Accident Analysis and Prevention 66 (2014) 89–103

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Simulation of safety: A review of the state of the art in road safety simulation modelling

William Young[a,*], Amir Sobhani[a,1], Michael G. Lenné[b,2], Majid Sarvi[a,3]

[a] Institute of Transport Studies, Department of Civil Engineering, Monash University, Clayton, VIC 3800, Australia
[b] Monash University Accident Research Centre, Monash University, Clayton, VIC 3800, Australia

ARTICLE INFO

Article history:
Received 14 August 2013
Received in revised form 4 December 2013
Accepted 9 January 2014

Keywords:
Simulation
Safety
Models
Surrogate safety measures

ABSTRACT

Recent decades have seen considerable growth in computer capabilities, data collection technology and communication mediums. This growth has had considerable impact on our ability to replicate driver behaviour and understand the processes involved in failures in the traffic system. From time to time it is necessary to assess the level of development as a basis of determining how far we have come. This paper sets out to assess the state of the art in the use of computer models to simulate and assess the level of safety in existing and future traffic systems. It reviews developments in the area of road safety simulation models. In particular, it reviews computer models of driver and vehicle behaviour within a road context. It focuses on stochastic numerical models of traffic behaviour and how reliable these are in estimating levels of safety on the traffic network. Models of this type are commonly used in the assessment of traffic systems for capacity, delay and general performance. Adding safety to this assessment regime may allow more comprehensive assessment of future traffic systems. To date the models have focused primarily on vehicular traffic that is, cars and heavy vehicles. It has been shown that these models have potential in measuring the level of conflict on parts of the network and the measure of conflict correlated well with crash statistics. 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. The paper also explores the general data types used to develop, calibrate and validate these models. Recent technological development in in-vehicle data collection, driver simulators and machine learning offers considerable potential for improving the behavioural base, rigour and application of road safety simulation models. The paper closes with some indication of areas of future development.

1. Introduction

Traditionally, road safety analysis has relied on crash statistics as their main data source (Hauer, 1982, 1997). The collection of this data, its analysis, development of countermeasures, introduction of these countermeasures and assessing their impacts is an ongoing approach used to improve the road safety system. It has been a very successful approach. The lack of such data; its slowness in being collected; the difficulty in using it to observe the crash process; and its inability to assess the introduction of new technologies that are not presently used in the traffic system; have encouraged researchers to develop complementary approaches (Perkins and Harris, 1967; Laureshyn et al., 2010; Davis et al., 2011) to assess potential safety improvements. One approach that has increasing in interest over the last decade (see Table 1) is the use of computer simulation models of driver behaviour to replicate the interaction between the factors contributing to the conflict and/or crash process. This paper reviews these developments and discusses the future development of these models. Traffic simulation models have long been used to assess the performance of the traffic system and the impact of the introduction of new traffic systems components, vehicles and driver-assistance technology. They can provide estimates of traffic system capacity, delay, and general flow conditions. The question being explored in this paper is: Can these models be expanded to include the assessment of the safety impacts of existing and new traffic systems?

Traffic simulation models utilise stochastic sampling of the distributions of driver behaviour 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 behavioural constructs which enable measures of the safety performance of the road system to be evaluated. Road safety

* Corresponding author. Tel.: +61 3 9905 4949; fax: +61 3 9905 4944.
E-mail addresses: Bill.Young@monash.edu (W. Young), Amir.Sobhani@monash.edu (A. Sobhani), Michael.Lenne@monash.edu (M.G. Lenné), Majid.Sarvi@monash.edu (M. Sarvi).
[1] Tel.: +61 3 9905 1851; fax: +61 3 9905 4944.
[2] Tel.: +61 3 9905 1389; fax: +61 3 9905 4363.
[3] Tel.: +61 3 9905 4956; fax: +61 3 9905 4944.

0001-4575/$ – see front matter © 2014 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.aap.2014.01.008

Table 1
A chronology of road safety simulation models.

