

A COMPARATIVE ANALYSIS OF CURRENTLY USED MICROSCOPIC AND MACROSCOPIC TRAFFIC SIMULATION SOFTWARE

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الخلاصة:

إن التقدم الكبير في التكنولوجيا المعلوماتية ساهم في تطور برامج محاكاة الحركة المرورية، وهذا يشمل البرامج المجهرية (Microscopic)، ونطاق تطبيقات الحاسب الآلي ليسمح بمحاكاة منظومة النقل بما فيها من طرق وتقاطعات، وفي بعض الأحيان يشمل أيضاً محاكاة الطلب على النقل. وهذه الورقة تراجع وتقرن بين برامج محاكاة الحركة المرورية المجهرية (Microscopic) والشمولية (Macroscopic) مركزة على أوجه الاختلاف والتشابه بين هذه البرامج عند استخدامها في محاكاة الحركة على الطرق الحرة وشبكة الطرق الحضرية المكتظة، إضافة إلى تقدير التلوث البيئي وحساب أزمنا التأخر والطاقة الاستيعابية للطرق. وقد تبين أن البرامج AIMSUN و CORSIM و VISSIM مناسبة للطرق الحرة والشريانية المكتظة، إضافة إلى شبكات الطرق التي تتكون من طرق حرة متصلة بشبكات من الطرق السطحية. وقد ثبت أن برنامج AIMSUN مفضل في شبكات الطرق الحضرية الكبيرة كما أن البرامج AIMSUN و PARAMICS و INTEGRATION و CORSIM أكثر ملاءمة وفائدة في أنظمة النقل الذكية. وقد تم تطوير البرنامج MITSIMLab حصرياً لأنظمة النقل الذكية. إن مجموعة برامج TRAF و HUTSIM تحاكي الحركة المرورية على المستوى الشمولي لأنظمة النقل حيث يمكن استخدامها مع عدد من برامج المحاكاة تفاعلياً لحل مشاكل الحركة المرورية ومحاكاتها. إن استخدام برامج المحاكاة المرورية لشبكة من الطرق الحرة المتصلة بطرق سطحية لم يوثق إلى الآن في المملكة العربية السعودية إلا أن معايرة والتأكد من صلاحية برامج المحاكاة للطرق الحرة والطرق السطحية كلاً على حدة تم في عدد من الدراسات المحلية.

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ABSTRACT

The significant advancements of information technology have contributed to increased development of traffic simulation models. These include microscopic models and broadening the areas of applications ranging from the modeling of specific components of the transportation system to a whole network having different kinds of intersections and links, even in a few cases combining travel demand models. This paper mainly reviews the features of traditionally used macroscopic and microscopic traffic simulation models along with a comparative analysis focusing on freeway operations, urban congested networks, project-level emission modeling, and variations in delay and capacity estimates. The models AIMSUN, CORSIM, and VISSIM are found to be suitable for congested arterials and freeways, and integrated networks of freeways and surface streets. The features of AIMSUN are favorable for creating large urban and regional networks. The models AIMSUN, PARAMICS, INTEGRATION, and CORSIM are potentially useful for Intelligent Transportation System (ITS). There are a few simulation models which are developed focusing on ITS such as MITSIMLab. The TRAF-family and HUTSIM models attempt a system-level simulation approach and develop open environments where several analysis models can be used interactively to solve traffic simulation problems. In Saudi Arabia, use of simulation software with the capability of analyzing an integrated system of freeways and surface streets has not been reported. Calibration and validation of simulation software either for freeways or surface streets has been reported. This paper suggests that researchers evaluate the state-of-the-art simulation tools and find out the suitable tools or approaches for the local conditions of Saudi Arabia.

Key words: microscopic and macroscopic simulation, traffic simulation models, Saudi Arabia

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1. INTRODUCTION

A system exists and operates in time and space. A model is the abstraction of the system and can be better defined as a simplified representation of a system at some particular point in time or space which is aimed at promoting an understanding of the real system. As the model is the simplification of the real conditions, the level of detail depends on the specific requirements. Simulation is the manipulation of a model in such a way that it operates on time or space to compress it, thus enabling one to perceive the interactions that would not otherwise be apparent because of their separation in time or space [1]. In fact, simulation provides an understanding of the interactions among the parts of a system and the system as a whole. The evolution of computer technology has changed the general understanding of simulation. Nowadays, simulation basically means a computerized version of a model which is run over time to study the implications of the defined interactions. Simulations are generally developed by adopting an iterative approach.

