gets into focus.

Vehicular Communication

Figure 4 taken from Krajzewicz (*10*) shows the development of the topics SUMO was used for, over years. There is a clear dominance of research on V2X (vehicular communication or vehicle-to-vehicle and vehicle-to-infrastructure communication). V2X is a technology; vehicles equipped with a communication device send information about their state, including their position, speed, acceleration, etc. Other equipped vehicles as well as equipped roadside units (RSUs) can receive this information and trigger certain actions, starting with a warning if the vehicle in front performs a hard brake.

Within the development of SUMO, a first communication model was directly embedded into the simulation in 2008. But the usage of SUMO for V2X-research is not mainly driven by DLR. In 2007, other groups have used SUMO to obtain "traces"—vehicle trajectories containing position and sometimes speed updates for each equipped vehicle that could be used as input to communication simulators. The usage of SUMO within the MOVE framework was probably the first step in making SUMO interesting for research on V2X. In 2008, the Technical University of Lübeck extended SUMO by a socket-based interface that allows to obtain values from SUMO
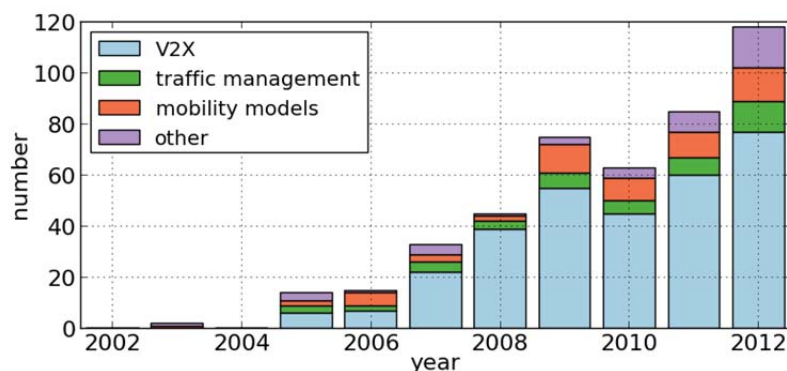
FIGURE 4 The distribution of research topics along publication years (multiple assignments possible).

and to control the behavior of simulation structures, such as vehicles or traffic lights (*17*). This extension allows interacting online with ns-2, a communication simulation. This extension was the first step towards opening SUMO for being usable in combination with a large number of other communication simulators and middleware solutions used for this purpose. In Joerer, Sommer, and Dressler (*18*), it was showed that SUMO is getting to be the most popular traffic simulation used for evaluating vehicular communications.

The work performed using SUMO ranges from very low-level evaluation of the behavior of the communication channel up to large-scale evaluations of the performance of a given application (mainly navigation) in citywide scenarios. The model implemented in 2008 was removed from SUMO meanwhile, to concentrate on the task of simulating traffic. In the following, a brief description of three of the investigated applications is given.

Bus Lane Management

The increasing mobility is a major challenge for large cities. Therefore, public transport is often prioritized by traffic managers. Likewise, the city of Bologna has lanes which are restricted to be used by public transport only. Furthermore, the city of Bologna has small, narrow streets which are frequently used at a normal week day. But there are also big events like football matches when the traffic infrastructure is confronted with a huge additional traffic demand. The idea of the application investigated in the iTETRIS project was to open the lanes restricted to buses and allow private cars to use these lanes in case of an additional traffic demand. A detailed description of the application can be found in Bieker and Krajzewicz (*19*). The simulation scenario is showed in Figure 5.

For implementing this application two steps were necessary:

1. Determining an unusually high traffic demand. RSUs have been placed at major intersections in the simulation scenario. The RSUs are collecting the cooperative awareness methods (CAMs) sent by all equipped vehicles in communication range.
2. Open bus lanes for private cars. If the average speed of the collected CAMs falls under a specific threshold an additional traffic demand was assumed. Therefore, the RSUs send messages to all equipped vehicles which inform the car that the bus lanes are open to private

(a)   **(b)**

FIGURE 5 Simulation scenario city of Bologna:
(*a*) chosen area in Bologna and (*b*) SUMO road network.

cars, too. The vehicles which receive this message are calculating the best route according to the new traffic situation.

Using speed as an indicator for recognizing an increasing traffic demand is rather uncommon, but in the evaluation of the simulation scenario it produced usable results. Especially for small equipment rates it was possible to indicate additional traffic demand using this measure. Note, however, that speed is just a proxy for the demand, so scenarios are imaginable where this proxy can be misled. To avoid this, further research with other measures and simulation scenarios is needed.

The simulation results of the application can be seen in Figure 6. The application could not prove it benefits for all equipment rates. For small penetration rates up to approximately 25% all vehicle classes benefit from the application. But with higher equipment rates too many vehicle are rerouted. Consequently, the rerouted vehicles decelerate the buses on the bus lanes and the vehicles are blocked by the buses and are forced to halt at every bus stop because no overtaking maneuver is possible in the traffic network.

Green Light Optimal Speed Advisory

One of the first V2X applications which are planned to be implemented in real life is the GLOSA application. The aim of GLOSA is to improve the traffic efficiency and traffic safety at a controlled intersection. The driver of a car equipped with GLOSA will be informed about the recommended optimal speed to pass the next traffic light at a green light phase. The focus of the GLOSA evaluation was to predict real-world test for the EU cofounded project DRIVE C2X.

For the GLOSA application a simulation of the city of Helmond was set up. The traffic lights within the scenario send the information about their program and timing to the equipped vehicles in communication range. The distance to the next traffic light is calculated using an internal map when a message is received by the vehicles. Using the calculated distance an advice for the speed needed to reach the traffic light in time can be given by a human–machine interface
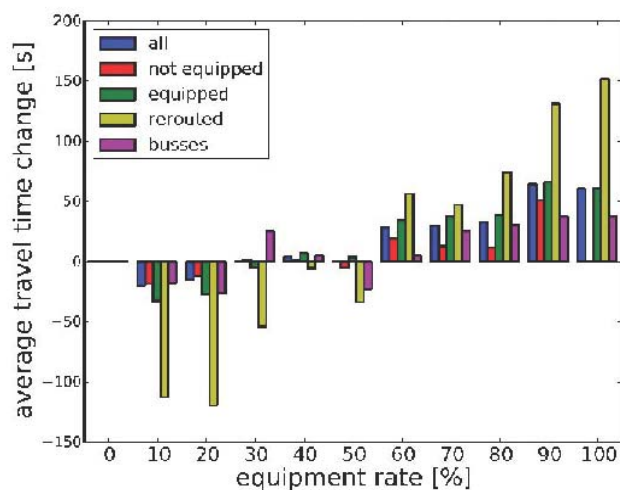
FIGURE 6 Average travel time changes per vehicle class over equipment rates.

display in the vehicle. In real life the driver has the choice to follow or ignore this advice. But in the simulation scenario the driver will always adapt her speed according to the recommendation. When the traffic light is red the driver is advised to drive slower than the speed limit (but never slower than 20 km/h) which led the driver pass the intersection after the traffic light turns green.

As a result, the GLOSA application can help vehicles to get through the traffic network without stopping at traffic lights. It turns out that the communication range is crucial for the success of the application. The driver is sometimes not able to adapt the speed early enough with a communication range of 300 m while the driver can pass the simulation without halt when a communication range of 1,000 m is applied (Figure 7).

Automatic Driving

One of the greatest benefits of dealing with traffic simulations is the possibility to implement traffic management strategies and new modes of traffic at an extremely low cost compared to a real-world implementation. This makes it possible to evaluate things like personal rapid transit (an automated taxi cab that may operate on a dedicated infrastructure) for small scenarios like a parking lot or to go for large-scale evaluation of advanced cruise control systems and beyond.

SUMO was used on both scales to evaluate the effect of traffic automation in the context of EU project CityMobil. While the large-scale evaluation involved mainly an adaption of vehicle parameters such as the aspired time gap to values which can be expected for automated vehicles, the PRT scenario did a fine-grained control of every vehicle in the simulation and will be explained in further detailed in this section.

Agent-Controlled Parking Lot

A centralized yet flexible approach to the management of automated systems is to employ agent-based technologies where every stakeholder is represented by a (software) agent giving bids and orders for the services. The network layout for this system was inspired by the Rome

| (a) | (b) |
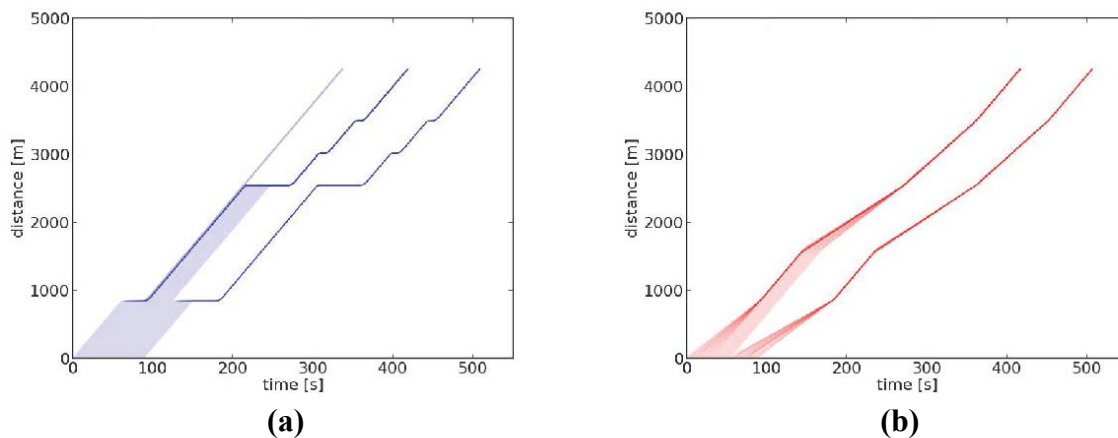
FIGURE 7   Trajectories of 90 simulated equipped vehicles with different departing times and with a communication range of (*a*) 300 m and (*b*) 1,000 m.

demonstrator of the CityMobil project which included a shuttle service from a central parking lot to the new Rome fairground.

The setup consisted of 160 parking spaces organized in eight (double) rows each served by a single bus stop (Figure 8). People had to walk from the parking space of their vehicle to the bus stop where they are picked up and travel to the main entrance. Streets and footpaths as well as the CyberCar (a small automatically driven vehicle that can carry up to 10 passengers) lanes are modeled without intersecting each other. The bus stops were served by a fleet of eight CyberCars.

The scenario involves a central control agency which assigns to every incoming vehicle a free parking space and directs the passengers to the nearest CyberCar stop. There the passengers request a ride to their destination (usually the main entrance of the fair) and the CyberCars serve the request in an optimized fashion minimizing the waiting times of the passengers. Not all of these control strategies needed to be implemented into the SUMO core but could be separated in to scripts which communicated over the TraCI interface with the main simulation. Using this approach one could perfectly separate the car following logic from the central management which is possible for automated cars only. The results showed a significant reduction in waiting time compared to a traditional bus scenario involving fewer but larger buses (Figure 9).
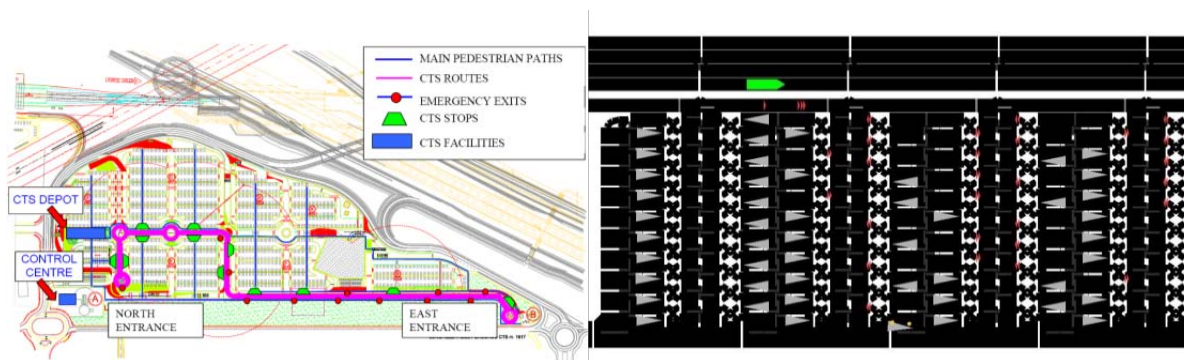
FIGURE 8 Network layout of the parking lot in Rome and its visualization in SUMO.
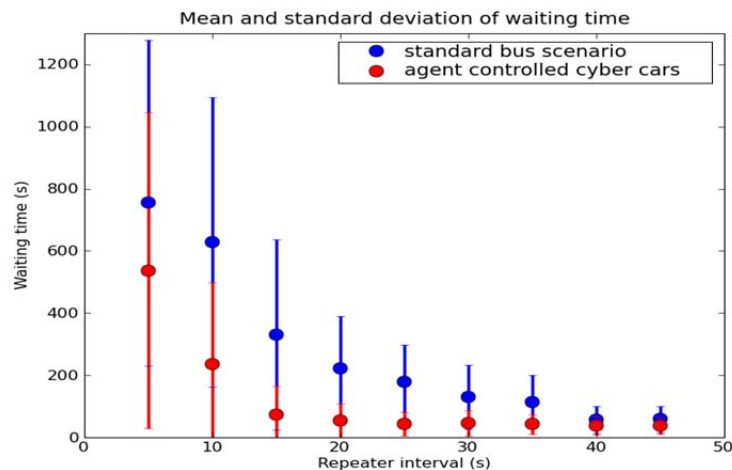
FIGURE 9 Waiting time depending on frequency of vehicle arrival.

VABENE

The traffic situation has a major impact on the success of rescue measures during a major incident. The authorities need to get to the relevant places in a short period of time and have to find their places such that they do not hinder the transport of material or injured persons. Furthermore, many people on site may try to leave the place by means of individual transport. This situation calls for a tool which enables the authorities to have an overview of the current traffic situation as well as a prognosis how the traffic situation may evolve. The EmerT web portal provides such a system, backed by SUMO which was enhanced by a mesoscopic simulation model to give fast results even for large number of scenarios in big conurbations. These developments are part of the bigger project VABENE which deals with traffic management during big events and in catastrophes.

The Model

For the type of scenarios within VABENE, the SUMO's default microsimulation model is too slow. The crisis scenarios need the computation of the traffic forecasts for the next 30 min to be completed in about 5 min. This led to the implementation of a different model, a so called mesoscopic queuing model by Eissfeldt (*20*). In contrast to the microscopic model where each vehicle has an individual position and speed the vehicles queue up in edge segments of about 100 m length and change between the queues. When changing to the next segment, it must be sure that there is space for the changing vehicle; in addition, the headway between subsequent vehicles leaving a segment depends on the traffic state of the current and the downstream segment. The basic model which gives good results for motorways was enhanced to reflect the special properties of city traffic. The resulting model is still about 10 to 20 times faster than the microscopic one with small deviations in the measured speeds to the microscopic model.

As already shown by Eissfeldt (*20*), the model reflects basic traffic properties such as back propagation of jams and the flow density relationship in the fundamental diagram. To model city traffic the following features were added:

- Lane queuing (to resolve blockings of cars with different destinations in front of junctions);
- Overtaking (to model different vehicle types without losing too much capacity); and
- Junction control (especially for traffic light systems).

Multiscenario Simulation

The output of the model is fed into a web-based decision support system named EmerT (Figure 10) that displays not only the simulation results but also induction loop data, floating car data, and images from aerial photography. All of these data sources are used to drive, to calibrate, and to validate the simulation scenario so that the traffic situation and its prediction are reflected accurately.

The simulation is already useful in itself by predicting traffic on roads not covered by real data and the evolvement of the situation. But the major application is the support of reaction forces during the event or to train them before. Using the EmerT portal the users will have the
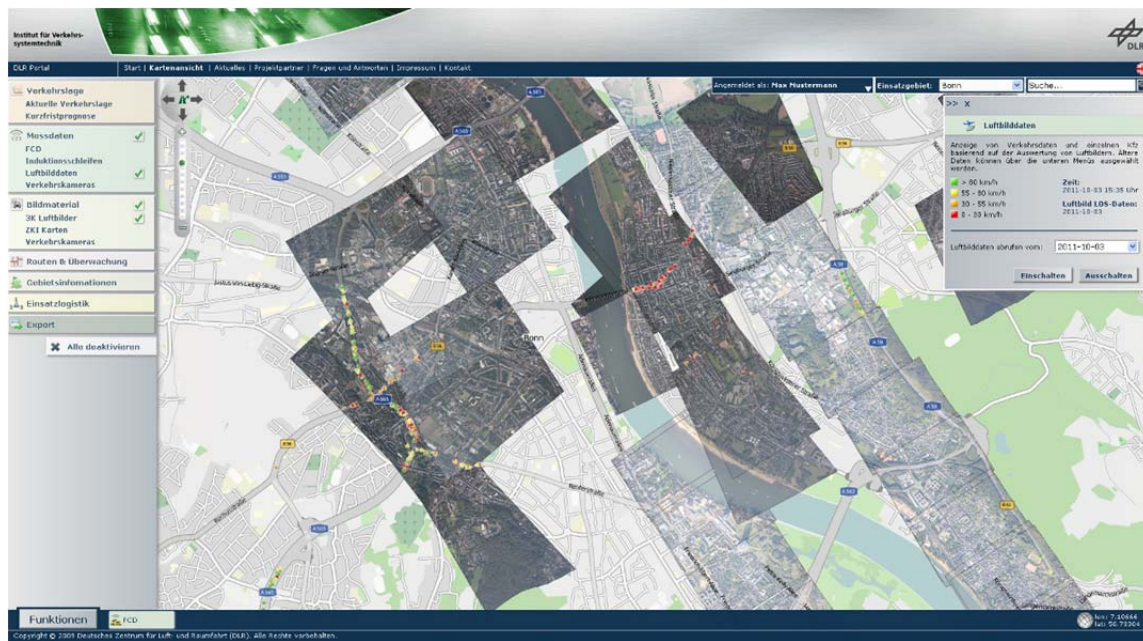
FIGURE 10 Presentation of enhanced map data in the EmerT portal.

possibility to study the potential traffic effects of different management measures (for instance road blockings) and adapt their strategies accordingly. They can also study in advance the weaknesses of the road network and identify critical roads in the case of emergencies at certain risky locations.

The simulation supports those endeavors by providing realistic traffic scenarios which give immediate feedback on the effectiveness of measurements. Unlike static analysis also spillback effects of jams and dynamic effects of traffic lights can be considered when optimizing scenarios.

The A92 Scenario: Lane Changing

The investigations described in the following were set up to measure the quality of SUMO's lane changing model. To evaluate this, the freeway A92 had been set up. The basic reason for using this piece of freeway was an unprecedented coverage by loop detectors and another project that has already sampled the infrastructure data (especially the network) and put it into SUMO's format. It consists of nearly 20 km freeway which connects Munich with its airport.

There are four on-ramps (green), four off-ramps (red), and a division at the airport where two lanes lead to the airport (240/33 and 240/34) and the two left lanes lead further northeast (Figure 11). The inductive loop detectors placed in this area measure traffic flow (separately for trucks or buses and passenger cars) and average speeds in 5 min intervals. Based on past projects, a large stock of data was available.

To use the detection values as input to the simulation, another tool from the SUMO suite is needed. The DFRouter uses those detector flow data as input and outputs the vehicles together with their routes. The resulting routes are put into the simulation which should lead to an exact fit between reality and simulation at the on-ramps. However, the off-ramps do not necessarily fit
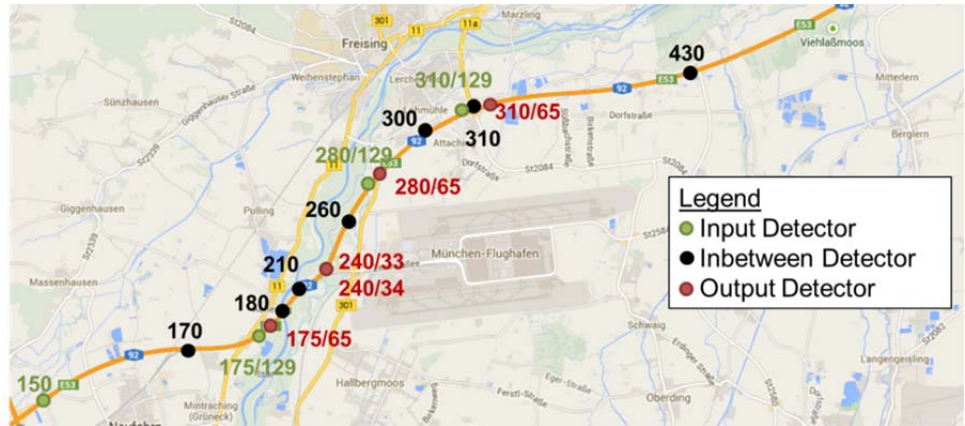
FIGURE 11 Freeway A92 (Munich, Germany) with loop detectors.

well, since there is a good chance, that a vehicle misses its off-ramp. Therefore, the results in Table 1 are not completely trivial.