No.	Measure of performance	Crash types considered	Key parameters	Model variables	Calibration and validation	Simulation framework	Reference
1	Traffic conflicts	Unsignalised T intersection	Turning vehicle gap acceptance function; deceleration rate to avoid a crash	Traffic flow, turning movements, speed, gap acceptance	Not clarified	Event step simulation program developed using a programming language	Cooper and Ferguson (1976)
2	Traffic conflicts	Unsignalised intersections	Traffic conflicts based on no variation in speed	Traffic flow	Not clarified	Event step simulation program developed using a programming language	Hodge and Richardson (1978)
3	Traffic conflicts	Unsignalised T intersection	Turning vehicle gap acceptance function. Turning vehicle gap acceptance function	Traffic flow, turning movements, speed, gap acceptance	Not undertaken, large data collection exercise required	Event step simulation program developed using a programming language	McDowell et al. (1983)
4	Traffic conflicts	Parking lot movement, intersections, midblock and parking and unparking manoeuvres	Conflict defined as any change in travel movement consequent on another vehicle	Traffic volume, origin destination, speed, unparking and parking times, intersection gap acceptance	Video images of parking systems, speed studies at parking lots	PARKSIM simulation package	Yue and Young (1992, 1993, 1998a,b)
5	Surrogate safety measure time to collision and risk of collision	Unsignalised T and four leg intersections. Crossing conflicts	Variable gap acceptance function, time to collision (<1.5 s)	Traffic volume, percent heavy vehicles, Intersection type, speed limit, percentage of driver type, number of lanes in all roads	Animation study of model outputs and vehicle movements, conflict observation on site	Traffic systems conflict simulation (TSC-Sim) developed using the general purpose simulation system (GPSS)	Sayed et al (1994)
6	Surrogate safety measures	Unsignalised T and four leg intersections. Crossing conflicts	Time to collision, required braking rate, logistic representation of gap acceptance	Traffic flow, speed, car-following, gap acceptance (binary logistic function), acceleration, deceleration, safety indicators	Video data of unsignalised T-intersection	VISSIM (With calibrated binomial logistic distribution of gap acceptance)	Archer (2005), Archer and Young (2010c)
7	Surrogate safety measures	Unsignalised and signalised four leg intersections	Post Encroachment time, conflict zone, time to collision	Traffic flow, speed, headway distribution	Existing model parameter, no calibration or validation outlined	PARAMICS	Pirdavani et al. (2010, 2011)
8	Surrogate safety measures	Signalised intersection, car-following, rear end accidents	Deceleration to avoid crash (DRAC), 15 key parameters in Wiedemann (1974) car-following model estimated	Traffic flow, speed, car-following, maximum available acceleration rate (average 8.45 m/s^2, Standard deviation 1.4 m/s^2)	Next generation simulation (NGSIM) data; Video data; 15 key parameters in Wiedemann (1974) car-following model estimated	VISSIM traffic simulation package	Cunto and Saccomanno (2008)
9	Surrogate safety measures	Signalised intersection with incident reduction function	Post encroachment time (PET), binary logistics stop/go function	Traffic flow, vehicle composition (Light and heavy vehicles) speed, car-following, gap acceptance, stop/go decision at red light (Binary Logistic function), acceleration, deceleration, safety indicator (PET)	Video data of signalised intersection in outer Melbourne, Australia	VISSIM with binary logistic stop/go decision process	Archer and Young (2009, 2010b)
10	Rear end crash potential 1. Between target and lead vehicle and 2. Between lead and following vehicle.	Link, rear end crash	Behaviour of target obstruction, lead vehicle, following vehicle	Traffic flow. Vehicle parameterisation using safe separation distance, safe speed, perception reaction time, preferred time headways, time to adjust target speed. distance travelled by lead vehicle	No calibration. A systems dynamics framework is developed and applied to the study of rear end accidents initiated by and target on the road	Programming language. Systems dynamics representation of system placed inside a simulation model	Mehmood et al. (2001)
11	Surrogate safety measures	Road links, car-following, rear end accidents	Vehicle tracking data, deceleration rate, acceleration rate, vehicle headways	Deceleration rate to avoid a crash (<3.35 m/s^2) and time to collision	Observed vehicle tracking data	TRITONE simulation model. Programing language	Astarita et al. (2012a,b)

Table 1 (*Continued*)

No.	Measure of performance	Crash types considered	Key parameters	Model variables	Calibration and validation	Simulation framework	Reference
12	Surrogate safety measures, Vehicle trajectory, Crash	Road lengths, links	Car-following and lane changing behaviour	Vehicle trajectories, vehicle type, driver aggressiveness, road geometry, pitch, yaw and roll characteristics of vehicle	Exploratory, no calibration and validation reported	VISSIM simulation program, CARSIM vehicle dynamic simulator, GNSS/INU driver vehicle control intervention model	Dedes et al. (2011)
13	Surrogate Safety Measures, Time to collision	Road networks. Intersections and road link sections	Car-following and cross movements time to collision (<2.5 s)	Traffic flow, route choice, car following, gap acceptance	The Netherlands, Department of Transport Crash Data Base	PARAMICS Traffic Simulation software	Dijkstra et al. (2010), Dijkstra (2012)
14	Surrogate safety measures	Road links, car-following and lane changing. Bus and car interaction	Car-following and cross movements time to collision (<2.5 s). Time to collision, Deceleration to avoid crash	Bus and car traffic flows, bus priority configurations, car-following and land changing behaviour	Video images, comparison of Time to collision and deceleration rate for observed and simulated situations	VISSIM traffic simulation model	Goh et al. (2013)
15	Crash, near crashes	Car-following, rear end crashes	Perception-response process based on visual perception, scan interval	Vehicle trajectories, deceleration rate, acceleration rate, following gap time, scanning interval, response delay	Video images on motorway, high resolution camera (0.1 s resolution), six crashes and four near crashes	Computer programming language	Xin et al. (2008)
16	Traffic conflicts and crashes	Rear end events (conflicts and crashes)	Continuum of conflicts and crashes	Following vehicle: speed, acceleration reaction time. Leading vehicle: critical headway, velocity, speed, acceleration	100 car naturalistic data set (Dingus et al., 2005)	Theoretical treatment with Markov Chain Monte Carlo simulation	Davis et al. (2011)
17	Traffic conflicts and crashes	Signalised intersection with unsignalised right turn manoeuvre	Reaction, Kinetic Energy, Injury Severity	Traffic volume, speed limit, gap acceptance, number of lanes in all roads, traffic signal phases	Traffic flow, headway, video data, crash data	VISSIM, binary probit, log gamma statistical models	Sobhani et al. (2011a, 2013a,b)
18	Traffic conflicts, surrogate safety measures, crashes	Run of road crashes, Encroachment rate	Encroachment rate, encroachment speed, encroachment angle	Impact, speed, impact angle, lateral extent of encroachment, vehicle type, vehicle orientation, multiple hazards, severity, incremental benefit and cost	Vehicle encroachment data (Cooper, 1980)	Road Safety and Analysis Program (RSAP)	Mak and Sicking (2003)