Based on the intended need, the traffic simulation models range from microscopic to macroscopic models that use gross traffic descriptors such as flow [2]. Dia and Panwai [3] have applied the terminology nanoscopic model to indicate finer representation of traffic. In general, the fine level of required details in a microscopic model limits its use mostly towards traffic operations over relatively small geographical areas in contrast to macroscopic models which are used in broader perspective to contribute in transportation planning rather than traffic engineering.

Use of simulation in Saudi Arabia is growing in importance because the number of vehicles is growing exponentially. At the beginning of 1970, there were approximately 100 000 vehicles active on the road in Saudi Arabia, and in 2000 the total number of vehicles active on the road was 1.8 million [4]. Traffic congestion is also becoming a daily problem on many arterials of the country. Traffic engineering professionals are mainly using SimTraffic, VISSIM, and Transyt-7F as simulation models to evaluate traffic signal strategies and reduce traffic congestion. But comprehensive scientific studies to evaluate the appropriateness and the effectiveness of these models under local conditions apparently are lacking. Research on the mentioned models application for Saudi Arabia conditions appears warranted. This paper is intended to shed light on the features and capabilities under varying conditions of many simulation software packages, which should be a first step in selecting any specific simulation software for the local conditions of Saudi Arabia. Future research on the calibration of the selected software and evaluation of the effectiveness of them should be considered also.

This paper is divided into six main sections. The second section addresses the major areas and approaches in traffic simulation. The third section introduces a number of simulation software types both microscopic and macroscopic, and the fourth section provides the comparative analysis of a number of simulation software packages. The fifth section focuses on the investigations of simulation software in the context of Saudi Arabia. Finally, in the sixth section the relevant conclusions are drawn based on this study.

2. MAJOR CATEGORIES OF TRAFFIC SIMULATION

The traffic simulation programs are divided into three main categories (microscopic, mesoscopic, and macroscopic) and two main approaches (continuous and discrete). Microscopic models continuously or discretely predict the state of individual vehicles and primarily focus on individual vehicle speeds and locations. Macroscopic models aggregate the description of traffic flow, and the measures of effectiveness, which are speed, flow, and density [5]. Mesoscopic models consist of the aspects of both macro and microscopic models. The mesoscopic models fill the gap between the aggregate level approach of macroscopic models and the individual interactions of the microscopic ones by describing the traffic entities at a high level of detail, while their behavior and interactions are designed at a lower level of detail [6]. There is also another type of simulation model which is known as the nanoscopic model. These concern the detailed modeling of driver cognition, perception, decision making, and errors. There are also a few hybrid models consisting of any two of the three mentioned models (microscopic, mesoscopic, and macroscopic) in order to combine the strengths and diminish the individual weaknesses.

Traffic simulation can be categorized into intersection, road section, and network levels. The simulation models can be categorized by functionality, *i.e.* signal, freeway, or integrated [5]. The other categories might include traffic safety and the effects of advanced traffic information and control systems [7]. Simulation programs started with the

modeling of specific components and continued to model the whole network of the transportation system. The simulation programs now address transportation planning (mainly demand modeling), policy (such as Transportation System Management), and traffic engineering (such as flow behavior) together to investigate the real life scenarios of the transportation system more comprehensively. Additionally, the theoretical research on the car-following analysis, which was initiated based on the GM models, is still under active analysis after almost 40 years from the first trials [8]. Research on traffic signal control achieved new avenues such as vehicle-actuated and adaptive traffic signal controllers, which added a new dimension to signal control simulation. Moreover, new system-level simulation models, although few in number, are used for network-wide transportation problems consisting of different kinds of intersections such as signalized, unsignalized, and links such as freeways, ramps, arterials, and city streets. A few attempts at system-level simulations have tried to develop open environments where several analysis models can be used interactively to solve the problems for which each one of them is most suitable. These include the TRAF-family programs and HUTSIM programs [7].

Increased computing power has contributed to precise modeling of the physical road and its environment in simulation of specific elements of the transportation systems such as the junction. In this case, the integration of Geographical Information Systems (GIS) and Computer Aided Design (CAD) systems, along with graphical user interface, can play a significant role.

In order to model traffic safety-related issues, a general approach to the problem and widely used safety simulation models to analyze the conflict situations should be developed [7]. Traffic safety simulation is mainly based on the field of human-centered simulation, where the perception–reaction system of drivers, with all its weak characteristics, has to be described [7]. In fact, safety aspects and human reactions in different traffic situations will be enhanced by the use of virtual reality in the simulations [9].