However, when looking more detailed, new and different discrepancies show up. Especially the lane distribution is not reproduced correctly at some of the loop detectors, but not at all of them. In Figure 12, the results at detector 170 are shown, which is located closely behind (approximately 3 km) the entry point of the study area: almost 5,000 vehicles per day do not use the correct lane. That could still indicate a problem with the lane selection.

But in fact there also exist detectors like detector 210 and 240 (located in the middle of the study area) in which the lane selection fits with a very small deviation (Figure 13).

**TABLE 1 Difference Between Simulated and Measured Data;
The Largest Error Is 4.4%, While the Smallest One Is 0.2%**

	Exit #175/65	Exit #240	Exit #280/65	Exit #310/65	Exit #430
Data	3718	27707	4103	6106	20632
Simulation	3556	28698	4112	6158	20616
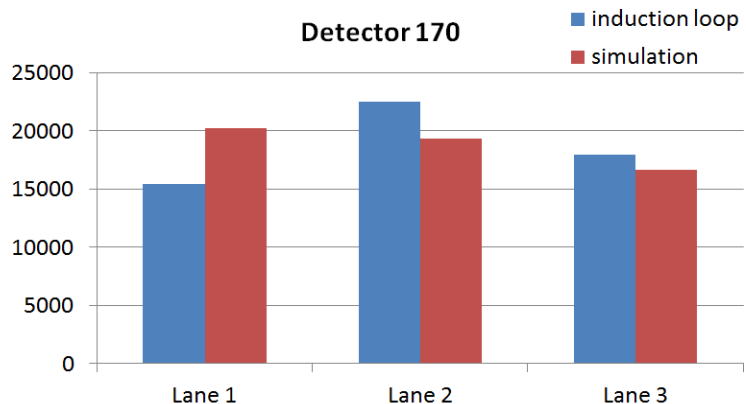
FIGURE 12 Comparison between simulation and reality of the lane flows at detector 170.
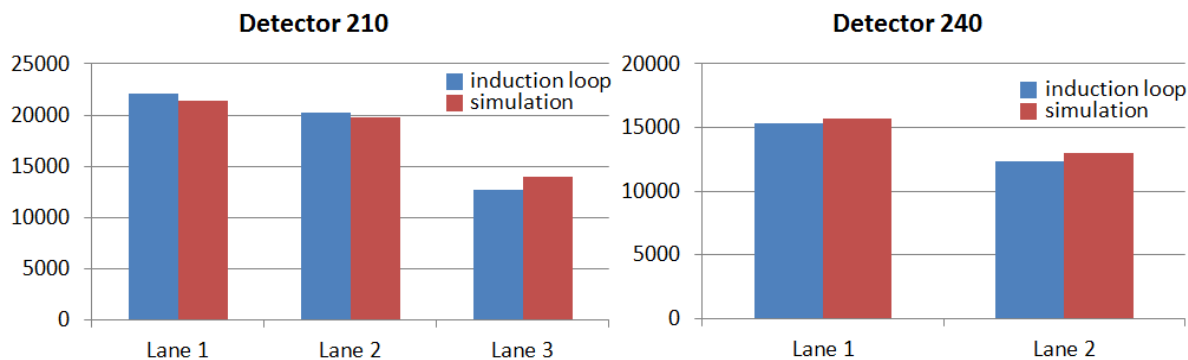
FIGURE 13 Comparison of the lane flows at detectors 210 (left) and 240 (right).

As could be imagined, the mismatch with the counts at detector 170 also comes with a mismatch in the speeds. In Figure 14 a comparison between the measured and the simulated speeds, for the right, middle, and left lane (from left to right) are shown. The bars represent the measured values and the blue line shows the simulated values.

Unfortunately the speeds are not that precise, there are large differences between detector and simulation values on the slow lane. On the faster lanes the speed fits better. In addition, there is a different problem. Reality has just one short jam in the morning peak, but in the simulation there is an additional jam in the afternoon, while reality shows just the beginning of such a jam. Repeating the simulation a couple of times with a different random number seed shows that the pattern to be seen in the simulation is robust, so there is definitely a difference between simulation and reality which will hopefully made smaller by a subsequent calibration of the parameters of SUMO.

These preliminary results are encouraging but far from being satisfactorily. At least, we have most of the basics correct and can now work out the details. Especially the lane-changing part, but also such problems like the correct speed and vehicle distribution. However, there are still lot things to do, like a distribution of the errors, and a detailed analysis of the lane distribution.
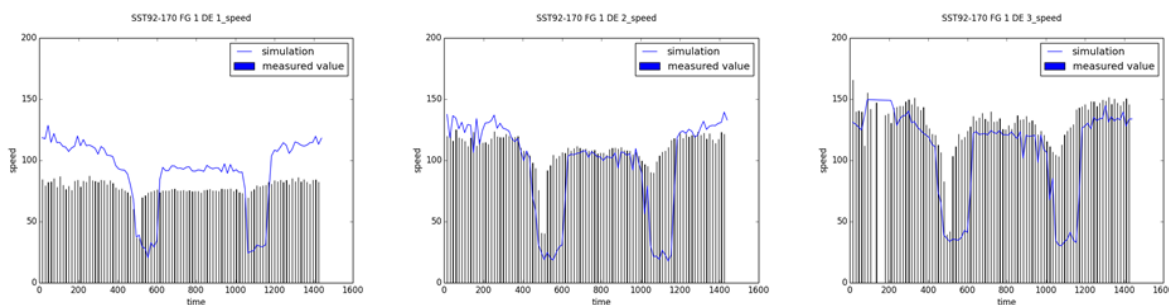
FIGURE 14 Speed at detector 170 as function of time of the day for the three lanes.

FUTURE PROSPECTS OF MICROSIMULATION

Despite the dramatic progress that has been made during the past 20 years or so, there are still a couple of dark corners left to be filled. This relates to microsimulation models in general, but also to the modeling and to the engineering in software tools like SUMO.

How Can We Be Sure that We Have Implemented the Correct Model?

Look at such complicated models as the ones of Wiedemann, Kerner, or the MITSIMLab model, which contain more than 10 parameters and an array of equations to advance the simulation by one time-step. The Wiedemann and one of Kerner's model had been implemented in SUMO. However, there is a big question here, and we use it to advocate a new culture: how can we ever be sure, that the code in SUMO implements the correct model? The answer is obvious: we do not.
　　　Therefore, we think it might be a really good idea that the creator of a new traffic flow model should make all efforts to share his or her code with the rest of the scientific world. In this case, anybody who would like to use this model simply uses this source code; this reduces at least one possible error when trying to reproduce the results of other groups, which is at the heart of the scientific endeavor.

When Do We Actually Need Microsimulation?

In general, this question is difficult to answer, and the answer is prone to rapid development. Instead of a general answer, just a nice example will be studied here which sheds some light on this question.
　　　When it comes to the planning of a traffic light, most traffic engineers look into the HCM or the closely related national guidelines (HBS and RiLSA in Germany). There, a few formulas based on the work of Webster will be used, that tell the engineer the correct cycle time and the corresponding splits for such an intersection. Especially the HCM approach is designed to handle additionally periods of oversaturation, which has been done by an extension of Webster's original work to handle nonequilibrium conditions; Webster's approach is essentially an equilibrium approach. Both Webster's approach and HCM's approach are based on queueing theory, however to arrive at the simple equation, e.g., for the optimal cycle time, a long and involved line of reasoning has to be followed, which involves more or less justifiable approximations. Note, that even the idea to describe an intersection by queueing theory is already an approximation, since traffic is definitely a spatio–temporal process.
　　　Be that as it is. To simulate such an intersection as a queueing process is ridiculously simple. For one leg of the intersection, the core is just a seven line simulation program:

```
for (t=0.0; t<=tMax; t += deltaT) {
 if rand() < q(t)*deltaT and n<nMax then n = n + 1
 if mod(t,c)<=g and t>=tLast + tau and n>0 then {
 n = n - 1;
 tLast = t;
 }
}
```

Here, `rand()` is the call to a random number generator, `n` counts the number of vehicles currently in the leg, and `q(t)` is the demand function. In addition, the variable `tau` is just the

inverse of the saturation flow s, and `deltaT` is the time-step size of this simulation. From a simulation of this simple source (of course with a lot of additional lines setting variables and collecting results) a very complete set of statistics can be drawn. It yields not only the delay itself, but in addition it also produces the whole delay distribution $p(d)$. The availability of this distribution has an important meaning for questions related to quality and reliability of the intersection at hand, and it is already beyond the capabilities of handbook methods. Of course, for this to happen require that the simulation is to be run multiple times to correctly arrive at averaged quantities and at the distributions.

It can even be run with hand-tailored (or data-driven) oversaturation periods (by specifying the demand function $q(t)$ accordingly), and it needs just three parameter s, g, c of which at least two of them are well-known (g, c) and the other one can be measured more or less easily. Obviously, even the handbook formulas in the HCM look more complicated than this, and it becomes even more dramatic for the equations that describe the time-dependent queueing approach.

In our view, this is a beautiful example (Figure 15). A simulation of a 5-h peak period with such a simple program needs a few seconds for 1,000 repetitions, it runs at least a factor of 100 or even 1,000 faster than any full-fledged microsimulation tool, and one gets a wealth of data out of it. Of course, it is possible to alter the function $q(t)$ into a function that models a traffic light upstream. In this manner, coordination can be properly accounted for. Also, simple traffic-actuated signal controls can also modeled by this approach, and the same hold true for the platoon dispersion.

As told already, this queueing approach is itself an approximation, therefore it might be better to switch either to a simplified microscopic approach like cellular-automata or use directly a serious micro-simulation tool. Which, however, needs more simulation time to arrive at good
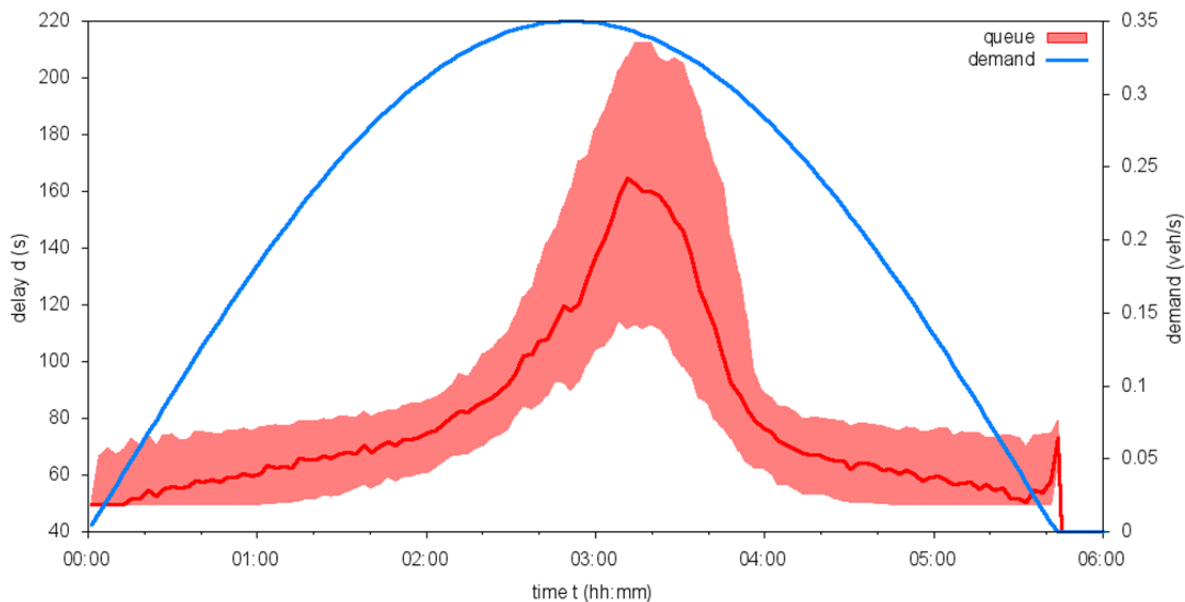

FIGURE 15 Simulation of a 6-h period with a sinusoidal demand function where peak demand exceeds capacity with the queueing model described above. Plotted are the median of the delay as function of time (red curve) and, as red area, the 25% and 75% quantiles of the delay distribution.

answers, and it is very likely that the 1,000 repetitions have to be reduced to 50 or so to arrive at bearable simulation times.

We pretty much think that such tools will be the future. Handbooks like the HCM will be superseded by such tools or even directly by the microsimulation tools.

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Some Thoughts on Future Directions for Managing Uncertainty in Stochastic Traffic Models
Abstract Only

VINCENZO PUNZO
University of Naples Federico II

SOME COMMON MISCONCEPTIONS ABOUT UNCERTAINTY IN TRAFFIC SIMULATION

A rapidly expanding range of traffic and transportation applications call for accurate dynamic modelling of traffic flow due to their potential impact on community and environmental decision making. The complexity of these applications dictates that detailed traffic simulation models are increasingly being used for such purposes.

These models, having either stochastic inputs or stochastic model components, yield stochastic outputs, which is relevant and a required feature being reality inherently uncertain. In order to consider a model valid, therefore, the analyst has to verify that the uncertainty in the model outputs be close enough to the uncertainty in the real world. Though apparently obvious, the requirement has nontrivial implications as it calls for a structured process of the 'management of the modelling uncertainty', intended as the identification, quantification and reduction of the model uncertainty (De Rocquigny et al. 2008). When applying mathematical models in support of policy decision making, this process can be considered as a step of a broader practice also referred as "sensitivity auditing": "*a practice of organised scepticism toward the inference provided by mathematical models*" (Saltelli et al. 2013). Among these techniques are those commonly known as uncertainty and sensitivity analysis.

It is claimed here that a shift towards the adoption of advanced techniques for the management of the modeling uncertainty in traffic simulation is highly necessary. The clarification of some common misconceptions—hindering a correct framing of the problem and a proper utilization of traffic simulation tools—is preliminary to the comprehension and the adoption of any such technique:

1. In the traffic microsimulation practice, stochasticity, i.e., uncertainty of model outputs is often considered only as an accident of the modelling process, and a source of indeterminacy when analyzing simulation results. This stems from the (correct) consideration that being the model output stochastic, analyzing results of one single simulation is neither meaningful nor informative. To address this issue, performing more runs of the same model (replications) and taking the average of their outputs is usually recommended. This practice, however, is conceptually wrong for at least two reasons:

     a. In order to be valid, a stochastic model has to reproduce the variability of the real system outputs. In traffic microsimulation practice, instead, only supply characteristics, like vehicle parameters, and event instants, such as vehicle entrance, are randomly sampled when performing replications of a traffic scenario. On the contrary, the input demand is left constant across replications. This has no equivalence in the reality, where concurrent variability of both demand and supply occurs (see variability from day to day). Therefore, results from multiple replications that do not account also for the

variability of demand, cannot be compared to real traffic data. In other words, a design of the experiments that excludes demand variability cannot be used to infer on the system behavior and to validate the model itself. For this reason, the current practice of comparing with real traffic data from one day only, the average results from multiple replications of a model fed with constant demand profiles, has no meaning indeed.

b.   Outputs of a stochastic model can be properly analyzed only in terms of probability or frequency measures, for instance, through the cumulative distribution functions or the percentiles of their outputs (such as flow counts, queue lengths or travel times). Relying only on output averages means discarding the most of the information provided by a stochastic model and desisting from a proper model validation. When comparing alternative scenarios, it means adopting a nonrobust measure.

2.   In the traffic simulation field, advanced methods for model output sensitivity analysis are vastly unknown (in the cross-disciplinary community of modelers, the term "sensitivity analysis" refers to the set of methodologies and statistical techniques that aim to "…study of how the uncertainty in the output of a mathematical model or a system (numerical or otherwise) can be apportioned to different sources of uncertainty in its inputs" (Saltelli et al., 2002). In the practice, sensitivity analyses of traffic simulation models are usually performed adopting simplistic experimental designs that is just varying one input or parameter at a time while keeping the others fixed at their nominal or default values. Such design is also referred as "one-factor-at-a-time" (OAT). Unfortunately, it is demonstrated to provide biased results in presence of non-linear models and uncertain inputs, for two reasons (Saltelli and Annoni, 2010):

a.   It is a local method as it explores only few points in the neighborhood of the chosen values (e.g., default values). If inputs (parametric or nonparametric) are uncertain and the model is nonlinear, the behavior at a point of the input space cannot be simply extrapolated elsewhere and, therefore, the analysis results at that point can be deceiving. For instance, the impact of a parameter on the outputs can be substantially different when running the model with the other parameters at values different from the default ones;

b.   Varying one input (or parameter) at a time does not allow the inputs interaction effect to be taken into account. However, it happens that the interaction effects of an input with the others transcend its standalone effect that is an input affects the outputs mainly when it is varied simultaneously with the others. Moreover, results of the experiments are not generally analyzed with appropriate statistical techniques. Eventually, OAT experimental designs are run with the only aim of investigating the influence of inputs or parameters on the outputs, while different settings for sensitivity analyses are established and recognized as extremely beneficial for the modeling practice (Saltelli et al., 2008).

3.   In the traffic simulation field, the term "sensitivity analysis" is sometime misused. In many traffic microsimulation guidelines, for instance, it is applied instead of "uncertainty analysis" (or "uncertainty quantification"). Quoting the Traffic Analysis Toolbox Vol. III (FHWA, 2004): "…A sensitivity analysis is a targeted assessment of the reliability of the microsimulation results, given the uncertainty in the input or assumptions. The analyst identifies certain input or assumptions about which there is some uncertainty and varies them to see what their impact might be on the microsimulation results." It is clear that this definition refers to the quantification of the uncertainty in model predictions and not, properly, to a sensitivity analysis that, instead, aims at apportioning such uncertainty to the different inputs.

Other times, stability analysis of the objective function in parameter estimation problems or, reliability analysis of traffic assignment solutions have been also referred as sensitivity analyses.

WHY TO MANAGE UNCERTAINTY: AN EPISTEMOLOGICAL PERSPECTIVE

A vast debate has been arising in the last decades about the change of the role of science in society. Many scientists pointed at the emergence of an issue of legitimacy of science when its production has policy as an interlocutor instead of academia. "…When models are used for policy analysis, one must acknowledge that today's role of scientists in society is not that of revealing truth, but rather of providing evidence, be it ''crisp'' or circumstantial, based on incomplete knowledge, sometimes in the form of probability, before and within systems of conflicting stakes and beliefs" (Funtowicz and Ravetz, 1992).

In such a context, mathematical models have been necessarily objects of severe critiques. Among the arguments against models, for instance, the apparent paradox known as "indeterminacy" or "equifinality" has been advocated (Young et al., 1996; Beven and Freer, 2001). The paradox refers to the condition of existence of many different models for the same system, often returning similar results though based on distinct assumptions. That is the typical situation in traffic simulation, whereas many alternative model formulations coexist and compete in the ability to capture traffic phenomena. Other scientists pointed at the impossibility of models to be validated or verified, but only confirmed or corroborated by the noncontradiction between observation and prediction (Konikov and Bredehoeft's, 1992, and Oreskes et al., 1994).

Increasing complexity and tendency of law-driven modes to be over-parameterized have been often suggested among the causes for model unreliability, as brilliantly explained by the words of Hornberger and Spear (1981): "…most simulation models will be complex, with many parameters, state-variables and nonlinear relations. Under the best circumstances, such models have many degrees of freedom and, with judicious fiddling, can be made to produce virtually any desired behaviour, often with both plausible structure and parameter values."

These considerations pose serious questions on the reliability and efficacy of simulation studies on the one hand and on the transparency of decision making processes where models are used in support, on the other hand. Such problems became dramatically apparent (outside the field of transport), with a series of sensational mistakes supported by erroneous modeling practices. The most famous being the arguments neglecting the existence of the climate change at the end of the last century, or the failure of financial models in predicting the economic crunch started in 2008 (Stiglitz, 2011).

Focusing on the sources of uncertainty at the basis of model unreliability, recently, researchers from many disciplines have started to give increasing importance to the model inputs (parametric and nonparametric). It has become clear in many modeling fields, indeed, that the correct characterization of the uncertainty in inputs and outputs bear the same importance for the result accuracy than other sources of error like the modelling assumptions or the mathematical structure and properties. For instance, the statement "Precision of outputs goes up as accuracy of inputs goes down" (Stirling, 2000) refers to the misleading practice of obtaining precise (but biased) outputs by arbitrarily restricting the input space, and describes one of the possible effects of a bad characterization of the uncertainty in the inputs. The intuitive and well-known GIGO

principle in computer science, namely "Garbage-In-Garbage-Out", is another way of referring to this problem.

In traffic simulation, in particular, the characterization of the input uncertainty has been limited to the parametric inputs while the main non-parametric input, i.e., the demand, is usually considered as deterministic.

Further, in stochastic (microscopic) models the estimation of parameters' probability density functions is rarely carried out (Ahmed, 1999). More frequently, constant parameter values are estimated, in analogy to deterministic (macroscopic) models, as if the driver population was homogeneous.