simulation models are a useful tool in contributing to the overall evaluation of road systems performance, in particular providing more appropriate outputs to calculate safety indicators than macroscopic modelling approaches (Levison, 1998; Huguenin et al., 2005). Table 1 presents some of the numerous studies of the application of micro-simulation to assess the safety performance of traffic systems. It is timely to look at these approaches and assess the state of their development.

In this paper the application of micro-simulation modelling approaches to studying the safety of components of the traffic system is reviewed and key advances in the development of these models noted. In Section 2, the paper traces the development of thought in modelling driver behaviour and safety using computer simulation in order to assess the areas where they can contribute to improving traffic systems design. It starts by looking at the structure and theoretical base of simple and complex road safety simulation models. The measures of performance output by these models and used to assess safety, are investigated. In Section 3, the paper considers the data used to develop the models. The quality of the data and its flexibility in replicating the situation being studies is important in the calibration, verification, validation and application of the models. The opportunity for utilising driver simulators and machine learning to refine and improve these models is also explored. The paper closes with some considerations of the strengths and weaknesses of the models and makes suggestions about their future development.

2. Model structures

Traffic micro-simulation models attempt to mimic the process of vehicle movement in a traffic stream by replicating driver and vehicle behaviour on transport infrastructure. Many of these models implicitly use "safe" measures of behaviour rather than actual behaviour (Bonsall et al., 2005). For instance, some models used a fixed critical gap in the estimation of gap acceptance, clearly this assumption is not realistic since different drivers will accept different gaps in different situations. In order to measure the safety of traffic systems, using road safety simulation models, it is necessary to incorporate realistic behaviour to capture the variability in road user performance in real world conditions.

Existing traffic simulation models tend to look at driver behaviour (e.g. car-following, lane-changing, gap acceptance) which is repeatable across the entire transport system. Table 1 shows that road safety simulation models tend to focus on particular interactions (e.g. intersection conflicts, rear end conflicts, run-off-road situations) between vehicles and other objects and model the process associated with the conflict and/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 process is rarely related to one factor but results from a series of low probability outcomes of a number of contributing factors. It is the method of modelling the stochastic process involving driver behaviour and vehicle movement on transport infrastructure that sets road safety simulation models apart from other models of the traffic system and crashes.

Furthermore, the "Sustainable Safety" (Koornstra et al., 1992; Wegman and Aarts, 2006), "Safe System" (World Bank, 2013) and "Zero Vision" (Tingvall and Haworth, 1999; Traffic Safety by Sweden, 2013) approaches to safety, focus on the functionality of the road safety system (road, vehicle and driver) and the forgiveness principle. They recognise the limitation in crash analysis and looks for the major factors which will commonly be involved in a casualty and sets about eliminating them. Road safety simulation models add to this approach by allowing the probabilistic links between these factors to be replicated and explored.

Although the potential benefits of a safer road system have long been recognised the incorporation of safety measures of performance into traffic simulation models has been slow. Road safety simulation models are in an early stage of development and are illustrated in Table 1. Interest in the application of simulation models to road safety can be traced back to the 1970s. However, a rapid increase in interest in the last decade has been due to improved computer capabilities, data collection technology and communication mediums. This development is likely to continue. This section of the paper will, in the light of Table 1, review road safety simulation models, the measures used to assess safety, the types of crash situation that has been investigated and the level of detail in the model, in order to get an indication of where they can contribute to the development of a safer road system and where new developments are needed.

2.1. Initial road safety simulation models

Formalisation of the traffic conflict concept was initially proposed by Perkins and Harris (1967, 1968) as an alternative to crash data, which at that time was very scarce. The objective was to define incidences which occur frequently, and are clearly observed and related to crashes. Amundson and Hyden (1977) defined a conflict as: "A conflict is an observed situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movement remains unchanged". Conflicts were measured by observation of the traffic stream by observers on the roadside and classified depending on the likelihood of a crash. Asmussen (1984) outlines the early application of this technique.