3. SIMULATION MODELS

Simulation is the abstraction of real world conditions by developing computer models and running them through time [10]. Five driving forces contribute significantly in the advancement of traffic simulation: the advances in traffic theory; the continuing improvement in computer hardware and software technology; the development of the general information infrastructure; and the society's demand for more detailed analysis of the consequences of traffic measures and plans [10]. Traffic systems are complex systems because of human interactions and man–machine interactions. Due to the complexity of this type of system, simulation is required to test, evaluate, and demonstrate a proposed course of action before implementation. In the subsequent paragraphs, the main features of a few simulation models are described. These are summarized in Table 1.

AIMSUN integrates in a single software application three types of transport models. These are traffic assignment models, a mesoscopic simulator, and a microsimulator [11]. The microscopic model is developed based on car following, lane changing, and gap acceptance algorithms like other software such as CORSIM. However, the new mesoscopic simulator in AIMSUN 6 provides an additional option to practitioners to model dynamic aspects of very large networks and removes most of the calibration burden when compared to a micro-simulator [11]. The software's home page provides demo software along with the many relevant resources.

SimTraffic is a microscopic simulation package which uses the SYNCHRO program to model street networks. It was initially developed to model the arterial signal system timings. It can simulate surface street networks, freeways, weaving sections, pre-timed and actuated traffic signals, stop-controlled intersections, roundabouts, transit operations, pedestrians, *etc.* [12].

VISSIM is based on a traffic flow model which is a discrete, stochastic, and time step based microscopic model. The model considers driver-vehicle-units as single entities and contains a psycho-physical car following model for longitudinal vehicle movement and a rule-based algorithm for lateral movements. The model is developed based on the research of Wiedemann [12, 14]. The simulation package VISSIM consists internally of two different programs, which include the traffic simulator, a microscopic traffic flow simulation model, and a signal state generator. The latter is a signal control software polling detector which compiles information from the traffic simulator on a discrete time step basis. Fellendorf [15] described the system architecture of VISSIM concentrating on its abilities as a simulation model for signal control. The simulation systems of VISSIM consist of a traffic flow model and a signal control model. VISSIM sends detector values to the signal control program every second, and the signal control uses the detector values to decide the current signal aspects [15].

ACTSIM is a dynamic micro-simulation model which simulates each vehicle independently, uses the distribution of population behavior, models changes in density, peaking in demand, curbside parking, and crosswalks, and

provides a continual picture of the network. Statistical data gathered over a period provides an average view as well. Individual vehicle parameters, including vehicle speed, vehicle size, desired maximum speed, destination location, dwell time, and gap acceptance, are assigned by random variants derived from vehicle mode characteristics. ACTSIM consists of a car following model, lane changing model, parking model, pedestrian crossing model, and passenger pickup/drop off model [10].

CORSIM is a microscopic, stochastic, link-node and periodic-scan based traffic simulation program designed for the analysis of freeways, urban streets, and corridors or networks. The combination of arterial (TRAF-NETSIM) and freeway (FRESIM) simulation models makes CORSIM one of the analysis models available to traffic engineers that allow all of the individual components of the arterial and freeway system to be analyzed and simulated as a complete system [16]. CORSIM stochastically determines the specific properties of each vehicle such as vehicle length, driver aggressiveness, acceleration rate, minimum acceptable gap, maximum free speed, and others. The car-following and lane-changing logic to simulate vehicle movements are done in CORSIM on a second-by-second basis.

Table 1. A Few Different Types of Simulation Models and Their Main Features and Capabilities

Name	Characteristics	Main Features/Capabilities
CORSIM	Microscopic	Surface streets, freeways, actuated signals, weaving sections, incidents, variable message signs, 2-D animation.
SimTraffic	Microscopic	Surface streets, actuated signals, pedestrians, roundabouts, 3-D animation.
AIMSUN	Microscopic, distributed computing technique	Surface streets, freeways, actuated signals, dynamic traffic assignment, variable message signs, 3-D animation, telematics.
VISSIM	Microscopic	Surface streets, freeways, ramp metering, pedestrians, transit operations, 3-D animation.
PARAMICS	Microscopic, distributed computing technique	Surface streets, freeways, transit operations, 3-D animation, roundabouts, congested networks.
INTEGRATION	Mesosopic	Surface streets, freeways, traffic assignment, intelligent transportation system, toll plaza, vehicle emissions, HOV.
DynaMIT	Mesosopic, real time computer system	Operation of Advanced Traveler Information Systems (ATIS) and Advanced Traffic Management Systems (ATMS), dynamic estimation of network state, a variety of real time scenarios, simulation of each trip.
MITSIMLab	Microscopic	ATIS and ATMS.
CORFLO	Macroscopic	Surface streets, freeways.
SATURN	Microscopic	Individual junctions, traffic assignment.
Micmac	Hybrid	SITRA B+ (microscopic model) and SIMRES (macroscopic model) are coupled, and the synchronization of the models is sequential.
Hystra	Hybrid	Macroscopic and microscopic models are combined, both models are based on the (Lighthill–Whitham–Richards) LWR traffic flow theory.
KRONOS	Macroscopic	Freeway lane changing, merging, diverging, and weaving, the simultaneous development of queues and propagation of congestion on both the freeway and its ramps.
KWaves	Macroscopic, discrete, deterministic	Freeways, throughput, bottlenecks, queues, ramp metering, incident management.