In the traffic microsimulation practice, even the calibration of homogeneous model parameters is not yet customary (Brackstone et al., 2012). A reason is that many theoretical issues are still open: a clear understanding of the relationship between calibration against aggregate and disaggregate data is missing as well as a clear definition of appropriate settings for calibration (i.e., fitness measures, algorithms) and suitable traffic data. Issues like the impact on microsimulation results of parameter heterogeneity or of adopting different probability density functions have not been really investigated. Similarly, overfitting and transferability of parameters are rather unexplored issues.

Computational issue is another major impediment. In traffic microsimulation software, for instance, the big number of parameters (often in the order of hundreds) and the high cost of a single run (often near to the real time) make automated calibration difficult in many real-world applications.

Future Directions

Recently, those issues fostered a growing amount of research in the field of the management of modelling uncertainty in traffic simulation. A notable example is the European Cooperation in Science and Technology (COST) Action MULTITUDE (MULTITUDE Project, 2013). Within this project an effort has been made, in particular, to introduce a framework for the management of modeling uncertainties (established in other disciplines) in the traffic simulation field (see Figure 1). In this framework, the traditional step of calibration (i.e., the Step B in Figure 1) is only a moment of a wider process aimed at corroborating and validating models.

Uncertainty quantification and sensitivity analysis, in particular, are the other main phases of the process.

The former (Step C), aims at quantifying the uncertainty in the outputs given the uncertainty in parametric and non-parametric inputs. In fact, as mentioned before, a proper validation of a stochastic model requires comparing simulated and real output distributions (pdfs). A model can be considered valid only when the pdf of the output of interest, e.g., the pdf of the average travel time on a certain corridor, can be considered statistically the same as the pdf resulting from the day to day observations (it is worth stressing here that, for the scope of the analysis, simulated output pdfs can be obtained by Monte Carlo simulations whereas real output pdfs require costly repetitive observations of the system).

A proper characterization of the input uncertainty, i.e., a calibration phase (Step B) has to be accomplished preliminarily in order to obtain statistically equivalent simulated and real output pdfs.

Unfortunately, it is infrequent that a model turns out to be valid after this first round i.e. after Steps B and C, a model refinement being needed often. The likelihood of success of this
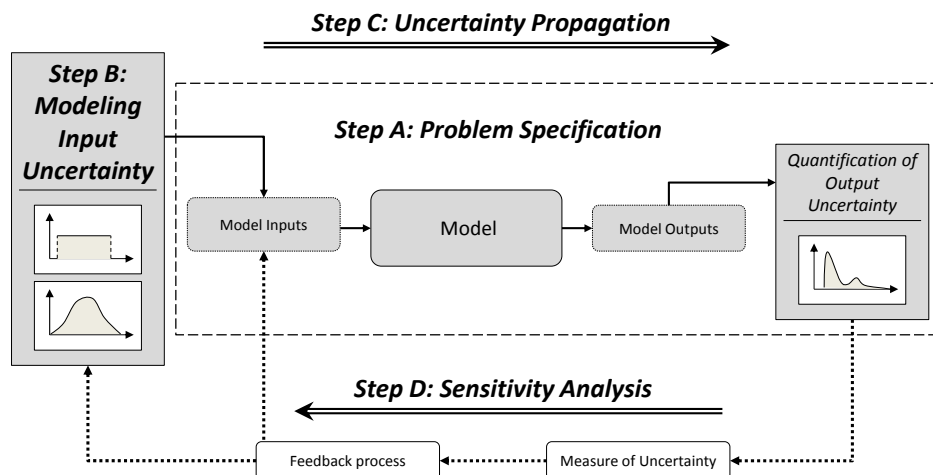
**FIGURE 1 Generic framework for the management of uncertainty
(Source: Punzo et al., 2014A)**

refinement dramatically increases if it is informed with a feedback from the modelling process. Such feedback is commonly referred as sensitivity analysis (Step D). Sensitivity analysis in fact allows quantifying how much every input contributes to the output uncertainty. This result is useful for many purposes, such as to refocus the analysis on some specific inputs, e.g., by devoting more efforts for the estimation of a particular input or for collecting specific data, or might be useful for identifying uninfluential parameters that do not need to be calibrated (see Punzo et al., 2014B) (the questions that can be answered by a sensitivity analysis and the corresponding 'analysis settings' are several; see Saltelli et al., 2008, for an introduction).

The framework just introduced (the reader can refer to Punzo et al., 2014*a*, for a more detailed introduction in the context of traffic simulation) is also useful to envisage and outline some possible future developments in the management of uncertainty in stochastic traffic models. First, as the whole process involves constructing an input–output relationship that is generally achieved by Monte Carlo simulations, a first requirement will be that traffic simulation software be provided with the capability of making custom design of experiments and running multiple simulations accordingly. This is necessary to spread these techniques in the simulation practice.

Research in the application and development of sensitivity analysis techniques to traffic simulation is called to address several issues.

The first concerns the computational cost. If a sampling approach as the one depicted in Figure 1 is applied, the computing cost becomes a problem when (*a*) a single model run takes appreciable time and (*b*) the uncertain inputs to sample are numerous; in fact the number of simulations necessary to cover the multidimensional input space grows exponentially with the number of inputs. The problem can be generally approached either relying on simplified sensitivity analysis techniques such as 'screening methods', requiring a lower number of simulations (see Ge and Menendez, 2013, for an efficient design method applied to traffic simulation software) or using emulators (meta-models) to run a high number of simulations (see Ciuffo et al., 2013, for an application of Kriging meta-model for sensitivity analysis of traffic simulation software). In the latter case, the analyst exploits the much faster emulator to construct the input-output relationship that makes the application of more advanced and demanding

sensitivity analysis techniques feasible, such as the "variance-based methods". The choice of which approach to follow might depend on the specific context or model: in the first approach, inaccuracy arises from the use of simplified sensitivity analysis techniques, though applied to full model runs. While in the second one, inaccuracy stems from the use of a simplified model whose fidelity, in its turn, depends on the number of full model runs made to build it. In the future, mixed approaches will also worth to be investigated (Ge et al. 2014).

Another major issue in sensitivity analysis is the correlation of inputs, as most techniques assume inputs independence. When inputs are strongly correlated, as often in traffic simulation, analysis results can be biased (Kucherenko et al. 2012) so that basic research is needed on this.

Concerning the input modelling phase that is the input estimation, or parameters' calibration, many challenging issues wait to be tackled. As mentioned, the characterization of day to day variability in the input demand is crucial to enable a proper validation of stochastic models. The impact of parameters' heterogeneity and of their correlation structure on the results of a traffic simulation is another challenging topic, as well as, the study of automated methods to estimate model parameters pdfs. The investigation of the relationship and the reciprocal meaning of calibration against disaggregate and aggregate data will be propaedeutic to develop effective calibration methodologies. Eventually, the collection of trajectories in a whole time–space domain, as in the NGSIM project, will be crucial to foster all the previous studies. New model validation techniques focusing on the probabilistic measures of simulated and real outputs are also required to finalize the process of uncertainty management in stochastic traffic modeling.

The studies herein envisaged would greatly benefit from close collaboration and cross-fertilization with other disciplines where these techniques are more established. The peculiar importance of uncertainty in traffic, its substantial implications on the modelling process, as well as, the complexity of the phenomenon to be modelled will need substantial efforts in order to produce advancements. The next challenge in researching traffic flow theory will be therefore to move from the mere analysis of models' mathematical properties to the study of characteristic and properties of complex traffic simulation environments. This might be envisaged as a new branch of research for which the name of "traffic flow simulation theory" seems appropriate.

ACKNOWLEDGMENTS

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Big Data and the Calibration and Validation of Traffic Simulation Models

KAAN OZBAY
HONG YANG
ENDER FARUK MORGUL
New York University

SANDEEP MUDIGONDA
The State University of New Jersey

BEKIR BARTIN
Istanbul Kemerburgaz University, Turkey

Real-world data are the essential elements in the validation and calibration of microscopic traffic simulation models. Availability, accuracy and relevance of real-world data can seriously affect the reliability of the models' predictions. Traditional sources of traffic data are either limited to a limited number of typical conditions or may not be reliable enough. With the advent of new technologies, information is on the fingertips of users by means of smartphones, GPS-equipped devices, and radio frequency identification (RFID) readers. The rapid rise in information technology has also resulted in innovative ways to obtain space- and time-sensitive information in real time. This, in turn, has led to massive amount of passively collected location and event data for various time periods, also called "Big Data." With the availability of Big Data there is an opportunity to validate and calibrate traffic simulation models in a way that has never been possible in the past. In this paper, we examine the current practice of calibration of traffic simulation models with an emphasis on data needs. We also describe the various sources of Big Data that might be available to the traffic simulation community now being collected through in-vehicle and infrastructure-based technologies. Various real-world case studies are presented to illustrate the importance and future of Big Data in the calibration of traffic simulation models. Future applications of Big Data are also discussed in detail.

INTRODUCTION

With increased access to computing power, simulation tools have become popular resources for modeling and analysis of various transportation systems. In highway transportation, micro simulation tools such as CORSIM (*1*), PARAMICS (*2–5*), VISSIM (*6*), AIMSUN (*7*) among others, allow traffic engineers and planners assess the performance of existing roadway systems in a detailed manner by constructing a model of the existing facilities, such as toll plazas, signalized and unsignalized intersections and traffic circles, as well as to predict the effects of potential operational or infrastructure changes. The value of these tools, however, lies in their ability to stochastically simulate drivers' behavior, such as lane changing, car following, gap acceptance, and route choice. The functions or rules that govern drivers' decisions in simulation software tools need to be fine-tuned to reproduce field conditions. Despite the advances in computing power and the ability of available simulation tools to represent complex driver

behavior, simulation modeling and analysis is still a long and painstaking procedure, requiring extensive field data for validation–calibration.

Model verification, calibration, and validation are important steps in the development of a valid simulation model, and crucial for ensuring reliable information gathered from these models.

Model verification means building the model correctly. This stage deals with accurately transforming the model concept from a simulation flowchart into a model specification using a computer program (*8*). Model calibration is the process to obtain a desired confidence level where the model and its results are reasonable for the objective it was developed for. The validation process ascertains that the output data obtained from the simulation model driven by the input data are close to the real system output data. When comparing the system and model output data, if there are substantial differences in the comparison, some correction factors are added in the input data. Then the model and system output data are compared again. This iterative procedure of input modification to meet the target output measures is called "calibration." In this study, for the sake of brevity, we use "calibration" as a generic term to describe the validation and calibration process.

It is evident that the real-world data are the key elements in microscopic traffic simulation model development and calibration. Availability, accuracy, and relevance of real world data can seriously affect the reliability of the models' predictions. If the model is calibrated and validated well for current conditions, the predictions may be accurate in the shorter time frame. However, in the longer term, the potential changes in traffic control and management and infrastructural properties could lead to significantly different driver behavior or other time-variant features of the transportation system. It is therefore important to reflect these possible changes in the model parameters based on the time frame of the model that is being developed. Clearly, this is when continuous and large amounts of data beyond data traditionally collected by traffic modelers will be needed.

With the advent of new technologies, information is on the fingertips of users by means of smartphones, GPS-equipped devices, etc. For example, the rapid increase in GPS-enabled mobile device adoption such as smartphones in the last few years provides the opportunity of geotracking using the location information of mobile device users (*9*). In city traffic, tens of thousands of smartphone users, traffic sensors, traffic cameras, GPS, and computers in cars generate very large data sets of travel time, speed, and location information.

These technologies not only provide valuable real-time operational information, but also generate large quantities of data that can be used off-line. These data, aptly termed as Big Data, does not require much effort in extraction, and are available in close to real time. It is well recognized that the resulting massive amount of traffic-related data will make important contributions to the operations and planning of transportation systems (*10*). The potential use of Big Data are countless: with the help of Big Data procedures, researchers and practitioners can make better transportation decisions such as optimizing operations, developing rational infrastructure plans, and examining the distribution and patterns of large public events.

Since Big Data are available in much greater spatial and temporal spread and available without a considerable time lag mainly due to post processing needs, they can be used to calibrate and validate traffic simulation models for a variety of conditions. Thus, the turnover time for providing accurate prediction scenarios that go beyond a typical hour or day scenario will become much smaller. Thus, the objectives of this paper are twofold:

1. Examine current practice of calibrating simulation models and challenges with an emphasis on data requirements, and
2. Provide a thorough examination and demonstration of potential sources of Big Data that can be used for calibration and validation of simulation models.

The next section reviews the existing literature in traffic simulation calibration. The third section provides information on data needs for calibration. The fourth section looks at some drawbacks of existing methods. Fifth section illustrates the role of Big Data followed by few case studies of Big Data in the sixth section. The final section provides the outlook for future of Big Data vis-à-vis traffic simulation calibration.

LITERATURE REVIEW

There are myriad of studies that deal with calibration of traffic simulation models (*1–7, 11–18*). Due to space constraint, we show a sample of them in Table 1.

Table 1 also shows the data used in these studies for the calibrating process. It can be seen that in most studies data used for calibration is limited to a.m. and p.m. peak periods no more than a few days. Thus, the data captures only a few specific conditions, or is a dilute sample of different conditions. Hence, it is expected that the model predictions will only be accurate for those specific conditions.

The effect of data and parameter uncertainty in traffic simulation models has received considerable attention recently (*17, 18*). Studies from other fields indicate that bias and variance in simulation output results are due to the bias and variance in the input models used, after simulation error is eliminated; the input models consist of simulation model inputs and parameters (*19, 20*).

Hence, it is important to consider a larger set of data with greater details in order to obtain accurate input and parameter distributions for simulation of traffic with stochastic variations.

DATA NEEDS FOR CALIBRATION

Typically, modeling traffic flow requires three types of data: model inputs, model parameters, and observed outputs. Model inputs involve the demand data for which the traffic simulation is performed. Model parameters involve different types of parameters used in the traffic simulation depending on the level of complexity in modeling. The output data observed in the real world is required to compare model outputs and evaluate the accuracy of the models.

The model inputs include the number and types of vehicles or agents for which the simulation modeling is being performed. These include the following:

1. Driver data. This type of data includes the characteristics of agents being modeled. Aggregate data such as drivers' age group, trip purpose, aggressiveness, awareness, familiarity with the modeling area, etc., can be used to categorize drivers into different classes.
2. Vehicle data. For vehicular simulation, the composition of vehicle population is an important input that influences the outputs of traffic simulation model. This includes the

TABLE 1 Summary of Literature on Calibration of Traffic Simulation Models

Authors	Complexity; Simulation Tool	Type of Roadway Section	Performance Outputs	Data Used in Calibration
Ma and Abdulhai (*2*)	Micro; PARAMICS	Urban	Traffic counts	Detector data for 1 h during a.m. peak
Kim and Rilett (*1*)	CORSIM, TRANSIMS	Freeway	Volume	Data 5 loop detector stations for 13.9-mi section of freeway for 1 h during a.m., p.m., and off peak
Hourdakis et al. (*7*)	Micro; AIMSUN	Freeway	Volume	5-min data from 21 detector stations for a 12-mi freeway section during p.m. peak for 3 days
Jha et al. (*11*)	Micro; MITSIMLab	Urban Network	Travel time	Detector data for 15 days for a.m. and p.m. peaks on a large urban network
Toledo et al. (*12*)	Micro; MITSIMLab	Freeway, arterial	Speed, density	Data from 68 detector stations on 3 freeways for 5 weekdays
Qin and Mahmassani (*13*)	Macro; DYNASMART-X	Freeway Network	Speed	Data from 7 detector stations on 3 freeways during a.m. peak for 5 weekdays
Balakrishna et al. (*14*)	Micro; MITSIMLab	Freeway, Parkway	Traffic counts	15-min data from 33 detector stations
Zhang et al. (*3*)	Micro; PARAMICS	Urban Freeway network	Flow, occupancy	5-min detector count during p.m. peak for 7 days
Li et al. (*15*)	Macro	Freeway	Flow	Loop detector data
Lee and Ozbay (*4*)	Micro; PARAMICS	Freeway	Speed, counts	5-min detector count during a.m. peak for 16 days
Sumalee et al. (*16*)	Macro	Freeway	Flow	Loop detector data for 7 h on 3 days in 2 years
Yang and Ozbay (*5*)	Micro; PARAMICS	Freeway	traffic conflict, lane change, volume and speed	NGSIM trajectory data for US-101 for 15 min
Henclewood et al. (*17*)	Micro	Freeway	Travel time distribution	NGSIM trajectory data for Peachtree Street in Atlanta, Georgia, for 30 min
Punzo et al. (*18*)	Micro	Freeway	Speed	NGSIM trajectory data for I-180

proportion of cars, trucks of different types, buses, taxis, and possibly the age of vehicles types.

    3.   Demand data. The above two types of data help define the classes for various agents modeled. Demand data includes the total number of agents in each class.

    4.   Pedestrian and bicycle data. In case the simulation involves nonmotorized transport as well, then the above types of data (agent type and demand) are required as inputs for modeling.

    The number and types of parameters depend on the level of modeling detail intended by the modeler. Based on the level of detail, the models can be classified as, macroscopic, mesoscopic and microscopic simulation models. The complexity and time consumed to execute the models increase in the same order, namely, macroscopic, mesoscopic and microscopic simulation models. While microscopic simulation models provide an ideal platform for detailed modeling, the number of parameters involved in the modeling and thus the effort in calibration is greater. Parametric data span a wide variety of items:

    1.   Link parameters. These involve link-level parameters such as number of lanes, capacity, free-flow speed, jam density, speed limit, and link's visibility characteristics (sign posting distance, ramp awareness, etc.) depending of the modeling resolution chosen.

    2.   Path parameters. The path parameters include aspects influencing the route choice of users such as toll, if any, along each path, travel time on possible alternative paths, etc. This manifests in the modeling process as proportion of users using different links at intersections, ramps, etc.

    3.   Network infrastructure parameters. Signal timings (variable adaptive timings, if any), at intersection and ramps are also another important parametric data that drives the traffic simulation model. Additionally other infrastructure data such as variable sign messages, work zones, etc. also influence the driver behavior in the simulation model.

    4.   Weather. Weather affects the performance of roadways and is important in modeling the traffic. Rain, snow, fog, etc. affect the pavement condition and visibility which in turn affect the link capacity, free-flow speed, etc.

    5.   Driver-level data. This is a very important parametric data for traffic simulation, especially so for microscopic simulation. Gap acceptance is a crucial parameter in simulation of merges (at traffic circles, ramps, lane drops, and turning at intersections) and lane changing on freeways. Similarly, lane selection is also an important factor in determining the model accuracy of specific geometric features such as toll plazas and intersections. In order to obtain gap acceptance and lane selection data, extensive video data of the modeling area is necessary.

    6.   Activity–behavioral data. An important input and parameter in, especially, in simulation of long-term aspects is the activity data. Activity data encompasses a wide range of user behavior to changes to link characteristics such as changes in toll, capacity or number of lanes (due to weather, maintenance or incidents), speed limit, other time-dependent restrictions (truck restrictions, high occupancy vehicle lanes). Activity data can be used as input data if it results in changes to demand and/or vehicle composition. It can also be used as different parameter set to model changes in capacity, free-flow speed, or other link-level parameters.

    Output data is essential in evaluating the accuracy of simulation models. The outputs that are measured in real world and can be used to validate the traffic simulation models include:

1. Flows and speeds. Flows and speeds observed at various locations of the modeled area are some of the most commonly used and widely available data for model validation.

2. Queue data. Queues and lane usage at various facilities such as, toll plazas, traffic signals, and circles can be used to determine the performance of the simulation model in congested conditions.

3. Trajectory data. Trajectories of vehicles are an important output of microscopic traffic simulation models and an important input to calibrating car-following, gap acceptance, and lane chance models.

4. Accident data. The frequency and location of crashes are very important data for evaluation of the accuracy of simulation model's predictive capacity of traffic safety. Many surrogate safety measures can be used in the prediction of traffic safety which is compared to the observed safety data of crash frequency and locations.

5. Emission data. Measurements of air pollution due to vehicular traffic are important output of traffic simulation model. The quantity is various pollutants considered in the model can be measured in the modeling area and used to evaluate the accuracy of the prediction of pollutant quantities. However, measuring the air pollutant levels in real world is far from a trivial task. The measurement can be cumbersome and estimates are dependent on many other factors unrelated to traffic, such as air temperature, humidity, wind speed, etc.