The early road safety simulation models (see Table 1 Studies 1–4) grew out of the conflict analysis literature (Perkins and Harris, 1967; Amundson and Hyden, 1977). Initially these models looked at the relationship between conflicts and traffic flow at intersections (Cooper and Ferguson, 1976; Hodge and Richardson, 1978; Darzentas et al., 1980; McDowell et al., 1983). The models had relatively simplistic measure of driver behaviour. They simulated vehicle behaviour, 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. These models provided estimates of the exposure to a conflict and point to the number of conflicts being the square root of the product of the traffic volumes. These models were developed using generic programming languages. The models were rarely calibrated and validated since the technology for collecting data was not that advanced and the labour involved in extracting conflict information was considerable. Such approaches, did not take into account driver behaviour and its relationship to traffic volume. 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.

An extension to this approach was incorporated into PARKSIM, a traffic simulation model, developed for the design of parking lots (Yue and Young, 1992, 1993, 1998a,b). Yue and Young (1993) defined a conflict as a change in the movement of a vehicle consequent on another vehicle's actions. They replicated conflicts for mid-block, intersection, parking, unparking and queueing (Yue and Young, 1993). A parking lot is a bounded transport system that could be observed easily using video technology. Calibration of the parameters in the model and validation of the overall conflict measures was undertaken utilising a video image of a parking lot in outer Melbourne, Australia. Observed and simulated travel times, conflicts and vehicle flows were correlated and showed a significant correlation at the 95% confidence limit. This model also showed the potential of traffic simulation models for replicating conflicts, and overcome previous limitations through the inclusion of traffic flow, but gave no indication of the likelihood of sever conflicts or crashes nor did it make any attempt to replicate driver behaviour in hazardous situations.

These early developments of road safety simulation models set the scene for future activity in this area. They introduced possible measures of performance and showed the models had potential. The next section describes the next major steps in the development of these models.

2.2. Models utilising surrogate safety measures

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

$$\begin{aligned}&\text{Expected number of crashes}\,(\lambda)\\&\quad=(\text{number of conflicts}\,(c))\times(\text{crash-to-conflict ratio}\,(\pi))\end{aligned}\tag{1}$$

This relationship can be disaggregated to look at different crash types and time periods, with these categories being combined to give an overall measure of the total expected number of crashes. The next stage in development of road safety simulation models (see Table 1, Studies 5–14) focused on the quantification of the conflict and its severity: the study of "surrogate safety measures".

The development of road safety simulation models gained a new lease of life in the early 2000s with the advent of generally available commercial traffic simulation packages and new data sets collected using fixed location video technology. These new models relaxed Hauer's (1982) paradigm and looked to measure the severity of conflicts. This section reviews this next stage in development of road safety simulation models (see Table 1, Studies 5–14). It outlines the measures of performance used in these models (surrogate safety measures) and then the development and application of the models.

2.2.1. Surrogate safety measures

A fundamental step forward in the development of road safety simulation models was the determination of the 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), Getman and Head (2003), Tarko et al. (2009), Pirdavani et al. (2010, 2011) and Wu and Jovanis (2012a,b)). 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. A number of the measures, used in road safety simulation models, are outlined below.

An early, and commonly used, measure of conflict used in road safety simulation models was time-to-collision (TTC) (Sayed et al., 1994). TTC is generally defines as: "the time to collide if two vehicles continue at their present speed and along the same path" (Hayward, 1972). This measure combines speed and spatial separation, the smaller the time to collision the more severe the conflict. A threshold of 1.5 s has been used to determine if a severe conflict has taken place (Hyden and Linderholm, 1984). FHWA (2008) undertook research that considers signalised and un-signalised intersection safety evaluation. It defines the safety of a facility as: "the expected number of crashes, by type, expected to occur at an entity in a certain period, per unit time". The project investigated the potential for deriving surrogate safety measures from traffic data taken from existing traffic simulation models. One of the surrogate safety measures used by this model was the minimum time-to-collision (TTC). Dijkstra et al. (2010) also used a TTC type measure in their study of traffic networks. They designate a conflict zone and measured the time take for the first vehicle to enter and exit it. The second vehicle is considered and its time of entry to the conflict zone is compared to a TTC threshold. Conflicts were defined as low risk, moderate or high. Dijkstra (2012) used a TTC threshold of 2.5 s to define a conflict. Other researches that have used time-to-collision in simulation models are Archer (2005), Archer and Young (2010a,b) and Astarita et al. (2012a,b). TTC surrogate safety measures have also been utilised in other safety studies and designs. Laureshyn et al. (2010) propose a framework for organising traffic encounters into a severity hierarchy for the analysis of conflicts measured from video images or models. Levison (1998) and Van der Horst (1991) and use TTC in determining the safety of roads. In particular, they use it to determine safe stopping and curve negotiation.