Quadstone PARAMICS is a suite of software models for microscopic traffic simulation which allows a unified approach to traffic modeling encompassing the whole spectrum of network sizes starting from single junctions up to national networks. It models the emerging ITS infrastructures. Programmer, which is a software development kit (SDK) for the PARAMICS suite, can be used for research of all aspects of ITS, real time connectivity and control, connectivity to real world hardware and software systems, and advanced or customized model behaviors [17]. The software's home page provides demo software along with the source information of many relevant resources.

TRANSYT is an off-line macroscopic deterministic simulation and optimization model that simulates traffic as cycle flow profiles (CFP), traces the flow of CFP from link to link throughout the network, and makes systematic changes to the offset, phase split, and cycle length of the traffic signals. It also simulates the associated traffic conditions to estimate a corresponding performance index (PI). This PI is composed of vehicle delay and number of vehicle stops. The simulation module within the TRANSYT model evaluates the objective function that is to be minimized [18].

KRONOS is a macroscopic model for mainly freeway operation and which uses a simple continuum model based on the Lighthill–Whitham–Richards (LWR) traffic flow theory [19]. It accounts for accelerating, decelerating, lane changing, merging, diverging, and weaving [19]. KWaves98 is a purely macroscopic model which is based on Newell's theory of kinematic waves in highway traffic with the objective to evaluate freeways under saturated conditions [19]. The major parameters, including flow rate, density, speed, and delay, are derived from the cumulative demand and the actual cumulative flow [19].

MICMAC is a hybrid model which uses the existing SIMRES macroscopic model and adapts the SITRA B+ microscopic model to fit some observed conditions [6]. SIMRES models the road in discrete cells, for which the flow, density, and speed are calculated for each time step. Hystra is also a hybrid model which attempts to use equivalent microscopic and macroscopic models [6]. Both the micro- and macro-models are based on the LWR traffic flow theory. Table 1 includes the main features and capabilities of different types of simulation models, including a few models which are not mentioned in the text.

4. DIFFERENT COMPARATIVE ANALYSES

Jones *et al.* [20] evaluated CORSIM, SimTraffic, and AIMSUN using a variety of criteria, including hardware/software requirements; difficulty/ease of network coding; data requirements and appropriateness of defaults; and relevance/accuracy of performance measures reported in the output. Each simulation package was evaluated using all corridor types, including freeways, signalized principal arterials, and an urban collector. SimTraffic was the easiest of the three models to use and its graphical interface resulted in significantly shorter coding times than the other two models. Its ability to export to a CORSIM format was found to make it an ideal starting point when creating coding for more complex networks. CORSIM can model more complex situations than SimTraffic and simulate the impacts of transit and parking on traffic operations. When CORSIM is used in conjunction with the Synchro/SimTraffic export capabilities, networks can be built relatively quickly compared to CORSIM alone. AIMSUN was found to operate acceptably well with outputs comparable to both SimTraffic and CORSIM, and it possesses features that would be useful for creating large urban and regional networks. Its dynamic traffic assignment capability is unmatched by either SimTraffic or CORSIM. AIMSUN requires relatively cumbersome coding compared to SimTraffic and CORSIM [20].

Shaw and Nam [21] compared VISSIM and PARAMICS in terms of “ease of use”, which consists of input data requirements, network coding/editing, and input/output review. Their study claimed that the network coding/editing and input/output review in PARAMICS are very good, but the input data requirements need improvement. On the other hand, all three criteria in the case of VISSIM are acceptable. Hidas [22] evaluated AIMSUN and PARAMICS with respect to the model building capacity. The input procedures of AIMSUN are easier and faster than in PARAMICS and some users claim it takes 30–50% less time to set up a model in AIMSUN than in PARAMICS [22].