DRAWBACKS OF EXISTING SIMULATION CALIBRATION METHODOLOGIES

In general, simulation models are mathematical models in which output is derived from a particular model given the input. The input consists of two main groups of data: physical data (e.g., volume counts, capacity, and physical features of roadway sections) and calibration parameters (i.e., adjustable components of driver behavior). Thus, a simulation system (S_s) can be described generally as (*21*)

$$S_S : f(I_S , C_S) \rightarrow \text{(simulation model)} \rightarrow O_{sim} \mid I_S , C_S + \varepsilon : O_{obs} \tag{1}$$

where

$\begin{aligned}
f(I_s , C_s) \;&= \; \text{functional specification of the internal models in a simulation system;} \\
I_s \;&= \; \text{physical input data observed in the field (O-D demand, geometric design,} \\
& \quad\;\; \text{operational rules, etc.);} \\
C_s \;&= \; \text{set of calibration parameters for a simulation system (user- and traffic-related} \\
& \quad\;\; \text{parameters);} \\
O_{sim} \;&= \; \text{simulation output data given the input data and calibrations;} \\
\varepsilon \;&= \; \text{acceptable margin of error between simulation output and observed field data; and} \\
O_{obs} \;&= \; \text{observed field data.}
\end{aligned}$

The process of calibration entails adjusting the calibration parameters (C_s) so that the error between the output from simulation and field conditions is minimized,

$$\min U [O_{obs} , O_{sim} (I_s , C_s)] \tag{2}$$

where

$$O_{obs}, O_{sim} = \text{observed and simulated outputs at location } I;$$
$$C_S = \text{parameter set for time period } t \text{ and iteration } k; \text{ and}$$
$$U = \text{error functions for outputs.}$$

From the previous subsection it is evident that many sources of data, as model inputs, calibration parameters and observed outputs, are required in traffic simulation modeling and calibration. FHWA's Traffic Analysis Toolbox recommends that if

$$\text{GEH} < 4 \; (\; \text{GEH} = \sqrt{\frac{\frac{1}{T}\Sigma_{i=1}^{T}(O_{sim,i} - O_{obs,i})^2}{\frac{1}{2T}\Sigma_{i=1}(O_{sim,i} + O_{obs,i})}} \;)$$

for link volumes for 85% of the links and average travel times are within 15% of observed values, then it is considered as a satisfactorily calibrated model (*22*). In order to achieve this level of calibration for various conditions (peak, off-peak, weekends, normal and inclement weather, under accident, and other events), detailed level of data is required.

As illustrated in Table 1, most of the studies in traffic simulation used limited amount of data focusing on a small set of conditions and/or time periods. As depicted in Figure 1, using only smaller samples of data will not accurately capture variation in traffic data (Additionally, the sources of field data in most of these studies, except (*4–5, 18*), have been traditional sources such as loop detectors or manually-acquired data from captured videos which can be cumbersome and not always accurate enough). Evidently, using these models for conditions other than the ones for which calibration data was available for would not yield accurate results. The following subsection briefly investigates this issue related to the lack of comprehensive data for calibration.
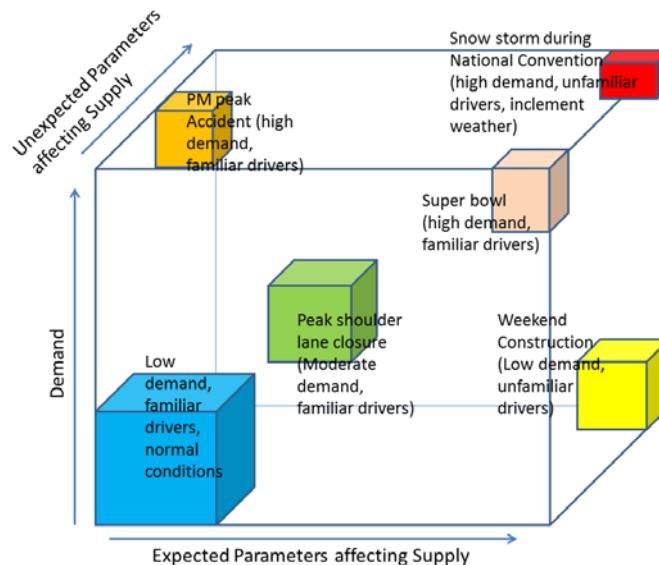

**FIGURE 1 Illustration of various traffic conditions for which
data is required for calibration (adapted from *23*).**

Distribution of Traffic Data and Its Impact on Calibration: Existence of a "Typical" Day

Most of the past traffic calibration is based on the assumption of a typical weekday or weekend day at best (*1, 2, 7, 12–14*). Analysis of demand data distribution can provide a useful insight into whether representative days do exist in traffic. For this purpose 15-min demand data extracted from E-ZPass data from the New Jersey Turnpike (NJTPK) for a year is analyzed as an example. Depending on how close or distant the demand values for each 15-min time interval are to each other, attempt is made to classify the demand data for each time period into clusters. Each cluster represents a group of demands that are similar to each other and can be represented by the centroid of the cluster. The basic hypothesis is that the greater the number of clusters, the lower is the likelihood of existence of a "typical" day.

There are 28 interchanges on NJTPK spread over different spacing. Considering the roadway between each interchange as a link, there are 65 links in northbound and southbound directions on the NJTPK system. For the purpose of clustering demand, the 15-min demand data between September 2011 and August 2012 for 5 a.m. to 9 p.m. is analyzed.

For clustering time series data, some of the common algorithms used are *K*-means clustering, hierarchical clustering and fuzzy *c*-means clustering (*24*). For the electronic toll collection data, we use *K*-means clustering. In order to determine the optimum number of demand clusters, silhouette statistics are generated for each of the links. Silhouette statistics show how dissimilar a particular demand value is from its demand cluster centroid. The results show varying number of clusters for various links in the NJTPK system. Table 2 shows the number of links for the optimum number of clusters. Also a sample of distribution of demands and their corresponding clustered demands of four different links are shown in Figure 2. It can be seen that there are links for which the demand falls into multiple clusters. Twenty-four links have demand falling into two optimal clusters, 32 links have three clusters, and so on. More than 63% of the link demands have three or more clusters. Among these clusters there are different weekend or weekday demand distributions. This means that considering a single distribution of demand for a weekday or weekend is not sufficient to accurately calibrate a simulation model that can be used throughout the year.

In order to show the representativeness of the clusters, we show the frequency of observations versus their cluster number. Figure 3 depicts the likelihood of an observation (i.e., the demand on a link for a day in the whole year) to fall into a particular cluster. It shows that 35% of observations fall into clusters one or two and 20% of demands fall into four other clusters. Although 35% of observations do fall into one or two clusters, the distribution of the observations within the cluster is fairly large, as can be seen from the spread of observed demands around the clustered demand in Figure 2.

**TABLE 2 Distribution of Number of Links on
NJTPK and Optimum Number of Clusters**

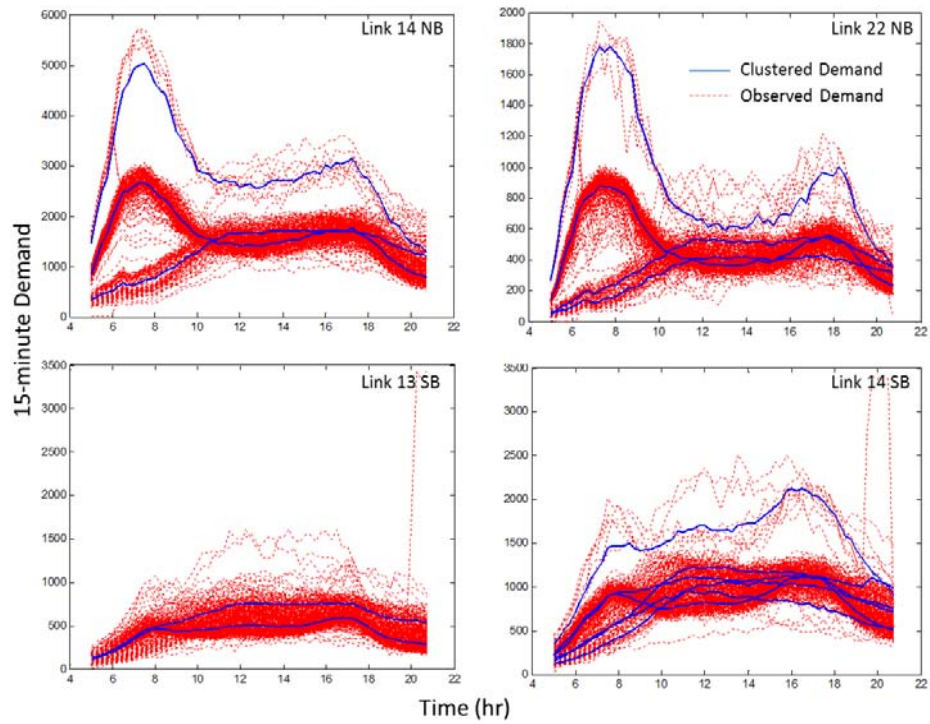| Optimum Number of Clusters	Number of Links
2	24
3	32
4	7
5	1
6	1

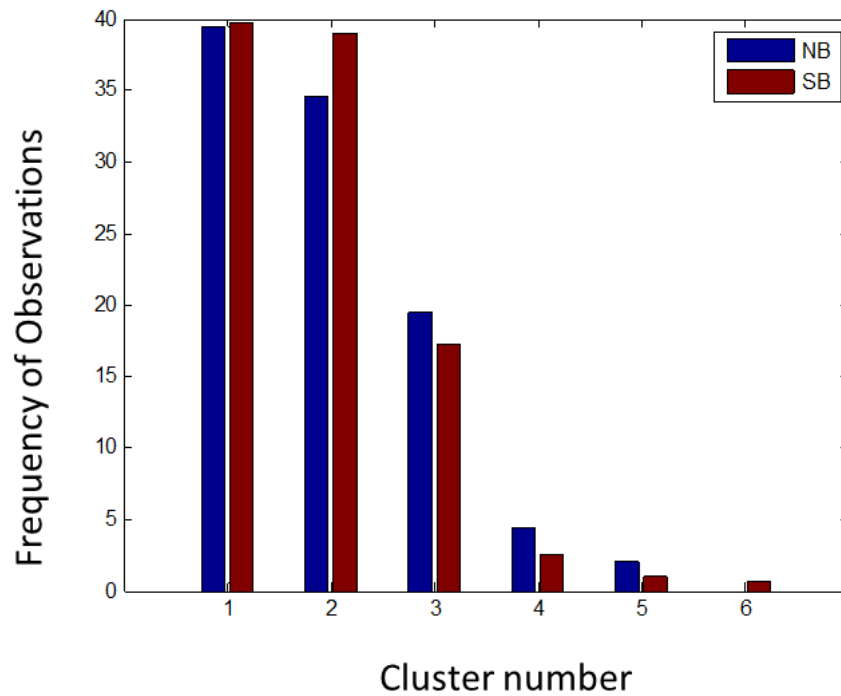**FIGURE 2 Illustrations of clustered demand for four different links on NJTPK.**

FIGURE 3 Frequency of number of observations for all links in each cluster

This analysis illustrates that the existence of a typical day in traffic demand is not always likely. Hence, to obtain accurate predictions from a traffic simulation model, it is important to consider not only the demand from various clusters, but also the variation of demand within each cluster. The above discussion is based on the distribution and spread of traffic demand. However, the actual traffic flows along the section of interest would also vary based on many conditions such as, incidents, work zones, driver–vehicular variability, and other unobserved phenomena. With the availability of event data, an additional part of the variability in flow can also be captured.

ROLE OF BIG DATA FOR TRAFFIC CALIBRATION

Based on the discussions above, making accurate predictions using traffic simulation models requires calibration data from many sources and in great detail. This data need can be effectively addressed by the advent of new technologies such as GPS, cellular phones, RFIDs, etc. The ubiquity of these technologies ensures that data of great detail and variety are available. These devices can provide location data at less than a second frequency over the whole vehicular network.

RFID tag readers provide detailed demand and vehicle data at locations such as toll plazas. Additionally they provide flow and speed data along the roadways with RFID readers. Data from GPS devices and cellphones can also provide speed data along almost all roadways. Aside from demand, speed and flow data, Big Data can also include event data. Various applications on smartphone devices allow users to report events such as accidents, work zones, etc. Also, anonymized tracking and analysis of these devices over a longer duration of time also provides data about drivers' departure time choice and other behavioral data.

Thus Big Data has the potential to provide vast amounts of demand, vehicle, speed, flow, event, and behavioral data. All this data are obtainable with very low human intervention. As an illustration, suppose that there is a need for collecting flow and demand data for calibration. Without the availability of Big Data, the analysts and modeler must collect data from field at the study section. This may be available through loop detector data on some sections such as freeways. However, reliability of such inductive loops may not be satisfactory. For example, the data from loop detectors in the California DOT system that are not missing and statistically reliable vary between 25% to 78% (*25*) Without loop detector data, modelers can capture video data from the field or obtain the manual counts. Then these counts have to be used to predict demands using estimation algorithms. All this requires much greater effort and time, and the resulting sample size is still limited.

Big Data provides an excellent opportunity to improve traffic simulation modeling and prediction. Due to the ease of collection, Big Data is available fairly quickly after the period of interest. This helps in obtaining data even for conditions that may change driver behavior such as changes in control at intersections, lane configuration at toll plazas, toll rates, etc. Thus Big Data could even help in modeling traffic for various conditions.

FHWA recommends areas where analysts can focus their attention to avoid creating models that produce inaccurate results, such as, not adjusting default values, spending more time on calibration, and problems within the model in terms of network geometry and data collection (*26*). Big data ties in well with all these recommendations and can additionally save time and money per unit of data collected.

Description of New Data Sources for Calibration

In this section we describe various sources of Big Data available.

ETC Data

The electronic toll collection (ETC) data is collected for all tollways in the United States and in New Jersey for New Jersey Turnpike, Garden State Parkway (GSP), and Atlantic City Expressway. Taking toll facilities in New Jersey as an example, its NJTPK is spread over 150 mi with 28 interchanges and 366 toll lanes. GSP is about 170 mi long with 50 toll plazas and 236 toll lanes. Each freeway carries up to 400,000 vehicles per day (*27*). The ETC data is collected at toll plazas on these freeways (*27*). The ETC dataset consists of the individual vehicle-by-vehicle entry and exit time data. It also consists of the information regarding the lane through which each vehicle was processed (both E-ZPass and cash users), vehicle types, number of axles, etc. Similar ETC facilities are operated in many parts of the country, for example, many states along the east coast of United States are using the E-ZPass system; Florida has the SunPass system on its tollways; and Illinois has the I-PASS system on tollways.

Traffic Data Providers

There are several traffic data providers such as INRIX, NavTeq, TomTom, etc. INRIX monitors traffic flows across more than 260,000 mi of U.S. and Canadian highways, provides real-time traffic information for 32 countries across North America and Europe as well as information that comes from 800,000 vehicles equipped with GPS devices (*28*). In addition, INRIX receives information from road sensors located in about 9,000 mi of highways. It is the only crowdsourced traffic network and it receives the information from commercial fleets: taxi cabs, delivery vans and long-haul trucks, and mobile devices. INRIX also reports incidents and unique local variables (*29*). INRIX offers developers real-time traffic and routing information using API access. Kim et al. (*30*) evaluated the accuracy of travel times based on Bluetooth sensors, electronic toll tag readers, and INRIX data. They compared the travel times with the ground truth data and worked on the study segment of I-287 in New Jersey. They concluded that the speeds of probe vehicles are closer to the estimated speed using Bluetooth sensors than the INRIX data. In addition, INRIX data showed some latency issues.

GPS Data from Large Vehicle Fleets

There are several large vehicle fleets with individual vehicles instrumented with GPS that transmits location data regularly to a central database. Such fleets include taxis (*31–34*) and trucks (*35*) which generate such location data. For example, the position data collected from GPS devices attached to taxis are also a great source of Big Data. Among several North American cities where this type of taxi data is collected, Taxi–GPS data provided by New York City Taxi and Limousine Commission consists of more than 40 million records per year integrated to a single database. A trip is defined as the time period between customers hire a taxi cab and get off the taxi cab, therefore empty trips are not included in the dataset. Data is recorded per trip, including fields such as trip start–end times, trip duration, location of O-D, and trip fare. Routing information is not available since location recording is not performed in a continuous manner.

The data includes GPS recordings from more than 13,000 taxis covering all time periods and almost all regions in New York City. According to the calibrated New York Best Practice (NYBPM) travel demand model, taxi traffic accounts for 11.9% of total traffic flow in Manhattan (*36*). Several studies in the literature agree on penetration rate ranging from 1% to 5% of total traffic can be adequate for representing overall network traffic conditions (*31–34*). Privacy issues are important challenges to scaling of GPS data-based traffic monitoring. Daus provides a good summary of legal background and unsolved problems regarding the privacy issues for collecting taxi-GPS data. A recent study by Xie et al. (*36*) have already illustrated that the similar taxi–GPS data can provide rich information to calibrate traffic safety model. The taxis as probe vehicles can cover more areas, even those without traffic surveillance units. Therefore, they can provide more data sources (i.e., routing and travel time) for both analytical traffic models as well as simulation models.

Cellular Network Data

Cellular telephone networks have the potential to provide near real-time information about human mobility on a large scale and at a low cost. Since people usually carry their cell phones with them, the location of a phone is a good proxy for the location of its owner. Thus cell-phone signals can provide useful traffic and travel demand data. Data points are only generated when a call received or dialed, SMS is received or sent and when the user connects to the cellular internet network, thus obviating the need for active user input for data collection. Usually the cell phone data cannot be directly obtained from the carriers. Users have to purchase or contract with the other companies such as AirSage, ComScore, Inc., and SAP AG that take mobile-user data from carriers. A number of field studies already examined the feasibility of using the cell phone data for the traffic analysis (Table 3).
    Despite their large scale, cell phone data still have a number of issues that should be carefully addressed when used for calibrating simulation models. The primary issues include data coverage, sample bias, data availability and resolution, data suppression, and geographic level of detail. Especially, due to the lack of various demographic characteristics required for travel demand models, the cell phone data may not be useful per se. Extensive amount of survey data used in calibrating the travel demand models of regional planning models (*47*) are required to obtain the correct order of magnitude of O-D travel demand matrices. Thus, instead of independently used, the cellphone data can be used in conjunction with baseline data using travel demand surveys and fine tuning using the travel demand data.

Crowdsourcing Data (Virtual Sensors)

Travel times can be collected using crowdsourcing data from online services that provide real-time or historical traffic data. API services that are available for developers offer collecting, storing and processing large volumes of network-level data. The web mapping APIs deliver several HTTP web services such as static map, directions, distance matrix, elevation, geocoding, and places. While web mapping applications provide very efficient methods to visualize large amounts of datasets, real time traffic data are also available to users. Responses from the mapping services are usually delivered in XML or JSON formats which can be easily processed in almost any computer language. Services such as Google Maps, Bing Maps, and MapQuest

TABLE 3 Summary of Studies on Cellular Phone Data Collection

Study	Scale	Target Data	Validation	Indicators	Results
Caceres et al. (*38*)	Corridor (simulation); 24-h period	O-D matrices	Loop detectors	Relative error of vehicle counts	Estimation errors tend to decrease as observation intervals increase
Calabrese et al. (*39*)	Urban, suburban, extra urban area; 200 measurement points	Position; Travel time	GPS data	Position: 50th, 67th, 95th percentile error; travel time: mean absolute percentage errors (MAPE)	Average error in meter: 159 (urban), 295 (suburban), and 1,457 (extra urban); MAPE: 10.08% ~ 17.66%
Calabrese et al. (*40*)	8 counties (5.5 million people); 25% of available users	O-D matrices	Tract–tract worker flows dataset from the Census Transportation Planning Package	R^2 for the linter regression	Estimated O-D matrices resemble O-D matrices generated from gravity model
Frias-Martinez et al. (*41*)	City of Madrid and 48 municipalities (6.5 million people and 8,000 km^2); 2-month data (3.5 million unique phones and 300 million interactions)	Commuting O-D matrix	Commuting matrices from National Statistical Institutes (NSI)	Correlation between matrices	Good correlation; not completely comparable with NSI matrices; the generated matrices contemplates more situations
Zhang (*42*)	A county in Wisconsin; Small part of Shanghai	Mode shares; Static- and dynamic O-D matrices	Local trip survey results; Traffic counts from loop detector/ simulation	Root mean square error (RMSE); RMSE normalized (RMSN) volume; MAPE; R^2 for the linter regression	Feasible method for O-D estimation; largely capture mode share patterns

TABLE 3 (*continued*) Summary of Studies on Cellular Phone Data Collection

Study	Scale	Target Data	Validation	Indicators	Results
Yoo et al. (*43*)	6,398 taxi trips in Cheongju; 3 weeks	O-D estimation	GPS-based taxi O-D	Scatter diagram, correlation coefficient; MAPE; RMSE	Scatter diagram shows high positive correlation between observed O-D and estimated O-D; Relatively low value of MAPE
Bekhor et al. (*44*)	16 weeks; an average sample of 10,200 phone numbers/week; 79 million positions	Long-distance trips O-D matrix estimation (trips longer than 2.5 km)	National household travel survey (NTHS, 10-year old)	Direct comparison	Trip rates and length is higher than the NTHS data; cellular phone data produce more trips than the NTHS survey
Gonzalez et al. (*45*); Yang et al. (*46*)	100,000 phone users; 6 months	Travel behavior; trip distribution	Surveys	Direct comparison	

have very comprehensive real-time traffic coverage around the world. Recently Morgul et al. (*48*) give a comprehensive review and present a virtual sensor methodology based on BingMaps API and MapQuest Map API traffic data. Table 4 is the summary of selected web- based services with the data characteristics that are promising for transportation research. In Morgul et al. (*48*), data quality is tested by comparing the travel time estimations from virtual sensors with physical loop detector and electronic tag reader data for different sections of NJTPK. The results of these statistical comparisons show high correlations between physical sensor and virtual sensor data. With the advances in data collection technologies, more and more data have been generated every day and the future of web-based virtual sensor concept is encouraging since it offers low-cost and high-quality data for research and deployment purposes. The virtual sensor methodology can be an attractive approach to transportation agencies as an alternative low-cost traffic surveillance method.