Most of the simulation models presented in Table 1, consider a vehicle as a point moving along a trajectory, most commonly the road centreline. This may not truly represent the conflict situation. Refinements in the TTC measure to take into account the size, dimension, direction of a vehicle and its turning movement at intersections has been explored. Xin et al. (2008) looks at the headway between the rear of the leading vehicle and the retina of the driver of the subject vehicles as a basis for determining driver's reaction to car-following conflicts. Laureshyn et al. (2010) used TTC in their study of conflicts between turning vehicles and vehicle moving straight through an intersection. They pointed out that for angle crashes vehicles do not approach each other at right angles and that the impact between the two vehicles is between the corner of one vehicle and the side of the other. Alhajyaseen et al. (2013) have focused in detail on stochastic variations in the turning path of vehicles at intersections. This clearly will impact the calculation of safety measures like TTC. Sobhani et al. (2012) incorporated the entire vehicle in their measure of TTC during turning manoeuvres. They look particularly at turning vehicles at intersections and the impact between the corner of one vehicle and the side of the other vehicle. Mak and Sicking (2003) in their study of run-of-the-road accidents present a detailed representation of the vehicle in terms of size and rotation (Yaw). These subtleties, in measuring the TTC in a road safety simulation model, may have considerable impact in their prediction of the type and severity of crashes. Further investigation and the inclusion of these in road safety simulation models are required.

One of the challenges of using TTC in road safety simulation models is their computational difficulty. Most models measure them using a post processor on the simulation model outputs. Another commonly used surrogate safety measure, which can be more easily incorporated into models, is the Post Encroachment Time (PET). "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, 2011). Archer (2005), Archer and Young (2009, 2010a,c) and Young and Archer (2009) studied the application of conflict measures for signalised intersection safety assessment. They investigate the dilemma zone in stop/go decisions using PET. FHWA (2008) also provided a mechanism for measuring Minimum Post Encroachment time (MPET). Pirdavani et al. (2010) used Post Encroachment Time (PET) to study the relationship between traffic volume, speed limits and safety. The measure was obtained by placing four detectors on each outgoing link. The detectors were located behind the conflict zones in order to determine the speed and position of each vehicle to calculate PET easily. Time Advantage (TAdv) is another measure which can be seen as an extension of the PET (Laureshyn et al., 2010). PET is the time between the first road user leaving a common spatial zone and the second arriving. Thus PET has a single value and can be measure directly. TAdv broadens the concept saying that for each movement what PET value is expected to be if the road users continue with the same speed path.

Incorporating the severity of conflicts was an important development and has been achieved using Hyden's (1987) definition regarding the required braking rate (RBR) for each conflict or deceleration rate to avoid a crash (DRAC) (Cunto and Saccomanno, 2008; Archer, 2005; Archer and Young, 2010b; Astarita et al., 2012a,b). Required braking rate can be measured within the road safety simulation model and offers a clear view of the severity of the conflict.

The most common approach to measuring surrogate safety measures is using a post-processor on the data output from the simulation model. The FHWA (2008) developed a post processor (SSAM) to develop surrogate safety measures from traffic simulation packages. This model builds on the outputs of existing traffic simulation models like VISSIM (2007), AIMSUM (2007) and PARAMICS (2002a,b). The SSAM model can determine the number and severity of conflicts in each conflict point at intersections. The approaches could be used for links, but consideration of the relative dynamics of the target and bullet vehicle need to be considered. The SSAM approach was assessed and verified by comparing the surrogate safety assessment results of pairs of simulated design alternatives. It was also validated using a field exercise where the output from SSAM was compared to real world crash records. The calibration of the models (FHWA, 2003, 2004) related to such factors as variable time steps, time steps less than 1 s, gap-acceptance criteria changes with delay, consideration of vehicle gap in gap logic, variable headways and variable queue discharge headways. Variations in the cost to get the model suitable for the output required by the SSAM model were also determined. The surrogate safety measures quantified in this model include the Minimum time-to-collision (TTC) and Minimum post-encroachment time (PET) discussed above, and also provide estimates of Initial deceleration rate (DR), Maximum deceleration rate (Max$D$) and Maximum speed (Max$S$), Maximum speed differential (ΔS).

A expansion of surrogate safety measures is the concept of a safety index. The advantage of a safety index is that it provides an opportunity to map the level of safety on the road system for comparison purposes. It does not necessarily measure the crashes at a location but rather the general level of safety. Cunto and Saccomanno (2008) defined a "crash potential index" (CPI) to assess the safety performance of intersections. The crash potential index sums a comparison of the deceleration rate to avoid a crash ($\mathrm{DRAC}_{i,t}$) with the maximum available deceleration rate ($\mathrm{MADR}_{i,t}$. or the breaking ability) of each vehicle: (i) over the time interval; and (ii) a vehicle is in the study zone; if the $\mathrm{DRAC}_{i,t}$ is positive. This is multiplied by the time interval for each vehicle and divided by the total simulation time. Clearly the higher the CPI the more unsafe is the intersection approach. Sobhani et al. (2013a) presented a Road Safety Index (RSI) determined as a function of traffic volume, number of conflicts, crash risk and crash severity risk. It is calculated from the Injury Severity Score (ISS), number of conflicts, number of crashes and the traffic count during the simulation run (μ) output from model (Sobhani et al., 2013a). Data collected on crashes may also be used in the determination of this index.