VISSIM and CORSIM are used for modeling individual vehicle interactions on complex roadway networks and require inputs such as lane assignments and geometries, intersection turning movement volumes, vehicle speeds, percentages of vehicles by type, and pre-timed and/or actuated signal timing. Total delay, stopped delay, and queue lengths are the common output of the models. In general, CORSIM is suitable for the models which do not contain a transit element such as buses, LRTs, *etc.* On the other hand, VISSIM is recommended by users for its easy

manipulation capability in the context of complex geometry and traffic control, and transit elements. There are three significant differences between the models. CORISM uses a link-node structure while the network of VISSIM is built over a graphical map. The car-following modeling in CORSIM sets a desired amount of headway for individual drivers but VISSIM relies on the psycho-physical driver behavior model [20]. VISSIM reports total delay by link and not for each turning movement, but CORSIM provides average control delay for each approach.

This study attempted to summarize the research on the comparative analysis of the microscopic simulation software (Table 2), but it is not intended to provide a comprehensive list of comparative studies.

Table 2. Different Comparative Studies of Simulation Software

Author(s)	Software Compared	Findings
Rakha and Van Aerde [18]	TRANSYT and INTEGRATION	The types of more complex signal timing problems, which at present cannot be examined by the TRANSYT model, can be examined using the dynamic features of INTEGRATION. INTEGRATION simulates traffic-signalized networks in a manner that is consistent with TRANSYT for conditions in which TRANSYT is valid and it can simulate conditions that represent the limitations to the current TRANSYT model.
Taori and Rathi [28]	NETSIM, NETFLO I, and NETFLO II	The models were evaluated for the traffic networks with fixed-time signal control. The speed values generated by NETSIM were found to be the lowest; NETFLO II values were the highest. NETFLO I values in all cases were between NETFLO II and NETSIM values. The execution times for NETSIM were found to be higher than those of NETFLO II and NETFLO.
Wang and Prevedouros [29]	INTEGRATION, TSIS/CORSIM, and WATSim	The models can simulate traffic operations on mixed arterial and freeway networks and produced reasonable and comparable results on most network links. Only INTEGRATION can simulate U-turns, and TSIS/CORSIM is the best at replicating lane-changing behavior. Although WATSim needed the least calibration for producing good results, its animation is inferior and its capacity-based car-following parameters are undesirable.
Middleton and Cooner [30]	CORSIM (FRESIM component), FREQ and INTEGRATION	Models were used to simulate congested freeway conditions. Although all models performed relatively well for uncongested conditions, they were inconsistent in their ability to accurately model congested conditions.
Prevedouros and Wang [31]	INTEGRATION, CORSIM, and WATSim	Field data for a large integrated (street and freeway) network were used as input and all three software programs were able to replicate field-measured volumes well. INTEGRATION required extensive modifications to approximate complex signal timing plans and WATSim needed the fewest modifications. WATSim and CORSIM speeds were close to each other.
Bloomberg and Dale [24]	CORSIM and VISSIM	Models compared for congested arterials. They found that models produced consistent results among them. Moreover, both models are equally user friendly with respect to initial coding.
Boxill and Yu [5]	CORSIM, INTEGRATION, AIMSUN and PARAMICS	The study evaluated the models based on their ability to simulate ITS. AIMSUN and PARAMICS have significant potential for modeling ITS but require more calibration and validation for the CORSIM and INTERGRATION seem to have the highest probability of success in real-world applications with respect to familiarity and extensive calibration/validation.
Prevedouros and Li [19]	INTEGRATION, KRONOS and KWaves	INTEGRATION produced acceptable results for all traffic conditions but its lane-changing replication was not realistic. KRONOS required the fewest modifications to achieve good results but it overestimated the benefits of adding a lane to the mainline freeway. KWaves98 is limited to the simulation of freeway operations under heavy traffic conditions.
Barrios <i>et al.</i> [32]	CORSIM, VISSIM, PARAMICS and SimTraffic	The simulation tools were evaluated based on their graphical presentation (animation) capabilities specifically to simulate bus operations. A review of transit-related and visualization capabilities of each model is presented and the study selected VISSIM due to its 3-D capabilities.