TABLE 4 Summary of Selected Web-Based Services That Offer Traffic Information for Developers (*48*)

	API	Geocoding Service	Transit Integration	Live Traffic Information	Directions	Distance Matrix	Map Data Providers	Offered Services	Mobile App
Nokia Maps (*49*)	JavaScript, REST, Mobil HTML5	2,500 daily limit (base plan)/10,000 daily limit	Yes	Yes	2,500 daily limit (base plan)/10,000 daily limit (core plan)	2,500 daily limit (base plan)/10,000 daily limit (core plan)	Navteq	Positioning, routing, traffic	Yes
Bing Maps (*50*)	AJAX.WPF, WP, Android, iOs, Silverlight, REST, SOAP, Win 8 (.NET, JS)	Yes	Yes	Yes	Yes	Yes	Navteq, Intermap, Pictometry, International, NASA	Geocode, imagery, route, search, common classes, and enumerations	Yes
Google Maps (*51*)	Javascript, iOS SDK	Request per day 2,500 (free license)/ 100,000 business)	Yes	Yes	Request per day 2,500 (free license)/ 100,000 business)	100 elements per query (free license)/635 elements per query (business license)	MAPIT, TeleAtlas, DigitalGlobe	Direction, distance, matrix, elevation, geocoding, max. zoom imagery, street view	Yes
MapQuest (*52*)	Javascript, AS3/Flex, SDK, iOS	No present limit (open data)/5,000 cals/day (licensed data)	Yes	Yes (only for licensed data)	No present limit (open data)/5,000 calls/day (licensed data)	No present limit (open data)/5,000 route pairs/day	Navteq, Open Street Map user contributions	Directions, geocoding, search, route matrix, traffic	Yes
NextBus (*53*)	Yes	No	Yes	No	No	No	Cubic Transportation Systems, Inc.	Real-time passenger information	Yes
TomTom (*54*)	Yes	Yes	No	Yes	Yes	No	TomTom International BV, Whereis	Maps, routing, geocoding, traffic	Yes

Event Data

Several agencies collect event data related to all the accidents, incidents, and crashes as well as other road related events. For example, Transportation Operating Coordinating Committee (TRANSCOM), an agency that coordinates the activities of all of the transportation agencies in the New York–New Jersey region, collects volume, speed, and travel time data through electronic readers, known as TRANSMIT data (*55*). TRANSCOM also provides data specific to specific events in the transportation network. Events such as, major constructions activity, major accidents, hurricanes, sporting events, conventions, etc., may cause disruptions in the transportation network. Having such data available provides the ability to calibrate the simulation models accurately for these special events as well. The event data can be generated from an XML feed from the TRANSCOM database. Around 5,000 event records are obtained on an average in a month.

CASE STUDIES

We have shown that existence of typical days in traffic data is very unlikely. Hence, for calibration of traffic simulation models on a larger scale and in a comprehensive fashion requires richer variety and larger quantity of data. As mentioned in the previous section, Big Data provides the data required for this purpose. The three inputs required in traffic simulation models: model input, calibration parameters and observed output, can be obtained by using various Big Data sources. ETC transaction data can be used to generate accurate demand and vehicle type estimates for model input. Observed outputs such as speed and travel time can be obtained from numerous sources such as INRIX, GPS tracks and data from cellular phones and Bluetooth devices. Travel time can be obtained from cellular phone, Bluetooth devices and crowdsourced data. For calibrating models for specific incidents, event-specific data such as speed and congestion information during accidents, inclement weather, etc. can be generated from TRANSCOM databases. For calibrating model specific parameters and algorithms, fine grained data such as trajectory data is required. Currently, such data are available by conventional databases, such as Next Generation Simulation (NGSIM) (*56*) or MULTITUDE (*57*).

The following sections illustrate the use of Big Data in various case studies conducted by the authors of this paper.

Newark Bay–Hudson County Extension PARAMICS Simulation Model

This study was conducted to estimate the regional traffic impacts of a proposed one-lane closure along a very critical area of the Northern New Jersey highway network, and within one-mile of the Holland Tunnel (*58*). A number of sources, of both traditional data and Big Data, were used for the purposes of constructing and calibrating the simulation model. The Big Data sources in this study were ETC data, INRIX data and TRANSCOM event data. Model inputs related to infrastructure were collected using the satellite imagery of the study area and site visits.

NJTPK ETC dataset, an important Big Data source, was used to generate traffic demand for the simulation model. This provided detailed hourly volume data for the entire NJTPK system, and most importantly the entries at Interchange 14C on the Newark Bay–Hudson County Extension (NB-HCE). Manually acquired volume counts, turning movements,

automatic turn reader data, estimated hourly turn counts, volume counts from web traffic viewer tools of New Jersey DOT and New York State DOT and optimized traffic signals timings are used to construct and calibrate downtown Jersey City network. Where detailed volume data were not available, output from the regional travel demand model North Jersey Regional Transportation Model–Enhanced (NJRTM-E) was used.

TRANSCOM provided data for three critical holiday weekends in 2010: Memorial Day, Independence Day, and Labor Day, primarily to determine the change in traffic levels during holidays. Additionally, traffic conditions during major incidents are also provided by TRANSCOM. The event data were generated from an XML feed and saved as Excel files. Around 5,000 event records were obtained on average in a month.

Speed data collected by INRIX's New Jersey network were used to calibrate the link speed outputs from the simulation model. INRIX's data include 2,786 links, covering most major highways and arterial roadways for 2010 with over 300 million total data points. Figure 4 shows the speed profile on I-78 West NB-HCE within the project limits for a given weekday. It indicates that the slowest period is in the p.m. peak, from 5:30 to 6:30 pm.

This study illustrates the synergistic use of traditional data sources and Big Data in constructing a large scale calibrated traffic simulation model. All of the above data were used to calibrate the simulation model shown in Figure 5. The final O-D demand matrix was composed of 82 zones. Twenty-eight of these zones are the NJTPK interchanges, six zones are located in the Manhattan side, and the rest of the zones are located in Jersey City.
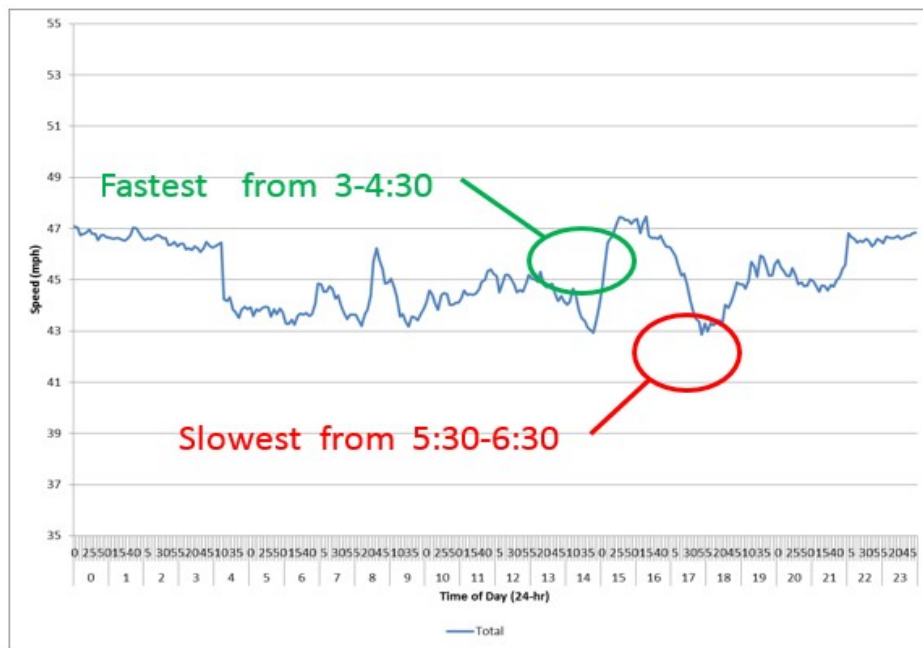

FIGURE 4 NB-HCE westbound average weekday speeds from INRIX data (*58*).
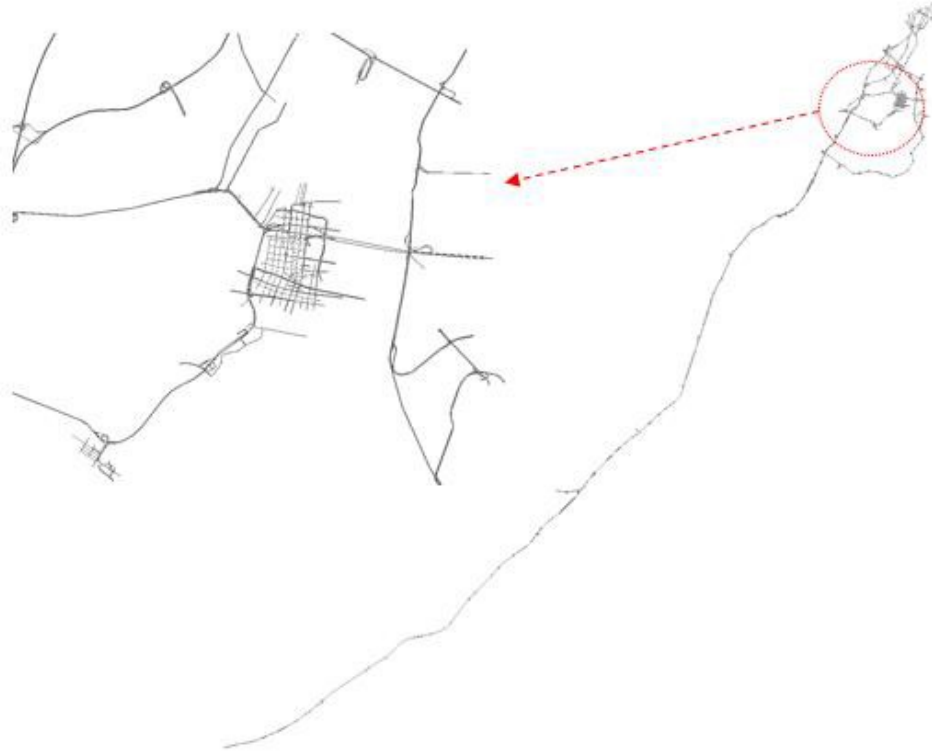
FIGURE 5 Complete simulation network (*58*).

The results showed that simulated volume counts are within 10% of observed volume at these critical locations during the afternoon peak hour. The overall error is 6.2%, 1.2%, and –4.9% for I-78 westbound, Route 139 westbound, and Route 495 westbound, respectively. Simulated link speeds are within one standard deviation of average observed speeds extracted from the INRIX database in almost all locations.

Calibration of Models with Specific Features

Calibration of traffic simulation models with specific control features such as roundabouts, toll plazas is more involved than that of freeway sections. In addition to considering variability of basic traffic flow parameters, there is a need to consider the effect of special geometric characteristics of the individual components of the modeled network such as merge locations on freeways and traffic circles, lane configurations for toll plazas, etc. Moreover, user behavior in relation to these specific geometric characteristics need to be captured by calibrating model parameters such as, mean reaction time, mean headway, route choice parameters, aggressiveness and familiarity of drivers with the system, etc.

The calibration microscopic simulation models of freeways involves calibrating parameters for car following such as mean reaction time and target headway, parameters for lane change and gap acceptance and even parameters for route choice. However, microscopic simulation models involving specialized modeling of geometric features also involve many parameters.

Calibration of Toll Plazas

For the purpose of calibrating traffic simulation models of toll plazas, Big Data, in particular, ETC data for generating demand distributions was very useful for this study. For example, Ozbay et al. (*59*) modeled and calibrated a microscopic simulation model of NJTPK, including its 28 toll plazas. The modeling process involved customization of driver behavior at the toll plazas based on entry and exit ramps. Along with the global mean reaction time and headway the other parameters used in the calibration process were link-level reaction time and headway at the toll plazas. The authors used peak and peak shoulder ETC data during a.m. and p.m. periods in 2003 involving around 100,000 vehicle transactions per hour, to calibrate the model.

Mudigonda et al. (*60*) developed a generic approach for modeling toll plazas and calibrated the models for different toll plazas. Their methodology entails modeling the drivers' lane choice decision process using a linear utility model. The utility model is expressed as a function of the entry ramp of the driver, the queue at each toll booth of the toll plaza and the exit ramp that the driver intends to take after exiting the toll plaza. The authors evaluated the algorithm for three different types of toll plazas, namely, one with two entry and exit ramps, two entry and one exit ramp, and one entry and one exit (barrier) toll plaza. In addition to the demand data, the probabilities of choosing specific lanes given the entry and exit of the vehicles are also generated using ETC data involving 3,500 vehicle transactions per hour for each of the three toll plazas. The authors implemented the model in PARAMICS and compared the lane usage at the toll plazas (*60*). The ETC data from a.m. peak period from October 2007 and May 2008 was used to estimate the utility model parameters and simulation model calibration.

Ozbay et al. (*61*) modeled the driver behavior at the toll plazas on the New Jersey Turnpike using a discrete choice model. They use approach ramp, exit ramp and queue lengths at the toll booths as the model parameters. The authors implemented the model in PARAMICS. The ETC data from a.m. peak period May 2008 (3,500 vehicle transactions per hour) and video recording from July 2006 were used to estimate the discrete-choice model parameters and simulation model calibration.

Freeway Merge Section

A proposed freeway merge with a three-lane inner roadway merging with a three-lane outer roadway, on NJTPK south of interchange 8A was evaluated for operational and safety performance for current and future conditions (*62*). In this study as well, the source of Big Data is ETC data using which demand distributions were generated from 38,000 vehicle transactions per hour for four Fridays in September 2006. Two geometric designs were compared, first, a 3,600-ft straight taper in which one lane drop would transition immediately into the next lane drop; and second, a more gradual broken back merge that would incorporate a 1,500-ft tangent section between each lane drop. The microscopic simulation model was simulated in PARAMICS. The demands representing the average Fridays in September 2006 were generated from ETC data and used in the calibration of the model. In addition to demand data, extensive accident data is used to evaluate the safety using surrogate safety measures (*5*).

Analysis of Off-Hour Deliveries of Commercial Trucks Using Macroscopic Traffic Models

Quantification of the economic effects of an off-hour deliveries (OHD) program to roadway users requires a detailed analysis of the benefits from potential reductions in travel time and other externalities. In order to assess the impacts of the shifts associated with the OHD scenarios, two different methodologies were used. The first method uses a comprehensive macroscopic travel demand model (*65*), which is developed for the TransCAD software tool, New York Best Practice Model (NYBPM) (*36*). The second method uses New York City taxi–GPS data to observe the travel time differences by time-of-day. In this second method, actual trips that are associated with daytime deliveries are determined and taxi–GPS data is used to estimate the travel time benefits for the case when same trip takes place in off hours.

Calibration of a Travel Demand Model Using Big Data

NYBPM covers almost all major transportation facilities within the Lower New York–Western Connecticut–Northern New Jersey region. It uses a typical four-step transportation modeling procedure with multiclass assignment for the assessment of the changes in truck travel patterns (*66*). The following sources of Big Data were identified for validating and calibrating the output of NYBPM:

- New York City bridge and tunnel counts (from New York City DOT), Metropolitan Transportation Authority, and Port Authority of New York and New Jersey. The New York City DOT's Bridge and Tunnel Volume datasets (New York City DOT, 2007) are most useful since the focus area is Manhattan. Since Manhattan is an island, counts are available at all entry points. However, the collected data does not perfectly hold suit for comparison to NYBPM output; several agencies own and operate the crossings into Manhattan and collect and provide data differently. Additionally, some links could not be used for calibration since data was not collected, especially during overnight hours. In all such cases of discrepancies, appropriate simplifications were made.
- New York and New Jersey State DOT weigh-in-motion (WIM)–volume data. WIM stations are located on highways throughout the region, where class-wise volume data is collected by time of day. Aggregation and filtration of this data enables the researchers to determine the average and aggregate volume for a given link by vehicle class. Then the counted volume on that link can be compared to the assignment output of NYBPM for the same or similar link on the highway network. The collected data was aggregated and postprocessed to obtain average link volumes for the links in network, for all the hours of the day.
- New Jersey Turnpike truck ETC volumes at all interchanges. Using the ETC data from NJTA, vehicular flows can be estimated for every link of the system, and separated by class. This data is available for all hours of the day, thus it can aggregated and directly compared to the output of NYBPM.

Benefit Assessment of an OHD Program using Large Taxi-GPS Data

Taxi–GPS data is used as a way of measuring the benefits from an OHD program. Realistic travel time estimation for urban commercial vehicle movements is challenging due to limited observed data (i.e., trip tables), large number of O-D pairs, and high variability of travel times

due to congestion. Moreover, most traditional data collection methods can only provide information in an aggregated form, which is not sufficient for micro-level analysis. On the other hand, the usage of GPS data for traffic monitoring and planning has been continuously growing with significant technological advances in the past two decades. Therefore a practical integrated methodology is developed for using a robust source of taxi–GPS data for commercial vehicle travel time prediction (*67*). Statistical methods are used to validate the methodology and the estimations for OHD travel time savings are presented. Figure 6 shows estimated travel time savings for all O-D pairs where customers are located. Travel times are obtained by taking the median of taxi–GPS travel time data distribution, red stem bars show the daytime travel times and blue solid bars are the differences observed when the same trip is done at night period. A negative value in the solid bar means that night period travel times are shorter than daytime travel times. It is seen that significant improvements can be obtained in daytime to night shifts from all daytime periods and the maximum travel time savings can be up to 5 min per trip in median travel times.

Surrogate Safety Assessment Using a Simulation Model Calibrated with Trajectory Data

Most calibration studies only focus on one objective, for instance, minimization of the difference between simulated speed and observed speed. However, the calibration of simulation model can hardly be a single-objective process. This is because that minimization of one objective may be associated with other simulated measurements far from truth. In other words, the trade-off among different objectives (i.e., operation versus safety) should be balanced while calibrating the simulation models. When more objectives are considered, more input data are necessary to support the calibration of each objective. For example, instead of only using speed measurements from loop detectors to calibration the simulated speed distribution, a large-scale high resolution trajectory data are needed for calibrating the traffic safety indicators while also considering the speed distribution.

   Using the NGSIM data as a precursor to the anticipated large-scale trajectory data, Yang and Ozbay (*5*) have conducted a case study to demonstrate the needs of balancing both operational and safety objectives in calibrating simulation model as well as the use of detailed
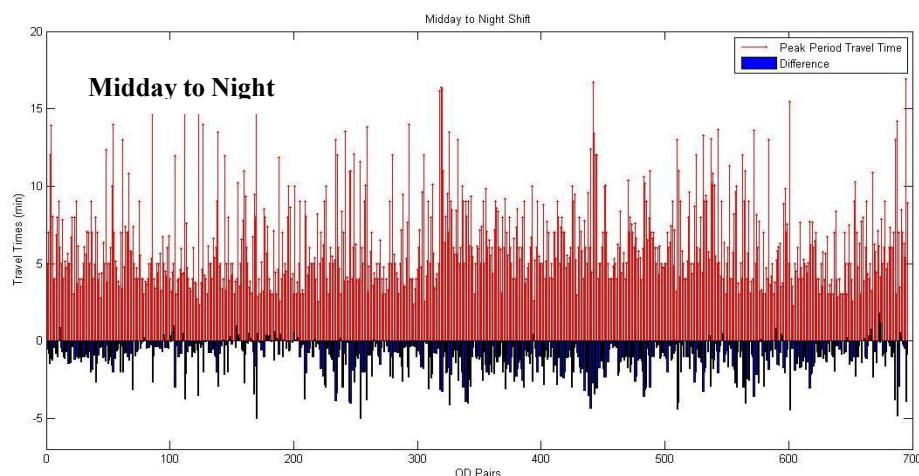

FIGURE 6 Travel time differences by OHD shifts using taxi–GPS data.

vehicle trajectory data. Other than the three operational objectives (traffic flow, speed, and lane change), the safety objective function defined by comparing the surrogate safety measure with the field observations was also used. The surrogate safety measure was defined as the conflict probability to identify the potential risk of traffic conflict (*68*). To make the study more practical, these objective functions were aggregated using a multicriteria optimization approach as shown in Equation 3. The simultaneous perturbation stochastic approximation algorithm was then used to calibrate the parameters of microscopic simulation model.

$$\text{Min } z(\theta) = \omega_1 z_1(\theta) + \omega_2 z_2(\theta) + \dots + \omega_m z_m(\theta) \tag{3}$$

where

ω_i = is a user defined nonnegative scalar weight of the ith performance criterion $z(\theta)$. $z(\theta)$ becomes the aggregated objective function. Θ is the possible domain of parameters to be calibrated.