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). Wu and Jovanis (2012a,b) present a screening approach, based on Binomial Logit and Probit estimation, which can be used to define the contribution of particular factors to a near crash turning into a crash. The screening approach starts from normal driving, locates events of interest, groups these events by etiology (e.g. road departure events), then categorises them as crash or near crash. 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. Clearly this knowledge will improve models ability to replicate the driver, vehicle and environmental relationship between the conflict and the crash.

Surrogate safety measures have been used in many studies to estimate the level of safety in a particular traffic situation. The fact that so many measures have been used indicates that different measures may be more appropriate for particular crash situation; there is still some uncertainty as to which is the most appropriate measure; and/or there is still development in the measures being used. The next section will look at the road safety simulation models and investigate their contribution to better replicating road safety in models.

2.2.2. The models utilising surrogate safety measures

Table 1 (Studies 5–15) shows a number of road safety simulation models that provide measures of safety using surrogate safety measures. These models are developed for particular conflict situations: un-signalised intersection, signalised intersection, rear end, lane changing and bus stop conflicts. These will be reviewed here to highlight the types of traffic situations that have been investigated using the surrogate safety measures approach. It will also highlight the behavioural developments in the models which assist in providing more realistic measures of safety performance. The review will look at intersection (un-signalised and signalised), link and network models. It also discusses preliminary studies of multimodal conflicts. Initial applications, of road safety simulation models, focused on *crossing conflicts at un-signalised intersections*. Sayed et al. (1994) describes a computer simulation model of crossing conflicts at unsignalised T and 4-leg intersections, called Traffic Safety Conflict Simulation (TSC-Sim). TSC-Sim was a step forward in road safety modelling as it incorporated driver behaviour, vehicle type and variations in gap acceptance. It also was the first attempt at trying to calibrate and validate the model. The model was developed using the General Purpose Simulation System (GPSS) developed to provide a framework for developing discrete event based simulation models. It moves vehicles from block to block. Blocks are actions (e.g. GENERATE, ADVANCE, QUEUE, LEAVE) that effect transactions with other vehicles. The model replicated entry into the intersection using a shifted negative exponential distribution of headways. The vehicles move through the intersection aiming at achieving their desired speed but in most cases, queues and interactions with other vehicle mean the speed is lower than that. Major roads are assumed to be not impacted by vehicles in the minor road. Vehicles in the minor road must find gaps in the major road traffic flow. Minor road vehicle are assumed to have a critical gap and the gap (or lag) accepted depends on what is provided. It should exceed the critical gap. Unlike the previous models TSC-Sim has a detailed description of the driver, using age and gender (young male, old male, young female, old female) to determine the gap acceptance behaviour. The mean and standard deviation of the accepted gap was used as a basis for simulating behaviour. It also used the number of lanes being crossed by adding a 0.25 s onto the critical gap for each lane. Vehicle type was also included, with heavy vehicles having a 30% larger critical gap than car drivers. Finally, the length of delay experience by the driver reduced their critical gap. The model used TTC as a measure of performance. The model was verified using computer graphics and validated using video field data from intersections with conflicts being recorded by trained observers and compared to the model output. The TSC-Sim was a significant step forward in road safety simulation models it suffered in a number of areas. The first was the definition of severity of conflict was limited to a small number of intersections, a broader study would be required to generalise the results. The second pointed to the need for more research to confirm the link between traffic conflict to safety and risk. Sayed et al. (1994) concluded with a call to describe the road safety problem unambiguously with the complex relationship between driver behaviour and roadway and traffic parameters being defined. Archer (Archer, 2005; Archer and Young, 2010b) also studied intersection safety at un-signalised T intersections for light vehicles using the VISSIM (2007) traffic simulation software (see Table 1). The main manoeuvre modelled was crossing conflicts. They adapted VISSIM (2007) used a probability approach to develop a gap acceptance model for un-signalised T-intersections in order to determine the number and severity of conflicts. The use of a binomial logistics function to model gap acceptance was a step forward since it enabled drivers to accept gaps which were clearly unsafe. This adaption is now an option in VISSIM (2007). The probabilistic model was based on variations between people and vehicle types. This is consistent with many decision making models that use a log normal, logit, probit or other error function to replicate variations in behaviour in a population. The model was calibrated and validated using video data from and intersection in Sweden. TTC and required braking rate were the measures of performance in the model. This model showed how the introduction of an error function into driver behaviour could allow a realistic representation of vehicle conflict.