Trueblood [33]	CORSIM and SimTraffic	There was little difference between models for arterials with low to moderate traffic. The study focused on the importance of user familiarity with models and need to properly validate and finally compared the ability of models to accurately simulate a freeway interchange.
Choa <i>et al.</i> [23]	CORSIM, PARAMICS and VISSIM	According to this study, CORSIM outperformed others due to the least difficulty in coding and its ability to compute control delay for individual approaches. The simulations of PARAMICS and VISSIM, along with their 3-D capabilities, were more closely reflected actual conditions.
Tian <i>et al.</i> [27]	CORSIM, SimTraffic and VISSIM	Signalized arterials were studied in this study. It was found out that outputs varied with link length, speed range, and volume levels, and the variation was greater when volume approached capacity. CORSIM displayed stable results compared to SimTraffic.
Bloomberg <i>et al.</i> [34]	CORSIM, INTEGRATION, MITSIMLab, PARAMICS, VISSIM and WATSIM	All six models were applied to signalized intersections and freeways and the study revealed that all models performed reasonably well and were fairly consistent.
Kosman <i>et al.</i> [26]	VISSIM and CORSIM	Either model may perform adequately for estimating average speeds as input to project-level emissions analysis, provided that proper validation is adopted.
Jones <i>et al.</i> [20]	CORSIM, SimTraffic, and AIMSUN	AIMSUN was found to operate acceptably well compared to both SimTraffic and CORSIM and it possesses features that would be useful for creating large urban and regional networks. Its dynamic traffic assignment capability is unmatched by either SimTraffic or CORSIM, but AIMSUN requires cumbersome coding.
Middleton and Cooner [25]	CORSIM (FRESIM component), FREQ and INTEGRATION	The authors aimed to find appropriate models for simulating congested freeways, and test the calibration and validation performance of those models using data collected for Dallas freeways. The CORSIM program had the best overall performance in this project and shows promise for future application for the operational evaluation of congested freeway facilities.
Panwai and Dia [35]	AIMSUN, PARAMICS and VISSIM	They evaluated car-following behavior in the mentioned traffic simulators and found lower error values for the Gipps-based models implemented in AIMSUN and similar error values for the psychophysical spacing models used in VISSIM and PARAMICS.
Xiao <i>et al.</i> [36]	AIMSUN and VISSIM	It was found that both simulators are capable of incorporating most of the standard features used in traffic modeling. The accuracy of both simulators was found to be similar.
Hadi <i>et al.</i> [37]	CORSIM, VISSIM, AIMSUN	For all three models, it was required to calibrate model parameters to produce acceptable reductions in capacity due to incidents. In the case of AIMSUN and VISSIM, there was a need to introduce incident-specific time-variant calibration parameters.

4.1. Freeway Operations

The required key factors to consider in selecting a simulation model for a typical freeway interchange study include model development, calibration to field conditions, validation requirements, simulation or animation, and model output and consistency with the 2000 Highway Capacity Manual (HCM). Choa *et al.* [23] conducted a study in order to find out the effectiveness of CORSIM, PARAMICS, and VISSIM in the context of freeway interchange. The study was concerned with a proposed improvement project for the U.S. Highway 50/ Missouri Flat Road interchange near the historic gold mining town of Placerville, California. Based on the studies of Lindgren and Tantiyanugulchai [2] and Choa *et al.* [23], the following conclusions are summarized comparing the mentioned three traffic simulation programs.

- Simulated interchange delay results provided by PARAMICS and VISSIM seem to be consistent with delays predicted by HCM2000 methodologies.
- CORSIM took the shortest set-up time while PARAMICS and VISSIM required about an additional day for model refinement.

- The path-based routing in VISSIM eliminated the problem associated with link-based routing, which is used in both CORSIM and PARAMICS.
- Three dimensional animations are available in both PARAMICS and VISSIM but not in CORSIM, which relies on two-dimensional animations.
- The models report total delay by link, not for each turning movement. But CORSIM provides average control delay for each approach.
- An artificial barrier in CORSIM can cause inaccuracies, including the metering of traffic on high-volume on-ramps or backups of traffic on high-volume off-ramps.
- Due to their stochastic nature, CORSIM, PARAMICS, and VISSIM produce new results each time the model is seeded with a new random seed.
- Considering all concerned issues, PARAMICS and VISSIM provided simulation results that better matched field-observed conditions, traffic engineering principles, and expectation or perception of reviewing agencies.

Prevedouros and Li [19] tested the ability of INTEGRATION, KRONOS, and KWaves to simulate freeway operations under moderate-to-heavy traffic with and without an incident, and heavy traffic, and inspected the sensitivity with respect to freeway mainline lanes, capacity, and jam density. In order to ensure objective comparisons the cross-sectional (spot) speeds and segment average speeds were used. In this study, INTEGRATION and KRONOS gave better results than KWaves. INTEGRATION produced acceptable results for all traffic conditions, but its lane-changing replication was not realistic. KRONOS required the fewest modifications to achieve good results, but it overestimated the benefits of adding a lane to the mainline freeway. KWaves98 is limited to the simulation of freeway operations under heavy traffic conditions.

4.2. Congested Network

Bloomberg and Dale [24] conducted a comparative study between VISSIM and CORSIM for a congested network of State Route (SR) 519 (S. Royal Brougham Way), Washington State Department of Transportation (WSDOT). Based on this study they concluded the following:

- Relative travel times were consistent between the models and lead to the same conclusions about the design options analyzed in this study, although there were differences in the absolute predictions of the two models for some scenarios.
- Both models are appropriate for modeling congested arterial street conditions.
- Although the parallel modeling effort added credibility to the analysis results, either model alone was adequate for the analysis.
- On a selected section upstream of a signalized intersection, both models produced similar throughput.
- It is estimated that coding the SR 519 network took approximately the same amount of time in CORSIM and VISSIM.