The study examined the results of calibrating the simulation parameter set either by minimizing a single objective function or the multicriteria objective function $z(\theta)$. The calibrated results imply that minimization of safety performance function cannot guarantee the minimization of the operational performance functions, and vice versa. However, by taking into account all objective function, the calibrated simulation model provides a better balance among different objective functions.

CONCLUSIONS

In this study, various data requirements for calibrating traffic simulation models are illustrated. It is argued that the practice of using field data from a short time frame or a typical day, is not useful in providing predictions in a wider variety of conditions. Using real-world data, it was shown that the existence of a typical day in traffic data is not evident. We illustrate the need for field data in greater detail and from a greater time span to be able to accurately calibrate traffic simulation models.

The availability of new technologies provides endless possibilities of large datasets, also called Big Data. We illustrate various kinds of data that can be obtained from various Big Data sources Table 5 shows a summary of various Big Data sources, their applicability and the size of data used in studies. It can be seen from the data samples used in various studies that the size of these data is much larger when compared to conventional data sources used in traffic simulation modeling and calibration. Typically, speed data from inductive loop detectors involve about 300 to 1,000 records per day, whereas the speed data from GPS data involves hundreds of thousands of records. We provide case studies of simulation model calibration using sources of Big Data such as, INRIX, ETC transaction data, New York City taxi–GPS data, cellular phone data, and crowdsourced data.

TABLE 5 Summary of Applications of Big Data in Traffic Modeling and Calibration

Big Data Source	Application	Size of Data
ETC Data	Travel demand (*55, 59, 60–63*); Travel time (*59, 62*)	200,000 vehicle transactions (*55*); 150,000 vehicle transactions (*59*); 3,500 vehicle transactions (*60, 61*); 38,000 vehicle transactions (*62, 63*)
GPS data (INRIX)	Speed (*55*)	300 million data points (*55*)
GPS taxi data	Speed (*31-36, 65*);	80 million taxi trips (*65*); 200 million trips (*32*)
Cellular phone	Travel demand (*38, 39, 41–46*); travel time (*40*); speed (*70*); V/C (*70*)	1.6 million people (*40*); 300 million call records (*41*); 6,398 taxi trips (*43*); 78 million GPS points (*44*); 100,000 phone users (*45, 46*)
Bluetooth device detection	Speed (*69*); travel time (*76*); travel demand (*71*)	300,000 devices (*71*); 2,000 detections (*69*); 3,000 detections (*76*)
TRANSCOM	Event-specific data (*55*)	5,000 events per month
Crowdsourced data	Travel time (*48, 73, 74*)	88,000 data points/week (*48*)
Transit transactions	Travel demand (*75*)	57 million transactions (*75*)

Future of Big Data in Traffic Simulation Calibration

As mentioned earlier, there are three types of data required in calibration, model input data, data for calibrating parameters, and observed output data. Accurate model input data of travel demand and vehicle type can be obtained from Big Data sources such as ETC transactions and cellular phone data as well as traditional O-D surveys conducted for regional planning models. On the other hand, data such as INRIX, taxi–GPS data, TomTom, and Garmin GPS data provide representative data for speeds and travel times—extensive observed output data. These data sets can be integrated to provide accurate model inputs as well as observed outputs for the traffic simulation models. In addition, detailed event data such as TRANSCOM data (*55*) provides geographic and time information about specific events and weather conditions. This information can be integrated with the speed, travel time and demand information to provide a wider and improved representation of various conditions for which the traffic simulation model are to be calibrated.

Fusion of data from loop detectors and probe vehicles has been previously performed previously using techniques such as, variations of Kalman filter (*69*), evidence theory (*76*), neural networks (*77*), etc. Large amount of data emerging from multiple and such varied emerging sources can also potentially be combined into a data fusion framework using various artificial intelligence and data mining methods.

With Big Data becoming available in greater frequency, it is possible to calibrate traffic simulation models in real-time. The online data at each time interval t provides demand, vehicle type data (I_{St}) as well as observed flows, speeds and travel times (O_{Obst}). As shown in Figure 7, calibration process can be performed in real-time, and parameters can be estimated for each time interval by minimizing the error with the simulated output (O_{Simst}).
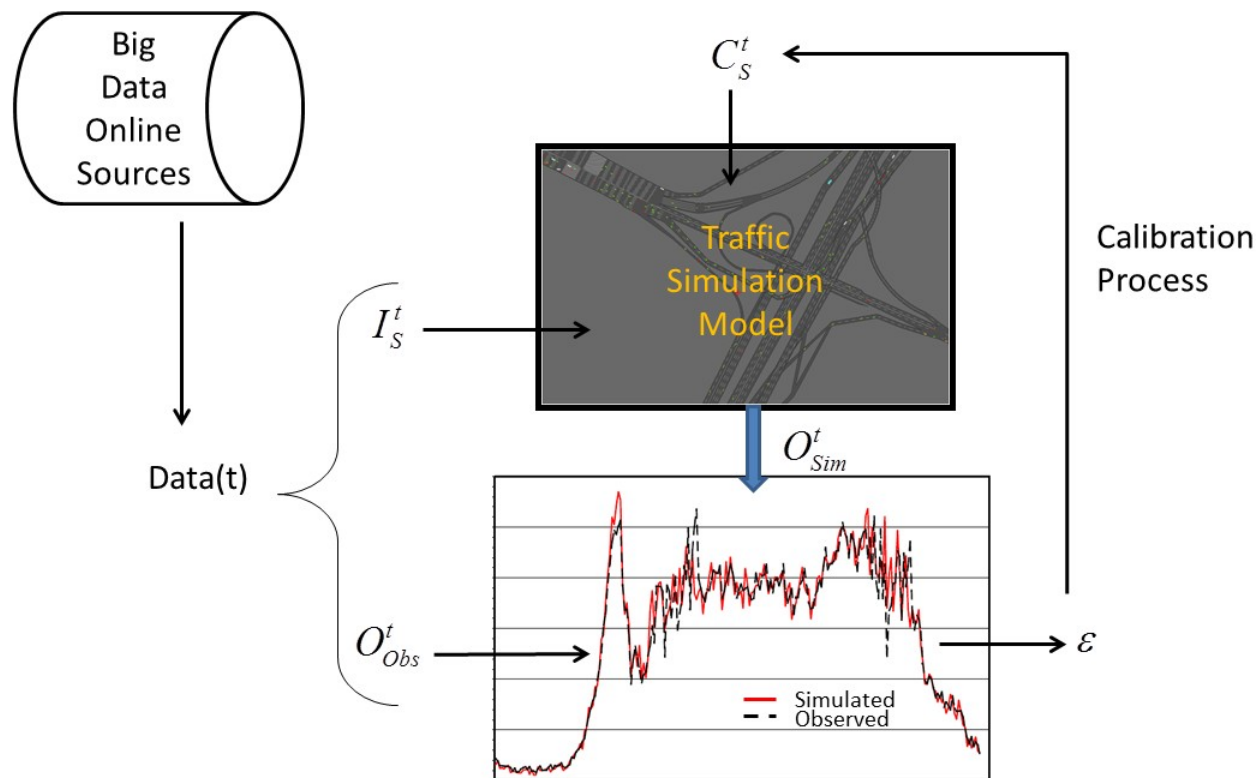
FIGURE 7 A feedback based methodology for online calibration using Big Data.

The technological advances are not just limited to devices such as smartphones. Motor vehicles are increasingly being instrumented with various sensors that not only allow detection of other vehicles but also mutual information sharing. These connected vehicles are also a great source of Big Data. One of the commonly used sensors to communication between vehicles is directed short-range communications (DSRC). The SAE J2735 Standard (*76*) defines different types of messages that can be generated using DSRC. These include basic safety messaging (BSM) and probe data messaging among many others. These messages transmit data such as vehicle position, speed, and acceleration data every 0.1 to 1 s. Data acquired at a frequency of 1 s are very useful in estimating observed data such as speeds and travel time. Availability of such data is very helpful in calibrating traffic simulation models of larger networks.

The calibration of traffic simulation models assumes that the in-built driver behavior algorithms such as car following, gap acceptance, lane changing, etc., are mathematically accurate enough. However, the existing and new driver behavior algorithms also need to be tested and eventually calibrated. The process requires position, speed, and acceleration data at a higher resolution. Traditionally such a data set is acquired by tracking vehicles from high-resolution videos of vehicular movements. Consistent with these recent developments, detailed vehicle trajectory data collection initiatives such as NGSIM (*56*) and MULTITUDE (*57*) were undertaken at few locations. NGSIM program developed detailed vehicle trajectory datasets collected on freeways and arterials for 1,600-ft sections at a 0.1-s time increments and the detailed lane positions and locations relative to other vehicles. MULTITUDE (Methods and tools for supporting the Use caLibration and validaTIon of Traffic simUlation moDEl) program

conducted by European COST initiative collected trajectory data at different sites at every 0.1 to 0.06 s on European highways and arterial networks. These trajectory data have been used to calibrate–validate a number of simulation models for different research topics, for example, car following models (*79, 80*), lane change models (*81*), safety analysis (*5, 68, 82*), traffic flow characteristics (*6*), energy and emission (*83*), etc.

Manual or semi-automated extraction of this kind of detailed trajectory data from video recordings is cumbersome and produces data for only a few numbers of vehicles and only for specific conditions. However, data transmitted using some of the connected vehicle applications have a good potential for being a viable and much efficient alternative to collecting trajectory data from video data. BSM (*76*), which disseminates vehicles' position, speed, and acceleration data every 0.1 s, offers great potential for the future of Big Data. For instance, Ford Motor Company installed over 74 sensors in cars including sonar, cameras, radar, accelerometers, temperature sensors, and rain sensors. As a result, its Energi line of plug-in hybrid cars generates over 25 gigabytes of data every hour. The cars in its testing facility even generate up to 250 gigabytes of data per hour from smart cameras and sensors (*84*). In fact there have been an increasing number of studies towards the understanding of the impacts of massive amounts of data that will become available as a result of more vehicles becoming connected (*85–88*). Clearly the extensive amount of data from these vehicles can be invaluable for the calibration of traffic simulation models not only on a one-time basis, but on a continuous basis because data will be acquired continuously. Additionally, advances in computer vision technologies can be used with conventional traffic video data and potentially generate massive trajectories for supporting the multicriteria calibration of simulation models.

Another emerging trend with the booming of smart devices with location-sensitive components is the development of many geosocial networks such as Waze, FourSquare, Facebook Places, and Google Latitude. These geosocial networks collect user locations and provide users with crowdsourced location-based services such as traffic condition (*39, 45, 46, 70*), accident information, travel suggestion (*75*), etc. The available real-time crowdsourced traffic information provide opportunities to calibrate our simulation models so that the models can be more sensitive to infrequent but high-impact scenarios such as accidents and incidents.

A culmination of the above two trends, connected vehicles and geosocial networks has been several software applications both in vehicles and on the drivers' smartphones connected to vehicles. The tremendous amount of data generated by the in-vehicle and crowd-sourced sensors provide great scope for real-time software applications to exploit. Furthermore, car manufacturers have started open-source platforms for developing applications using speed, mileage, and data that is time and location sensitive. Ford and GM started to open the data provided by their cars to application developers (*89*). Similarly, Google in partnership with Audi, GM, Honda, and Hyundai started the Open Automotive Alliance (*90*). Ford's OpenXC open-source platform initiative provides application developers with data on acceleration pedal force, steering wheel position, etc. (*91*). A correlation of such extensive data over various dimensions time, space, and events is useful in providing information regarding behavioral data of drivers' under different time and weather conditions. Such data helps in improving the accuracy of not only the operational modeling of traffic simulation models but also safety modeling. Thus these data would go a long way to further the paradigm of traffic simulation model calibration.

Looking into the future, the role of Big Data can be summarized by the following quote (*92*):

> …Big Data collected from car sensors (with proper privacy protections) will enable us to know more about the world we travel through, it could help city and transportation planners design next generation systems able to move more people with greater efficiency and personal mobility.

AUTHORS' NOTE

The contents of this paper reflect views of the authors who are responsible for the facts and accuracy of the data presented. The contents of the paper do not necessarily reflect the official views or policies of the agencies.

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Looking Forward, Looking Back on Computer Simulation Models of Safety

WILLIAM YOUNG
AMIR SOBHANI
KAYVAN AGHABAYK
MAJID SARV
Monash University, Australia

The main measure of the safe performance of a traffic system is the severity of a crash. Recent developments in computer, data collection, and communication technology have had considerable impact on our ability to replicate driver behavior and understand the processes involved in a crash. This paper looks at the use of computer models to simulate and assess the factors influencing crashes in existing and future traffic systems. It focuses on stochastic numerical models of traffic behavior and how reliable these are in estimating the conflict–crash process on the traffic network. It has been shown that these models have potential in measuring the level of conflict on parts of the network and the measures of conflict correlated well with crash statistics. By using surrogate safety measures these models focus on the measures of speed and location in the conflict and do not include other factors contributing to the crash. Further, the models assume the driver has full information on which to make a decision during the conflict process. Interest in the prediction of crashes and crash severity is growing and new models are focusing on the continuum of general traffic conditions, conflict, severe conflict, crash, and severe crashes.

INTRODUCTION

Traffic simulation models utilize stochastic sampling of the distributions of driver behavior to replicate the interactions between vehicles in a traffic stream to determine the consequences of their actions. Road safety simulation models expand these models to incorporate behavioral constructs which enable measures of the safety performance of the road system to be evaluated. Road safety simulation models are a useful tool in contributing to the overall evaluation of road systems performance. In this paper, the application of the microsimulation modeling approaches to studying the safety of components of the traffic system is reviewed and potential advances in the development of these models discussed. In the next section the paper traces the development of thought in modeling driver behavior and safety using computer simulation. It looks at the structure, theoretical base, and output measures of performance of simple and complex road safety simulation models. In the section Looking Forward, the paper looks at recent developments in the modeling of crashes.

LOOKING BACK: MODELS OF CONFLICT

Traffic microsimulation models attempt to mimic the process of vehicle movement in a traffic stream by replicating driver and vehicle behavior. Many of these traffic models implicitly use

"safe" measures of behavior rather than actual behavior (Bonsall et al., 2005). They also assume drivers have full information in order to perform car-following, lane-changing and gap-acceptance maneuvers. In many crash situations this is not the case since drivers may not be aware of other objects location and movement. In order to measure the safety of traffic systems, using road safety simulation models, it is necessary to incorporate realistic behavior to capture the variability in road user performance in real-world conditions. Unlike traffic simulation models, road safety simulation models focus on particular interactions (e.g., intersection conflicts, rear end conflicts, and run-off-road situations) between vehicles and other objects and model the process associated with the conflict or crash. This may be because, unlike other events in the traffic stream, crashes are exceptional in that they are the outcome of a process. This section of the paper will review road safety simulation models, the measures used to assess safety, the types of conflict situation that have been investigated, and the level of behavioral detail in the model in order to get an indication of where they can contribute to the development of our understanding of crash situations.

Formalization of the traffic conflict concept was initially proposed by Perkins and Harris (1968) as an alternative to crash data. The objective was to define incidences which occur frequently and are clearly observed and related to crashes. The early road safety simulation models grew out of the conflict analysis literature (Perkins and Harris, 1968; Amundson and Hyden, 1977). Initially the conflict models looked at the relationship between conflicts and traffic flow at intersections (Cooper and Ferguson, 1976; Darzentas et al., 1980, McDowell et al., 1983; Yue and Young, 1993). These models allocated headways, desired speeds, acceleration characteristics, and vehicle size on entry of the system to the drivers and vehicles. Vehicles are generated at the boundaries of key points in the study area and then are progressively moved through the transport network. In terms of the roads system, the position when the vehicle enters is determined by the spacing or headway between these vehicles. Various headway distributions are provided in simulation models. Cowan (1975) introduces the main distributions used in most existing simulations and relates them to a data set collected in New South Wales, Australia (Figure 1). These distributions move from a random representation of vehicles, through displaced exponential distributions to mixed spacing and bunching models. The random distribution relates to the Poisson process and a negative exponential representation of headways. This approach enabled small headways and crashes to be present at a point of entry into the system. However, this distribution was not seen to fit data on single-lane traffic flow very well. Multiple-lane traffic could be represented by this distribution but there is no conflict across lanes without lane changing. A common distribution used to replicate entry into a traffic system is the shifted negative exponential distribution of headways (Sayed et al., 1994; Cowan, 1975). This distribution assumes that there will be no headways less than a certain value, often 1.5 s. Clearly no crashes can occur with such a distribution.

The third distribution introduced by Cowan (1975) comprised bunches of vehicles and gaps between these bunches. The bunch size could by a geometric distribution and the headway distribution is used to determine the headway between the last vehicle in a bunch and the first vehicle in the following bunch. Again no crashes are present. Generally one of the second two representations of headways is used in most traffic simulation models. These distributions do not provide zero headway and hence cannot predict crashes at the entry to the study area. Attempts to develop crashes using headway distributions are unlikely to be realistic. They may be a realistic representation of the probability of getting a crash at a particular point in the network
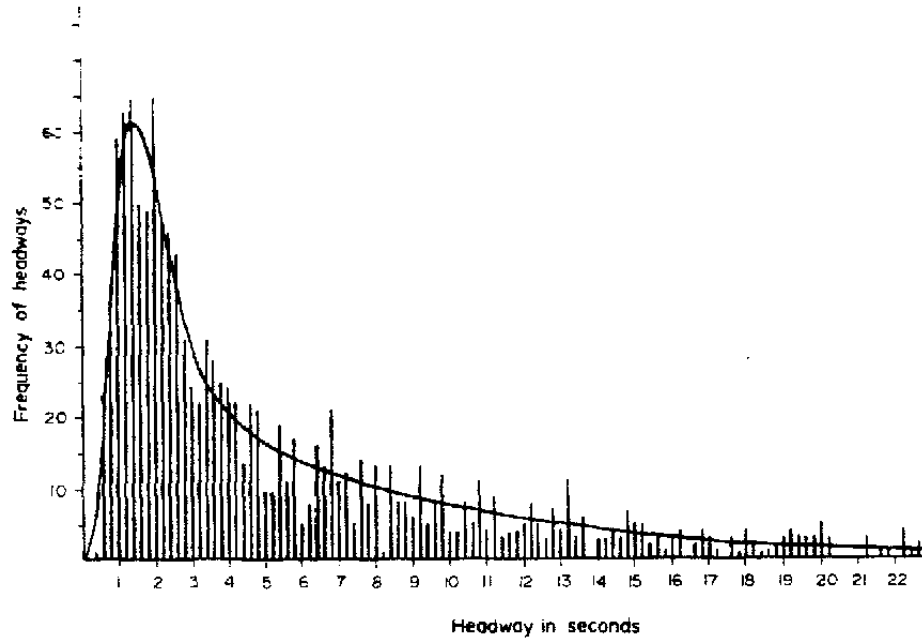
FIGURE 1 Headway distribution data (Cowan, 1975).

but crashes do not occur at a point rather they occur over a length of road. Further, to the headway distribution, the conflict models also had relatively simplistic measure of driver behavior. They focused on the kinematics of the situation and simulated vehicle behavior, with a speed and initial spacing randomly sampled from specific speed and spacing profiles through intersections at constant velocity and counted the number of times the vehicles conflicted. The models (Cooper and Ferguson, 1976; Darzentas et al., 1980, McDowell et al., 1983) were rarely fully calibrated and validated since the technology for collecting data was not that advanced and the labor involved in extracting conflict information is considerable. The models did however provide useful insights into the level of conflict at intersections and indicated there was potential for traffic simulation to be used to replicate traffic conflicts. These early developments of road safety simulation models set the scene for future activity in this area.

The initial development of conflict simulation models showed there was potential for models to provide measures of the level of conflict in a traffic system. Safety is often measured by the number of crashes. Hauer (1982) hypothesized the relationship between crashes and conflicts as

Expected number of crashes (λ) = [number of conflicts (c)] * [crash-to-conflict ratio (π)].

A fundamental step forward in the development of road safety simulation models was the determination of a measure of performance (or safety) to be used. The desire to quantify the kinematics of a conflict in road safety simulation models lead researcher's to introduce measures of the "risk of collision" of the conflict. These measures (FHWA, 2003) became known as Surrogate Safety Measures. Comprehensive lists of measures used to quantify Surrogate Safety Measures over the last 40 years have been provided by FHWA (2003), Tarko et al. (2009), Pirdavani et al. (2010), and Wu and Jovanis (2012). Many of these measures have not been used

in models, because of the structure of the model or difficulties in measuring them in existing models. An early and commonly used measure of conflict used in road safety simulation models was Time-to-Collision (TTC) (Sayed et al., 1994; Archer and Young, 2010*a*; Astarita et al. 2012; Laurenshyn et al. 2010; Van der Horst, 1991). TTC is generally defines as "the time to collide if two vehicles continue at their present speed and along the same path" (Hayward, 1972). Another commonly used Surrogate Safety Measure, which can be more easily incorporated into models, is the Post Encroachment Time. "It represents the difference in time between the passage of the 'offending' and 'conflicting' road users over a common area of potential conflict" (Pirdavani et al., 2010).