Another group of road safety simulation models have focused on *rear end accidents* since they are a major source of accidents at signalised intersections. Cunto and Saccomanno (2007, 2008) developed a micro-simulation model, for the study and safety evaluation of rear-end crashes at signalised intersection (see Table 1). Cunto (2008) defined a "crash potential index" (CPI) based on the rate of deceleration of vehicles to assess the safety performance of intersections. The study utilised the VISSIM (2007) simulation software, and calibrated the car-following and lane changing models for the approach to intersections using the 13 variables required by the VISSIM (2007) model. The estimated parameters 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 (Wiedemann, 1974; Wiedemann and Reiter, 1992) car-following model were replicated. The model was calibrated and validated using data from the intersection of Lankershim Boulevaard and Universal Hollywood Drive from the Next Generation SIMulation (NGSIM) data base (FHWA, 2006). A fractional factorial data design was used to calibrate and validated the model. A generic algorithm aimed at optimising the residual sum-of-squares error of the CPI for the simulated and observed vehicle track data was used to calibrate the model. It should be noted that no mention was made of crash events in the data nor was consideration given for such extreme events in the calibration process. Wiedemann's (1974) model has been shown to model normal car-following behaviour well, but the deterministic nature of the minimum car-following thresholds may not truly replicate the minimum headway between moving and stopped vehicle satisfactorily, in crash estimation. Notwithstanding this concern, the CPI developed from the field studies was compared to output from a sample of 10 simulation runs of the calibrated model and was found to be within the 95% confidence intervals.

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 signalised vehicle actuated intersections (see Table 1). The interaction between driver decisions, the dilemma zone and consequent red light running for light vehicles was explored. Further, Archer and Young (2009, 2010b) investigate the stop/go decision at signalised intersection to look at red light running. The model looked at the behaviour of both light and heavy vehicles. This model utilised a logistic curve to emulate red light stop/go decisions. This study showed how to use of a binary logistics function in road safety simulation models could estimate the number and severity of conflicts using surrogate safety measures. The model used PET as its performance measure and was calibrated and validated using video data of an intersection in outer Melbourne, Australia. Pirdavani et al. (2010) also looked at the modelling of un-signalised and signalised intersections. They utilised PARAMICS to show the relationship between traffic volume, speed limits and safety. PET was used as a measure of conflict. No calibration, verification nor validation of the model was outlined in the paper.

Modelling the conflict between *vehicles moving along road links* represents different behaviour and different crash situations. Several driver behaviour car-following models have been developed in this area (see Table 1). Mehmood et al. (2001) utilises system dynamics to model two-vehicle rear-end crashes where both vehicles are travelling in one lane. The crash environment is created by the introduction of an obstruction on the road in front of the lead vehicle. The systems dynamics model expands the traditional car-following situation through its consideration of crash avoidance. 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. The model replicates the behaviour of the target, the lead vehicle, the subject vehicle, the separation distance and the crash potential (distance separation) between the three vehicles (target, lead, and following) in the system. The systems dynamic component provides an explicit definition of the decisions and actions leading to the conflict and/or crash. A hypothetical model is developed and applied to illustrate the impact of potential countermeasures. Astarita et al. (2012a,b) developed a model called TRITONE using car-following procedures based on Chandler et al. (1958), Gipps (1981) and Yang and Koutsoupoulos (1996) studies. Astarita et al.'s (2012a,b) model was also applied to road lengths. The model was calibrated using the surrogate safety measures: Deceleration to avoid a crash (DRAC) and TTC. These car-following models use a variety of surrogate safety measures to measure safety.

To broaden the application of road safety simulation models to general *vehicle safety on links*, it is necessary to include lane changing and 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 GNSS/INU simulator which provides an integrated design framework for investigating the impacts of existing Global Navigations Satellite Systems (GNSS) and Inertia Navigation Units (INU). The model was aimed at exploring the adequacy on in-vehicle navigation and crash avoidance systems. The simulation package (VISSIM) is used to create the potential lane changing conflicts using time to collision (TTC) measures and safe headway distances. These are then simulated in detail using CARSIM to determine their level of conflict. CARSIM is a vehicle dynamics model which incorporates vehicle motion including position, linear and angular velocities, linear and angular acceleration and vehicle orientation (i.e. pitch, yaw and roll angles). The model was not calibrated and validated but used to explore the impacts of vehicle control systems. The application of the three models required a series of sequential applications, the latter two models being postprocessors to the VISSIM model.

Most road safety simulation models focus on particular crash types at particular parts of the transport 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 time-to-collision (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, The Netherlands. They aimed to provide information to users on both the safest and quickest route through the network. The model was calibrated for the network using the normal measures. They designated a conflict zone and measured the time take for the first vehicle to enter and exit it. The second vehicle is considered and its time of entry to the conflict zone is compared to a TTC threshold. Conflicts are defined as low risk, moderate or high. The model was compared to measures of volume on links, the level of crashes taken from The Netherlands crash data base and conflicts measured from video recordings. Comparisons were made for type of junction, type of conflict and classification of number of passing vehicles using statistical comparisons. Generally the simulation model was found to be a reliable predictor at a broad network level. Dijkstra (2012), in his study of "sustainable safety" on networks, expands the consideration of simulation to traffic networks to include links and intersections. He uses Paramics (PARAMICS, 2002a,b) to model traffic flow and defines: "An encounter between two vehicles as a conflict when the lowest Time-to-Collision is 2.5 second". The 2.5 s number is generally accepted in the design of highways as the reaction time of drivers. Dijkstra (2012) compares the conflict numbers with a measure of safety derived by allocating scores to the attributes of a road section. Both methods were found to provide good measures of safety when compared with crash statistics. The simulation approach being more appropriate for research activities and the score more useful for practitioners, who are looking for quicker guides on the safety of a network.