Middleton and Cooner [25] aimed to identify appropriate models for simulating congested freeways, test the calibration and validation performance of those selected models using data collected on Dallas freeways, and provide recommendations on the use of the best model for congested freeways in Texas. Although all models performed relatively well for uncongested conditions, they were inconsistent in their ability to accurately model congested conditions. The inability of the FREQ model to simulate vehicle speeds on freeway-to-freeway ramps resulted in the evaluation of the sites having two facilities incomparable to CORSIM and INTEGRATION. The FREQ model performed best on the site having only one freeway facility. However, in terms of ease of use and application, the FREQ was the most user-friendly. The INTEGRATION model required the most effort in terms of network coding and execution, and the input requirement of volumes in terms of origin-destination data made it more difficult than either CORSIM or FREQ. INTEGRATION requires long execution times and cannot handle networks that are too large and complex. It exhibited the lowest overall performance in terms of its ability to replicate known speed and volume profiles. The CORSIM simulation model was the most robust in terms of input and output capabilities. The calibration of CORSIM was very easily done by modifying parameters such as car-following sensitivity, lane changing, driver aggressiveness, *etc.* The CORSIM program had the best overall performance in the study, and shows potential for future application for the operational evaluation of congested freeway facilities.

4.3. Project-Level Emission Modeling

Kosman *et al.* [26] conducted a study in order to evaluate the performance of VISSIM and CORSIM for estimating the air quality impact of traffic signal improvements with the help of two different scenarios. The output from the two models was compared to average and spot speed data collected in the field for two arterials. The use of output in predicting emission reductions was evaluated for three Congestion Mitigation and Air Quality (CMAQ) projects. Due to the expected project improvements, changes in average speeds were higher in CORSIM than VISSIM. The obtained results of VISSIM and CORSIM were compared by using emission rates used by the Chicago Area Transportation Study (CATS) for Volatile Organic Compound (VOC) and NO_x . A table of emission rates in grams per mile by average speed originally created by MOBILE5 was used as a look up table and the values were multiplied by the study section length, link volume, and study days per year, thus yielding a total quantity of pollutant in kilograms. The comparison shows that emission reductions using CORSIM were greater than VISSIM. Kosman *et al.* [26] suggested that either model may perform adequately for estimating average speeds as input to project-level emissions analysis, provided that proper validation is adopted.

4.4. Variations in Delay and Capacity Estimates

Tian *et al.* [27] evaluated microscopic traffic simulation models for signalized arterials by using CORSIM, SimTraffic, and VISSIM in terms of the variations in the performance measures such as delay and capacity estimates. The models produced different results when the default traffic flow parameters from each simulation model were used. The outputs varied with link length, speed range, and volume levels, and the variation was greater when the traffic demand approached capacity. CORSIM displayed stable results compared to SimTraffic in terms of the variations of the performance measures. The variance reduction techniques used in CORSIM might have contributed in ensuring stability of the results. Generally, SimTraffic produces the highest delay and lowest capacity estimates, and VISSIM produces the lowest delay and highest capacity estimates. The study revealed that delays are affected by link length and speed in simulation models, and in general, shorter links with higher link speeds result in shorter delays.

5. STATUS OF SIMULATION SOFTWARE RESEARCH IN SAUDI ARABIA

Al-Ahmadi [38] conducted a study in order to find a potential network simulation model suitable for evaluating policy changes in the context of the Al-Khobar downtown area, Saudi Arabia. The study compared the performances of SIGOP III, TRANSYT, and NETSIM (non-freeway component of CORSIM), and found that NETSIM was the potential simulation model that may effectively be used to evaluate traffic policy changes for road networks in downtown areas.

Al-Ofi [39] calibrated TRANSYT for the urban signalized intersections in the cities of Dammam and Al-Khobar in Saudi Arabia in order to find out the effects of signal coordination on intersection safety and to develop a methodology by which intersection safety could be optimized by introducing the costs of rear-end accidents as functions of stops and delays. The study revealed that rear-end accidents are mainly affected by the number of stops at signalized intersections rather than volume.