Incorporating the severity of conflicts was an important development and has been achieved using Hyden's (1987) definition regarding the Required Braking Rate for each conflict or Deceleration Rate to Avoid a Crash (Cunto and Saccommanto, 2008; Archer and Young, 2010*b*; Astarita et al., 2012). It is required "the braking rate to be applied for a vehicle attempting to avoid the crash with other vehicles." Required braking rate can be measured within the road safety simulation model and offers a clear view of the severity of the conflict. The in-vehicle or naturalistic data set (Dingus et al., 2005) is moving Surrogate Safety Measures to another level by utilising a more quantifiably rigorous concept to define crashes and near crashes. A near crash being: "Any circumstance that requires a rapid, evasive manoeuvre by the particular the participant vehicle, or any other vehicle, pedestrian, cyclist, or animal, to avoid a crash. A rapid, evasive manoeuvre is defined as steering, braking, accelerating, or any combination of control inputs that approaches the limits of the vehicle's capability" (Guo et al., 2010). Surrogate safety measures have been used in many studies to estimate the level of safety in a particular traffic situation. The Surrogate Safety Measures are often built on the outputs of existing traffic simulation models like VISSIM (2007), AIMSUM (2007), and PARAMICS (2002). They generally assume that the driver has full knowledge of the conflict situation and can act appropriately and generally focus on the kinematics of the conflict, speed and location, in determining the cause of the conflict. The driver and vehicle factors influencing the crash may be broader than just the kinematics and the driver may not have full information. The appropriateness and adaptation of these models, to replicate severe conflict and crash situations, will be discussed latter.

The next aspect of road safety simulation models to be considered here is their underlying theory. It will focus on particular conflict situations: crossing conflicts at unsignalized intersection; stop–go decisions at signalized intersection; rear end; and lane-changing conflicts; since this is where the crash process takes place. It will also highlight the behavioral developments in the models which assist in providing more realistic measures of safety performance.

Initial applications, of road safety simulation models, focused on crossing conflicts at unsignalized intersections (Sayed et al., 1994; Archer and Young, 2010*a*). Both Sayed et al. (1994) and Archer and Young (2010*a*) recognized the need to develop gap acceptance representations more in line with risk taking behavior to estimate the number and severity of conflicts. Sayed et al. (1994) utilized different gap acceptance behavior for different driver groups. The use of a binomial logistics function (see Figure 2) by Archer and Young (2010*a*) to model gap acceptance was a significant step forward since it enabled drivers to accept gaps which were clearly unsafe.

Another group of road safety simulation models have focused on rear-end accidents at the approach to signalized intersections, since they are a major source of accidents at signalized intersections. Cunto and Saccomanno (2008) developed a microsimulation model, for the study and safety evaluation of rear-end crashes at signalized intersection. Cunto and Saccomanno

(2008) used VISSIM as the base traffic model. This model is built around a car-following model created by Wiedemann (1974). It is based on different thresholds, which form different regimes for looking at driver behavior (see Figure 3). The regimes are free driving, closing in, following, and emergency regime. The behavior of the driver and the magnitude of the vehicle's acceleration or deceleration are modeled within each regime. The use of these thresholds precludes certain situations from taking place one of these is a crash.
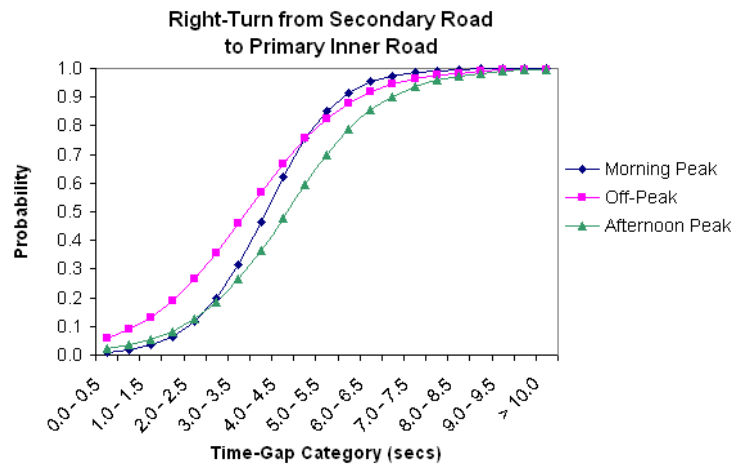
FIGURE 2 Probability functions for the acceptance of time-gaps in different yielding situations and time periods (Archer and Young, 2010*a*).
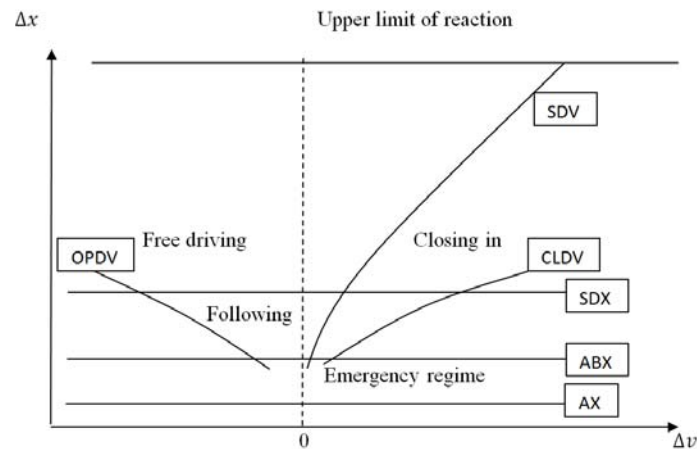
FIGURE 3 Different thresholds and regimes in the Wiedemann car-following model (1974). [Note: AX = the desired distance between stationary vehicles; ABX = desired minimum following distance at low speed differences; SDX = maximum following distance which varies between 1.5 and 2.5 times the minimum following distance; SDV = This threshold defines the points where driver notices that he/she approaches a slower driver (approaching point); CLDV = this threshold describes decreasing speed difference at short decreasing distances; OPDV = this threshold describes the points where the driver perceives travelling at a lower speed than the leader.]

Like VISSIM (Wiedemann and Reiter, 1992), PARAMICS (Fritzsche, 1994) utilized a risky distance variable where the distance headway is too close for comfort which also precludes crashes. The parameters in Cunto and Saccomanno's (2008) model were estimated from the NGSIM database. They were: desired speed (mean and standard deviation), desired deceleration, observed vehicle ahead, standing distance (for stopped vehicles), legal headway time, following variation, threshold for entering "following," speed dependency for oscillation, minimum distance to lead vehicle, factor applied to original safety distance, and maximum deceleration. Importantly, the "driver states" defined by six human thresholds, in Wiedemann's (1974) car-following model were replicated. Clearly the use of a minimum threshold precludes very close headways and crashes unless the thresholds are probabilistic. The incorporation of an error function into calculating safety distance could take the form:

$$ABX = AX + (BX_{add} + BX_{multi} * Rand(i)) * \sqrt{V}$$

where

ABX = desired minimum following distance;
AX = desired distance for standing vehicles;
BX_{add} = the additive part of the desired safety distance;
BX_{multi} = the multiplicative part of the desired safety distance,
$Rand(i)$ = a random value from a normal distribution (mean 0.5, standard deviation 0.15); and
$\sqrt{V}$ = the square root of speed.

The interaction between drivers and traffic signal information is another focus of road safety simulation models. Young and Archer (2009) investigated and incident reduction function at signalized vehicle actuated intersections. The interaction between driver decisions, the dilemma zone and consequent red light running for light vehicles was explored. Archer and Young (2009, 2010*b*) investigate the stop/go decision at signalized intersection to look at red light running by utilizing a logistic curve to emulate red light stop–go decisions.

Modeling the conflict between vehicles moving along road links represents different behavior and crash situations. Several driver behavior car-following models have been developed in this area. Mehmood et al. (2001) utilizes system dynamics to model two-vehicle rear-end crashes where both vehicles are traveling in one lane. The potential for a crash is a probabilistic function of the current vehicle separation (not headway) time distance, the minimum required stopping site distance, the current speed of the vehicle and the required safe speed. Astarita et al. (2012) developed a model called TRITONE using car-following procedures based on Gipps (1981) studies.

The Gipps (1981) car-following model, which is also used in AIMSUM, will be briefly discussed here to highlight potential areas for adapting the model to safety investigation. Gipps (1981) developed a model based on collision avoidance comprising the two following constraints for the follower's velocity: (*a*) the speed of vehicle n should not exceed from its desired speed and its free acceleration should first increase with speed as engine torque increases and then decrease to zero as the vehicle approaches the desired speed; and (*b*) the following driver must be sure his/her vehicle will stop safely if the proceeding vehicle brakes suddenly. Previous models of this type did not contain of any margin for error. He introduced a further safety margin

by proposing that the driver makes allowance for a possible additional delay before reacting to vehicle ahead. The result of these two considerations is the model:

$$v_n(t+T) = min \begin{cases} v_n(t) + 2.5a_nT(1 - v_n(t)/V_n)(0.025 + v_n(t)/V_n)^{1/2} \\ b_nT + \{b_n^2T^2 - b_n(2(x_{n-1}(t) - s_{n-1} - x_n(t)) - v_n(t)T - v_{n-1}^2(t)/b^\wedge)\}^{1/2} \end{cases}$$

where

    a_n =   the maximum acceleration which the driver of vehicle n wishes to undertake;
    b_n =   the most sever braking that the driver of vehicle n wishes to undertake ($b_n < 0$);
  s_{n-1} =   the effective size of vehicle $n - 1$; that is the physical length plus a margin into which the following vehicle is not willing to intrude, even when at rest;
    V_n =   the desired speed or the speed at which the driver of vehicle n wishes to travel;
  $x_n(t)$ =   the location of the front of vehicle n at time t;
  $v_n(t)$ =   the speed of vehicle n at time t;
    $b^\wedge$ =   the estimation of b_{n-1} employed by the driver of vehicle n; and
    T =   drivers' reaction time.

      The first term is related to the first constraint and the second term expresses the later one. The safe driving distance approach is utilized in Gipps (1981) model. The safe driving approach does not allow very small headway and hence crashes. However, the introduction of an error function in the acceleration term could enable the replication of errors in perception of drivers, which could lead to crashes.
      To broaden the application of road safety simulation models to general vehicle safety on links, it is necessary to include lane-changing as well as car-following models. Dedes et al. (2011) developed a model which combined a traffic simulation model (VISSIM) and a vehicle dynamics simulator (CARSIM) and places this within a Satellite Systems (GNSS) and Inertia Navigation Units (INU) simulator which provides an integrated design framework for investigating the impacts of existing GNSS–INU. The VISSIM model adopts an approach similar to Wiedmann's car-following model (Wiedmann, 1974) to lane changing. Some new thresholds and areas were defined to represent human perception of distances and speed differences in lane changing decisions. These are shown in Figure 4.
      Four types of lane changing to faster lanes and two types of lane changing to slower lanes were defined by applying the following parameters. The parameters considered for changing to a faster lane are

    1. Distance of reaction;
    2. Headway of reaction;
    3. Rear-to-front headway between the subject vehicle and its lead vehicle in the faster lane;
    4. Front-to-front headway between the subject vehicle and its lag vehicle in the faster lane; and
    5. Rear-to-front headway between the lag and lead vehicles in the faster lane.
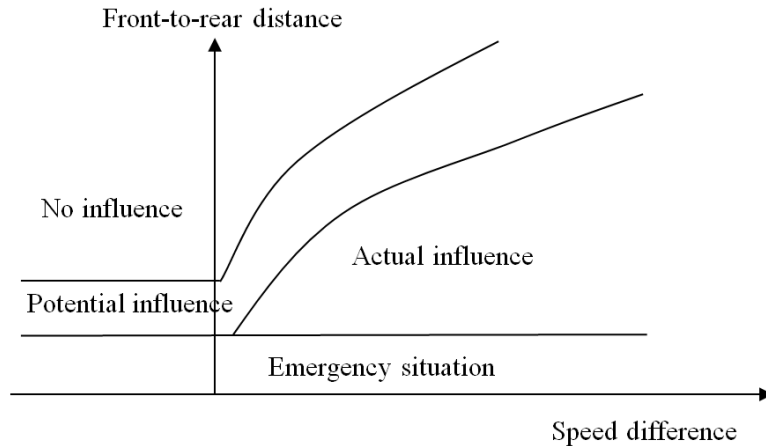
**FIGURE 4 Thresholds and distances defining actual and potential
influence areas in Willmann lane changing model (Wiedmann and Reiter, 1992).**

The parameters considered for changing to slower lane are

1.   Distance of reaction;
2.   Headway of reaction;
3.   Rear-to-front headway between the lag and lead vehicles of the subject vehicle in the slower lane; and
4.   Front-to-front headway between the subject vehicle and its follower in current lane (in seconds).

For both types:

1.   Length of lane changing manoeuvre (in meters); and
2.   Duration of lane changing manoeuvre (in seconds).

According to the above parameters four types of lane changing to faster lane and two types of lane changing to slower lane were defined. The four types of lane changes to faster lanes are

1.   FREE lane changes. The subject vehicle is only influenced by its leader in the current lane. The lead and lag vehicles in the faster lane do not influence the maneuver.
2.   LEAD lane changes. The lead vehicle in the faster lane is closer to the subject vehicle than the subject vehicle's leader in the current lane and the lag vehicle in the faster lane is not influenced.
3.   LAG lane changes. The lag vehicle in the faster lane is influenced by the maneuver and the subject vehicle's leader in the actual lane is closer than the lead vehicle in faster lane: and
4.   GAP lane changes. The lag vehicle in the faster lane is influenced by the maneuver and the lead vehicle in the faster lane influences the subject vehicle.

The two types of lane changes to slower lane are

1. FREE lane changes. The maneuver is not influenced by the follower in the current lane and

2. ACCEL lane changes. The following vehicle in the current lane influences the subject vehicle. Although it is also possible to put an error function in this model, no adaptations of the minimum distance estimate of drivers has been explored to look at the potential of crashes. This is most likely because of the lack of data on such situations. There is however a need to understand this maneuvers impact on crash potential.

The second stage in Dedes et al. (2011) model was the incorporation of the CarSim model. CarSim is a commercial software package that predicts the performance of vehicles in response to driver controls (steering, throttle, brakes, clutch, and shifting) in a given environment (road geometry, coefficients of friction, wind). The model was aimed at exploring the adequacy on in-vehicle navigation and crash-avoidance systems.

Most road safety simulation models focus on particular crash types at particular parts of the traffic system. Combining intersection and link road safety simulation models into network models requires simplification of the representation of the crash. Dijkstra et al. (2010) focuses of intersections to develop a link between TTC conflicts and crashes. Dijkstra et al. (2010) uses the PARAMICS model as a basis for studying the level of safety in a traffic network in Noordwijk, Netherlands. They aimed to provide information to users on both the safest and quickest route through the network. The introduction of an error function to replicate crash situations was not undertaken in this study.

In summary, road safety simulation models utilizing Surrogate Safety Measures are well developed and able to be applied in practice. This is the state of the art in the application of road safety simulation models. These models for simulating safety have made considerable developments of the past decade. Simulation models have moved from simple models of conflict to complex representations of vehicle conflict situations. The underlying theory of the model has also developed.

The models are still in an early stage of development. Some aspects worthy of further research are reviewed below. The first question to be asked of these models is: is there a relationship between Surrogate Safety Measures and crashes? Many studies (Archer and Young, 2010*a*; Cunto and Saccomanno, 2008; Dijkstra et al. 2010) point to there being such a relationship. Several researchers (Guo et al., 2010; Wu and Jovanis, 2012) have explored the relationship between Surrogate Safety Measures and crashes using a naturalistic data base. The models need to look at driver behavior during a conflict in more detail. Such questions like, are there any other driver and vehicle characteristics, than the kinematics related to speed and position, which contribute to the conflict–crash situation and severity?

Most of the models discussed above use the commercially available traffic simulation packages (AIMSUM, 2007; VISSIM, 2007; PARAMICS, 2002). These models have well developed gap acceptance and light vehicle car-following models (Gipps, 1981; Wiedemann, 1974; Fritzsche, 1994) and lane-changing algorithms. Generally these algorithms (Brackstone and McDonald, 1999; Panwai and Dia, 2005) revolve around safe driving characteristics and the drivers having full information. For instance, car following in AIMSUM (Gipps, 1981) revolves around safe driving distance; in VISSIM (Wiedemann, 1974) a minimum threshold on the spacing between vehicles is used; and PARAMICS (Fritzsche, 1994) utilized a risky distance threshold where the distance headway is too close for comfort. Clearly the general acceptance of these models and their application to general traffic flow situations provides evidence of their

validity. However, when attempting to measure safety, these assumptions may require refinement. The models are limited in their consideration of accident situations, if they do not include risk taking behavior and lack of information. Driver and vehicle characteristics are also related to the kinematics of the crash and do not explore the full range of characteristics describing these components.

Most models look at vehicle to vehicle crashes, no consideration of other crashes (e.g., multiple vehicles, vehicle fixed object, vehicle–pedestrian) appear to be present. Further, studies of accidents involving pedestrians, bicycles, and public transport are rare.

LOOKING FORWARD: MODELING CRASHES

The previous sections have focused on road safety simulation models, conflict analysis, and Surrogate Safety Measures. They have demonstrated the usefulness of the combination of these approaches in providing measures of the safety of elements of the transport system. However, the main concern of safety analysis is the crash, and more specifically, the severe crash or fatality. This section overviews initial attempts to incorporate crash measures into simulation models.

A commonly used simulation approach to the modeling of vehicle crashes focuses on the vehicle and the driver. These models tend to focus on the interaction between vehicles or vehicles and roadside objects, and do not consider general traffic conditions or driver behavior. They describe the vehicle-to-vehicle (or object) interaction in detail. Jacques et al. (2003) describes three groups of models that have been used to investigate crash situations. They are the Gross Motion Simulators, Human Vehicle Environment Software, and Finite Element Programs. Gross Motion Simulators (rigid body dynamic models) replicate the bodies (vehicle, person, objects) involved in the crash situation by using a set of rigid bodies connected by various types of joints. These models are used to examine the dynamics of the people in the vehicle. The Mathematical Dynamic Model is a commonly used model of this type. Energy-based programs replicate the interaction between vehicles and objects estimating the energy involved in the interaction. Human, Vehicle, Environment software are energy-based programs which can simulate the crash situation in details and estimate the trajectory of each vehicle after the crash in order that the severity of the crash can be measured (Jacques et al., 2003; Engineering Dynamics Corporation, 2006). Finite Element Programs (LS-DYNA, PAM-CRASH, Radioss, and MSC-Dytran) have been used to replicate the objects involved in a crash in great detail. Each body is replicated by a complex mesh of triangles. The extension of these models to take into account traffic conditions has not been attempted due to the considerable data requirements and the complexity of the general traffic conditions.

Most of the road safety simulation models discussed in the Looking Back section use existing simulation packages to model safe behavior. Several researchers (Bonsall et al., 2005; Xin et al., 2008) suggest that existing simulation models are developed to preclude collisions and are not an accurate representation of the safety environment. Xin et al. (2008) set out to develop a car-following model that includes a less-than-perfect driver. They develop a realistic perception response mechanism based on visual perception studies. Driver inattention is replicated by a driver-specific variable termed a scanning interval. Xin et al. (2008) considers the distance headways (and hence time headway) between leading and subject vehicle as that distance between the retina of the driver and the rear of the leading vehicle.

Clearly the development of a road safety simulation model which relates to crashes must pull together a number of events. By exploring the continuum between the initial conditions leading to the event [$P(u)$], the evasive or avoidance actions [$P(x|u)$], and the crash-related outcomes [$P(y|x,u)$]. Davis et al. (2011) generated the conditional probability relationship:

$P(y,x,u) = P(y|x,u).P(x|u).P(u)$

Tarko (2012) extends Davis et al.'s (2011) approach by addressing the question of a continuum of traffic events and expanding the mainstream statistical models of collision frequency and the conditional probability of injury. Tarko extends the direct relationship between the crash and factors affecting it to a continuum of four steps moving from (*a*) traffic factors, (*b*) through conflict, (*c*) collision to (*d*) injury outcome. He relates this to Heinrich's triangle (Heinrich, 1959) and the consequent road safety literature (Hauer, 1997; Svensson and Hyden, 2006; Dingus et al., 2005) which hypothesizes that safety event can be grouped in increasing severity and decreasing frequency. The important link connecting risky behavior and the crash (Step 3) is quantified using the Generalise Parato distribution to link the other models.

A further attempt to develop the crash continuum described by Tarko (2012) was undertaken by Sobhani et al. (2013). Sobhani et al. developed a Safety Analysis Chain (SACH) which combined five components of the safety continuum: the traffic system (flow, speed, etc.); the development of a conflict; the severity of this conflict; the likelihood of a crash; and the final crash. They used VISSIM (2007) as the overall simulation framework and the quantification of the first three steps in the SACH. They then took advantage of the considerable research into numerical and statistical models of crashes and imbedded a number of probabilistic models for each of the last three components of the crash: the driver reaction model, kinetic energy transfer model, and crash severity model. The inclusion of the crash models broadened the number of factors contributing to a crash that could be studied. The road and environmental characteristics include factors like road, weather, traffic, and trip characteristics. Human factors include demographics, behavior, occupant position in the vehicle, and anthropometric characteristics. The vehicle characteristics comprise vehicle type, safety features, size, mass, and age. Finally, crash information relates to factors like crash type, speed, angle of crash, and impact characteristics. Wu and Jovanis (2012) also explore a set of variables broader than kinematic variables in their study of crashes and near crashes. For road departure events they find lateral acceleration greater than 0.7 *g* is a common element while straight trajectories prior to the event and dry road condition reduce the link between near crashes and crashes.