Ratrouf [40] studied TRANSYT-7F as a simulation model in Saudi Arabia under local conditions along two major arterials that consisted of four pre-timed signalized intersections with four approaches in areas of mixed residential and commercial activities. He attempted to determine the value of the Platoon Dispersion Factor (PDF) of the TRANSYT model which best simulated the traffic flow. The study focused on the PDF because the reliability and effectiveness of the TRANSYT model primarily depends on a platoon dispersion algorithm for signalized intersections. The study concluded that the default PDF has to be changed in order to replicate the local conditions. TRANSYT-7F is used both as an optimization and simulation model. Generally, the optimization model intends to minimize the objective function whereas the simulation model intends to replicate the field conditions and then evaluate different geometrical and/or operational strategies.

Ahmed [41] calibrated the VISSIM model for the traffic conditions of Al-Khobar, Saudi Arabia by adjusting the default values of the number of observed vehicles, additive and multiplicative parts of desired safety distance, amber signal decision, and distance required in changing lanes. The results of the validation based on another network of Dammam revealed that the difference between the field-observed Measure of Effectiveness (MOE)'s and the VISSIM simulation results are within the acceptable range.

Olba [42] evaluated the TRANSYT-7F and SYNCHRO/SimTraffic models for the local traffic conditions of Al-Khobar, Saudi Arabia with respect to the queue lengths and the developed optimum signal timing plans were simulated using TRANSYT-7F and SimTraffic. The study revealed that the queue length calibration process was successful for TRANSYT-7F, but not for SimTraffic. The simulation output indicated that the signal timing plan developed through SYNCHRO provides better system performance compared to TRANSYT-7F.

Al-Jaman [43] successfully calibrated and validated the SimTraffic model for the signalized intersections of Riyadh, Saudi Arabia. The calibrated parameters are travel speed, turning speed, headway factor (a measure of saturation flow rate), and driver type. The study discovered that the intersection approaches in Riyadh seem to have high saturation flow rates, which supports the results from other studies indicating that driving behavior in Riyadh is aggressive.

The researchers successfully calibrated and validated the NETSIM, TRANSYT, SimTraffic, and VISSIM models for the local conditions of Saudi Arabia. The user-friendly nature of SimTraffic led practitioners to use it widely, although there are a few cases where VISSIM is also getting used. In fact, the use of simulation software is generally limited to either freeways or surface streets. This paper concludes that no significant study has been done up to this date in Saudi Arabia on the use of simulation software that has the capability of analyzing an integrated system of freeways and surface streets. This type of study might be the next step for the local researchers.

6. CONCLUSIONS

The development of computer technology and programming software has contributed to the significant development in traffic simulation from the early 1950's. Most of the development trends are related to microscopic simulation. The applications are now growing in size, moving from well-covered local or one-facility type applications to network-wide systems where several types of facilities are integrated in one system. The computing capability is being used in the precise description of the physical road and street environment, especially in local applications, along with the integration of graphical user interface, and GIS and CAD systems. The parallel computing, along with modern programming principles and methods, has tremendously increased the extent of simulation from single intersections to the traffic system of a whole city. Newly-adopted object-oriented programming approaches were found to be very suitable for modeling transportation systems. In traffic flow simulation, rule-based approaches can use artificial intelligence techniques to describe the human perception. Simulation of control systems as a part of traffic operations is also becoming more important. It can be expected that in the future more simulation systems will be embedded in control systems for predicting the state of traffic flow and the effects of alternative control measures. The increasing use of virtual reality systems in simulation will greatly benefit traffic safety-related simulation.

The analysis revealed that AIMSUN, CORSIM, and VISSIM are suitable for congested arterials and freeways, and integrated networks of freeways and surface streets, but AIMSUN is less user-friendly compared to others. The features of AIMSUN are favorable for creating large urban and regional networks, but it requires cumbersome coding. The models AIMSUN, PARAMICS, INTEGRATION, and CORSIM seem to have potential for ITS application. However, a few simulation models are developed that focus on ITS, such as MITSIMLab. The TRAF-family and HUTSIM programs apply system-level simulation approaches which try to develop open environments where several analysis models can be used interactively to solve the problems for which each one of them is most suitable.

Researchers have successfully calibrated and validated NETSIM, TRANSYT, SimTraffic, and VISSIM models for the local conditions of Saudi Arabia. The user-friendly nature of SimTraffic led the practitioners to use it widely. But the use of simulation software is generally limited to either freeways or surface streets. The calibration and validation of the simulation software were done mostly as case studies. Researchers should attempt to determine the prospect of using simulation software which can handle both freeways and surface streets together. It will be very beneficial for the local practitioners if the prospective simulation tools can easily be integrated with a transportation demand model. This integration will provide a platform to solve and evaluate the transportation problems in a broader perspective. Finally, the prospective simulation tools should be evaluated in terms of their capability of being used for ITS applications.

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