Another dimension of safety on links is run-off-road crashes. These crashes are usually single vehicle and occur in high-speed locations with high levels of severity consequent on the crash. Mak and Sickling (2003) developed a simulation program to investigate these crashes called the Roadside Safety Analysis Program. The model is based on the encroachment probability approach. The simulation model uses roadway and traffic information to estimate the expected encroachment frequency along particular highway elements. It uses data on tire tracks in medians and road sides collected by Cooper (1980) to develop encroachment probability. The road and traffic conditions are then used to convert this to frequencies. The crash prediction model assesses the encroachments that will result in crashes. The model looks at the encroachment angle, vehicle size, and vehicle orientation (angle, pitch, yaw, and rollover). Roadside features in the path of the vehicle are then determined and if a car will impact with

these the characteristics of the crash are determined. The severity prediction takes the data on the crash and determines a probability of injury based on historical police-reported crash data.

The explicit modeling of a crash in road safety simulation models is still in the development stage. The continuum of crash events provides a strong base for these models but the quantification of driver behavior or lack of behavior (no reaction) is an area of further research. Existing road safety simulation models can replicate car-following, lane-changing, gap-acceptance and other general traffic maneuvers. One of the main challenges is the data used in the development of most of the models to date does not explicitly include the crash, nor the behavior of the driver prior and during the crash. Possibly the next quantum step in these road safety simulation models could result from the collection of in-vehicle data, termed the naturalistic data set (Dingus et al., 2005; Campbell, 2012). The naturalistic data set is in essence the collection of conflict data from inside a vehicle rather than from a fixed position outside the vehicle. To collect this data advanced instrumentation (e.g., video cameras, vehicle sensors, GPS) are installed in vehicles (Dingus et al., 2005; Campbell, 2012) and used to continuously collect data on driver behavior. This gives useful information of driver behavior during the crash. A rapidly advancing technology which may also be able to complement field data on road safety is the utilization of driver simulators. Like road safety simulation models improved computer technology and communication systems has recently increased their ability to replicate driver situations. Driver simulators offer the opportunity for creating a virtual environment may be able to provide data for the calibration and validation of road safety simulation models. In turn, road safety simulation models can be interfaced with driver simulators to create a realistic traffic and safety environment within the driver simulator for the study subjects.

CONCLUSIONS

This paper reviews developments in the area of road safety simulation models. It focuses on stochastic numerical models of traffic behavior and how reliable these are in estimating the level of safety on the traffic network.

Road safety simulation models aim to provide a platform for assessing and predicting the safety performance of drivers, vehicles and the transport system. This requires an accurate representation of the behavior and character of each of these systems components. The stochastic nature of these models requires accurate measures of the variations in behavior of drivers and vehicles. These models were first seen in the 1970s when computer technology developed to the stage where traffic microsimulation models became a realistic option. Initially, development of the models was sporadic since data of crashes was limited and collection techniques were cumbersome and time consuming, hence the models never reached commercial use. The most recent phase of development started in the early 2000s with many of the models calling heavily on developments in traffic simulation models, refining the behavior of drivers, and developing Surrogate Safety Measures. Many studies have utilized existing traffic simulation approaches and software (VISSIM, 2007; PARAMICS, 2002; AIMSUM, 2007). They calibrate or changing parameters to better represent the dynamics of traffic behavior. It has shown that these refined traffic simulation models have potential in measuring the level of conflict on parts of the network using Surrogate Safety Measures. The Surrogate Safety Measures of conflict correlated well with crash statistics. In terms of the measures of performance, traditional Surrogate Safety Measures provide insights into the safety. These models represent the state of the art in practical

application of road safety simulation models to assess the safety of existing and new transport system improvements.

Clearly it is early days; however, there are signs that simulation will become a useful tool in analyzing the safety of the traffic system and will add to the conventional wisdom on remedial measures of safety. There are however, a number of areas where further work is required: the crash as the measure of performance; a study of behavior (or nonbehavior) during crashes; a more detailed representation of the driver, vehicle, and conflict situation; and a generalization of the models to look at more crash and complex traffic and modal environments.

New computer, information, and data collection technology are likely to facilitate the next stage in the development of road safety simulation models. This will occur in a number of areas. New in-vehicle naturalistic data sets are showing increased application in developing the models. The increase in this type of data will enable a closer link between crashes and driver, vehicle and traffic characteristics. Further, developments in technology are allowing driver simulators to improve and develop the models.

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Thoughts on Simulation Models

ALEXANDER SKABARDONIS
University of California Berkeley

S kabardonis presented his "Thoughts on Simulation" models at the 93rd Annual Meeting of the Transportation Research Board as part of the Simulation: Looking Back and Looking Ahead workshop sponsored by the Committee on Traffic Flow Theory and Characteristics (AHB45) and the Joint Subcommittee on Simulation [AHB45(1)]. This was in celebration and commemoration of the committee's 50th Anniversary. Skabardonis framed his remarks around a similar presentation entitled "Simulation Models: State of the Art" that he had presented at a simulation workshop at the 81st Annual Meeting in 2002. Skabardonis first pointed out that we have come a long way: there is no longer a need to ask the same questions as we did in 2002, but there are new sets of questions and challenges that lie ahead. While we still need to focus on the need for high-quality data and the need to apply simulation tools appropriately and systematically, we now have more than 80 simulation models available to us along with excellent graphical capabilities and a wide range of strengths, weaknesses, and challenges. We still face a wide range of issues, including ways of interpreting model output, calibration, and alternatives analysis. Skabardonis concluded with a list of do's and don'ts and looks forward to the next 50 years in the simulation field.
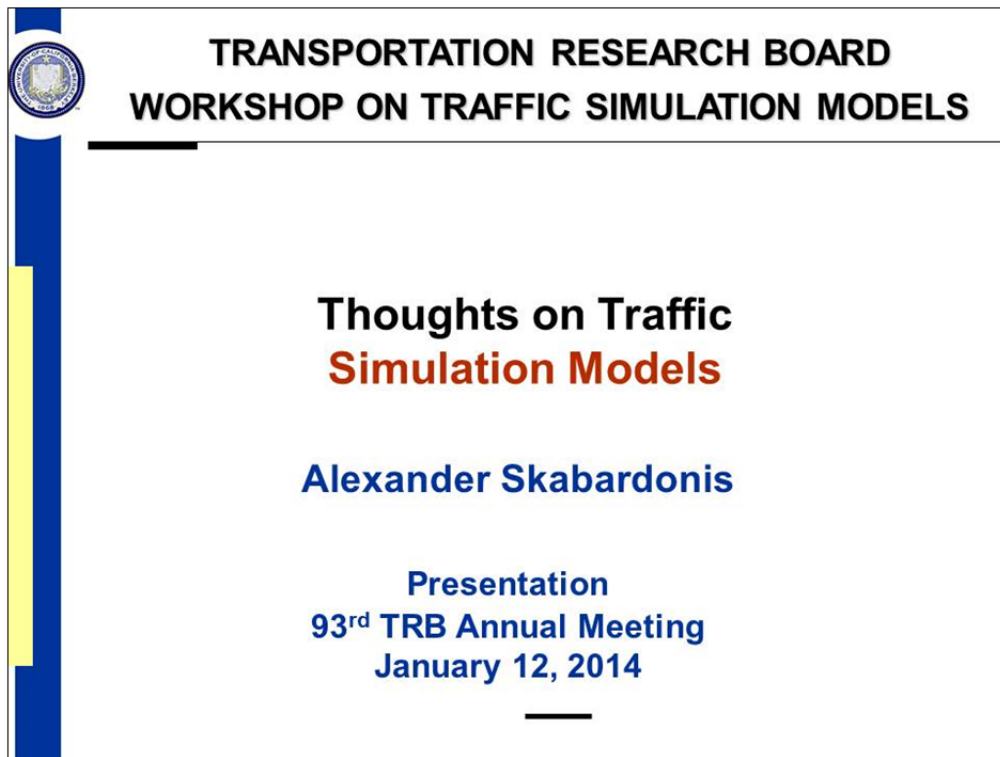
Outline

▸ **One Model too Many**
▸ **If it Looks Right…It is Right**
▸ **"Simulation Models = Loaded Guns"**
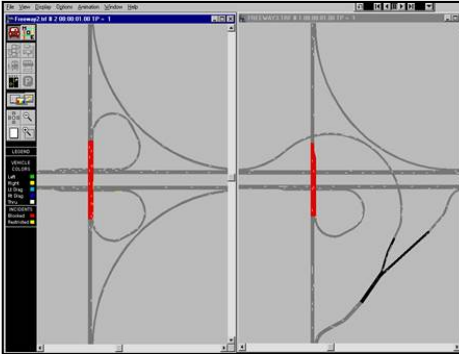
One Model Too Many…

1952	J. Wardrop, TRL England Intersection Delay
1956	D. Gerlough, UCLA Microscopic Modeling, "cells"
1960's	A. May, UC Berkeley Macroscopic Models, Corridor Control
1970's	FHWA, UTCS Experiment UTCS-1 (NETSIM), TRAF
	TRL, England TRANSYT, CONTRAM

1981 TRB Special Report 194 : Over 40 simulation models

1980's	Technology/Mainstreaming PCs/Graphics
1990's	"Advanced"/Systems/Corridors/ITS CORSIM, INTEGRATION,….
2000's	"Market Forces" *Over 80 simulation models*

Model Capabilities/Features (1)

▶ **Strengths**

- **Alternative Designs**
- **HOV facilities**
- **Conventional Control**
  - Fixed-time signals
  - Fixed-time ramp metering
  - Traffic actuated signals
  - Local traffic responsive ramp metering
- **Incidents/workzones**
- **Busses/LRTs**
  - Transit Priority
- **Route Diversion**

Model Capabilities/Features (2)

▶ **Challenges**

- **Not a Single Model all Strengths**
- **Lag Emerging Strategies/Technologies**
  - ATDM Strategies
  - DMA Applications
    - Connected Vehicles (V2V, V2I)
  - Understanding of Driver Behavior
- **New Data Sources**
- **Impacts on Travel Demand**
  - Regional/corridor analyses
  - Multi-resolution modeling
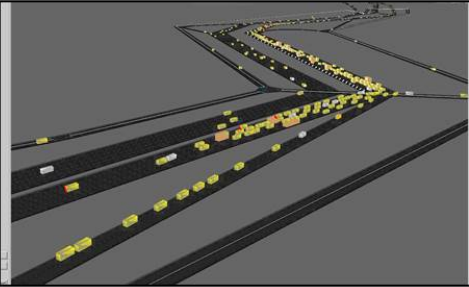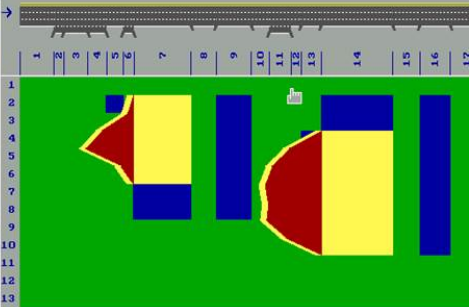
Model Capabilities/Features (3)

▸ **The Promise (?) = APIs**

- **Add External Modules = Plug and Play !**
  - Heaven for researchers
  - Users??
- **Acceptance Testing/Availability of APIs**

▸ **Time for a New Model/Approach?**

- Improved validated Algorithms
- Computational efficiency/scalability
- Full Automation of Data from various Sources/Users
- Off-Line Evaluation/On-line Operation
- Systems Interaction/Integration

If it Looks Right, it is Right..

▸ **Model Verification**

▸ **Understand Predicted Impacts**

▸ **May Mask Modeling Deficiencies**

Loaded Guns..

Source: MULTITUDE, 2003

Issues

Model Output
- Interpretation for design and operations decisions
- Micro analysis = Macro output *(average vs. distribution)*

Calibration
- Where are the data?
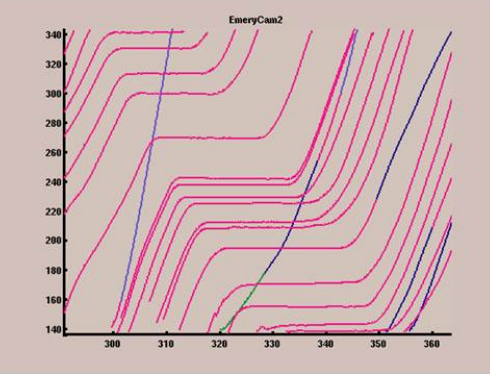- Best set of parameters may not make physical sense
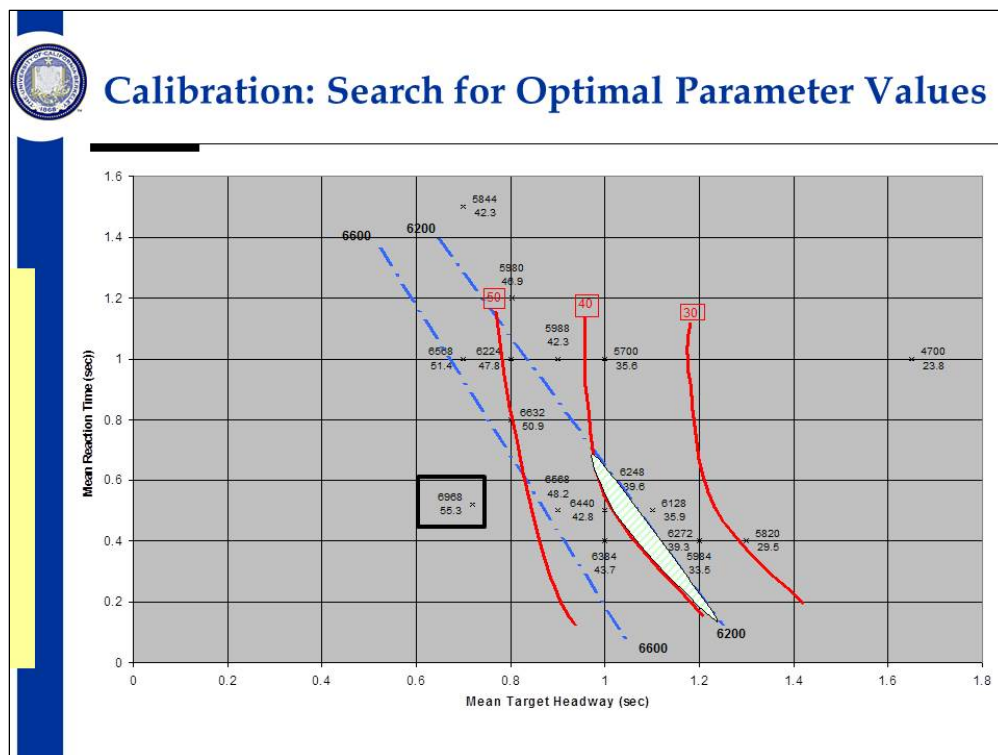- Can the model predict

Alternatives Analysis
- Levels of Analysis *(system vs. components)*
- Oversaturated conditions in the baseline
- Sensitivity to projected inputs
- Is 2% improvement significant

Data

Life after NGSIM
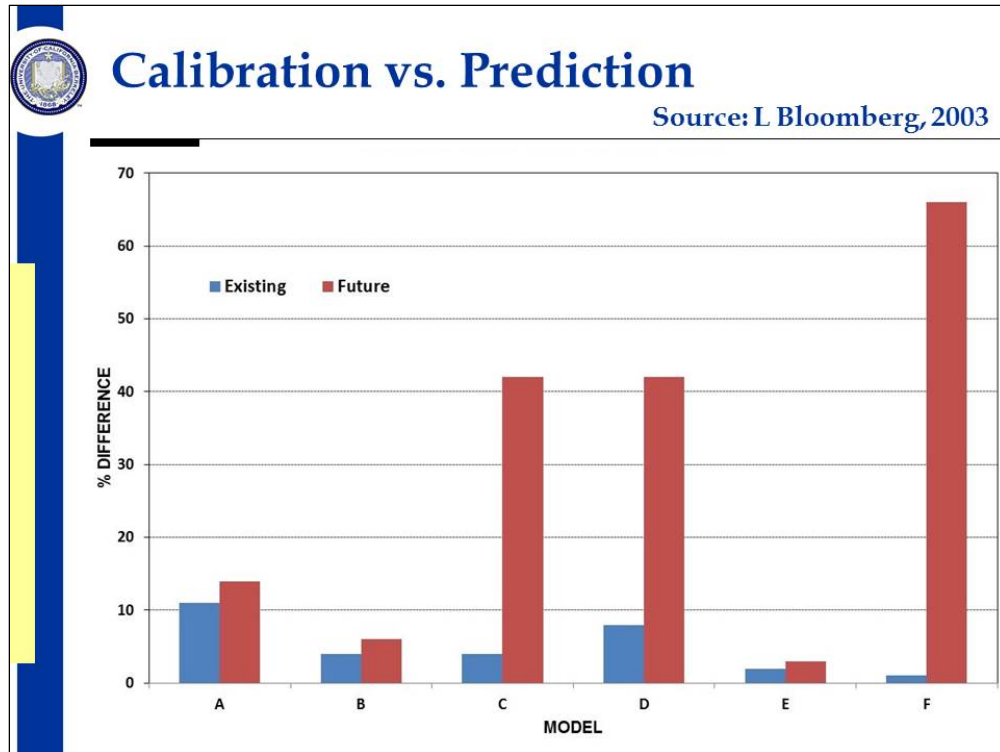

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Calibration: Search for Optimal Parameter Values
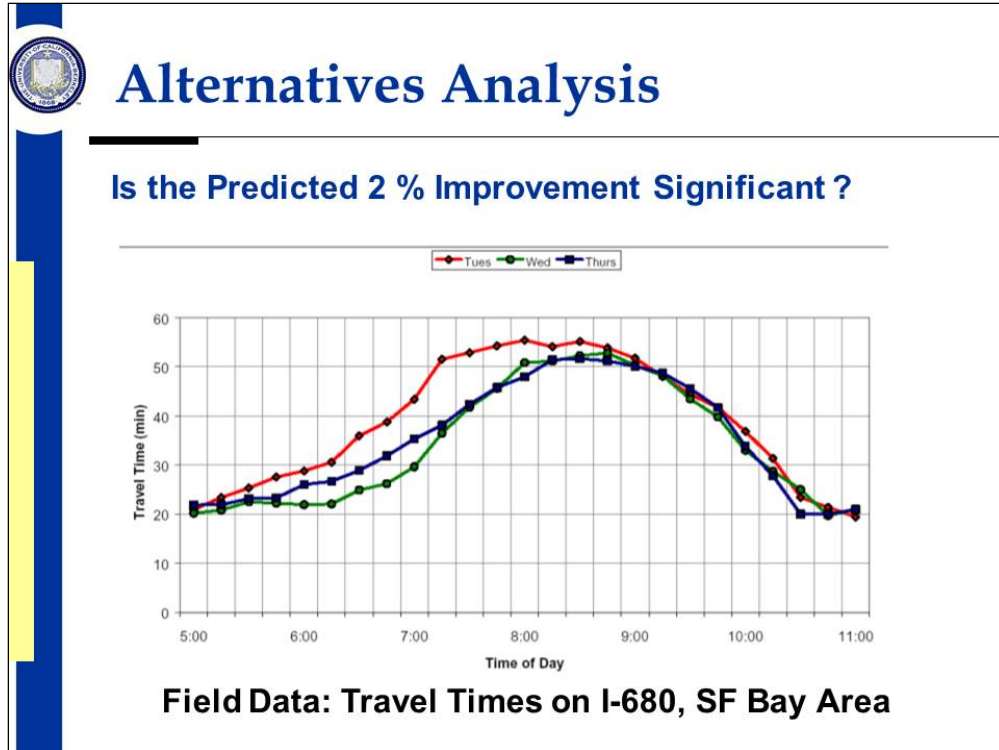

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Calibration vs. Prediction

Source: L Bloomberg, 2003

Issues

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Calibration

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- Best set of parameters may not make physical sense
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Alternatives Analysis

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Alternatives Analysis

Is the Predicted 2 % Improvement Significant ?

Field Data: Travel Times on I-680, SF Bay Area

Top 10 DOs and DON'Ts for Simulation Studies

Source: Caltrans, 2005

10.	DO	Identify the purpose of your study
9.	DON'T	Dazzle us with graphics and animation
8.	DO	Tell us if traffic forecasts are adjusted
7.	DON'T	Reduce detailed results down to LOS
6.	DON'T	Use unconventional MOEs
5.	DO	Make field observations
4.	DO	Calibrate & validate
3.	DON'T	Limit the size of the study area
2.	DON'T	Perform traffic counts in congestion.
1.	DO	Perform quality control

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