Most of the models considered above look primarily at passenger vehicle movement. Some have included heavy vehicle but investigation of *heterogeneous traffic* has not been common in intersection or link road safety simulation models. This is perhaps due to the lack of development of realistic car-following and lane-changing models for vehicles other than cars (Aghabayk et al., 2013). An initial attempt to look at the impact bus priority has on the safety of cars, was undertaken by Goh et al. (2013). This study used VISSIM in its analysis, calibrating it using TTC and Deceleration rate to avoid a collision. Data for the validation and calibration of the model was obtained from video cameras mounted on a near building. The study was very preliminary and full details of the bus driver and car behaviour were not collected. However, this research showed that the study of heterogeneous traffic is possible and is an area of new interest.

2.2.3. Discussion

The 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, 2005; Archer and Young, 2010a; Cunto and Saccomanno, 2007, 2008; Dijkstra et al., 2010) point to there being such a relationship. Several researchers (Gho et al., 2010; Wu and Jovanis, 2012a,b) have explored the relationship between surrogate safety measures and crashes using a naturalistic data base. In order to link surrogate measure to crashes, Wu and Jovanis (2012a,b) rework Eq. (1) in the form:

$$\begin{aligned}&\text{Number of crashes expected to occur on an entity during a certain period of time}\,(\lambda)\\&=(\text{Crash-to-surrogate ratio for that entity}\,(\pi))\times(\text{Number of crash surrogates occurring on an entity in that time}\,(c)).\end{aligned} \tag{2}$$

Wu and Jovanis (2012a,b) formulate this as a logistics relationship and investigate the various parameters influencing the crash-to-surrogate ratio (π). They point to such terms as the angle of the vehicle trajectory relative to interacting vehicle, the maximum lateral acceleration on non-dry surfaces, a non-divided carriageway, the shape of the horizontal curve by time of day (night and day) and the road environment (rural/urban) influencing this term.

The models need to look at driver behaviour in more detail. Many of the models discussed above use the commercially available traffic simulation packages (AIMSUM, 2007; VISSIM, 2007; PARAMICS, 2002a,b). These models have well developed gap acceptance and light vehicle car-following models (Gipps, 1981; Wiedemann, 1974; Fristzsche, 1994; respectively) and lane changing algorithms. Generally these algorithms (Brackstone and McDonald, 1999; Panwai and Dia, 2005) revolve around safe driving characteristics. For instance, car-following in AIMSUN (Gipps, 1981) revolves around safe driving distance, in VISSIM (Wiedemann and Reiter, 1992) a minimum threshold on the spacing between vehicles is used, and PARAMICS (Fristzsche, 1994) utilised a risky distance variable 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 could be questioned. Archer and Young (2010a) relax the constant critical gap assumption in VISSIM by introducing a binary logistics representation of the acceptable gap. Archer and Young (2010c) also incorporated a binary logistic curve to look at the probability distribution of stopping or driving through red lights. Wiedemann (1974) in his initial model formulation of his car-following model proposed a probabilistic minimum threshold for the space separation of vehicles. Archer and Young (2010c) explored a probabilistic approach to modelling the minimum car following gap in VISSIM (2007). Such procedures may be able to be used to relax the existing minimum headway restriction in car-following and lane-changing models and improve these models replication of crashes.

The models are limited in their consideration of vehicle types other than passenger cars. Some research has moved into consideration of heavy vehicles (Chong et al., 2013; Archer and Young, 2010c) but the behavioural consideration of these situations is limited. For instance, Aghabayk et al. (2013) has shown quite different reaction times and car-following behaviour when vehicle combinations vary between car/car, car/heavy vehicle, heavy vehicle/car and heavy vehicle/heavy vehicle.

The models are limited in their consideration of accident situations. 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 in the simulation models. Further, studies of accidents involving pedestrians, bicycles and public transport are rare. There is no doubt that road safety simulation models incorporating "surrogate safety measures" will be applied to these situations.

In summary, road safety simulation models utilising "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. There are clearly great opportunities for the development and application of this approach. The remainder of this paper looks at the developing research in this area highlighting the level of development and potential areas of future activity.

2.3. Modelling 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 road safety simulation models (see Table 1, Studies 15–18).

2.3.1. Numerical and statistical models of crashes

Before looking at the simulation of crashes, Numerical Models using Newtonian Mechanics and Statistical Models will be briefly outlined. Considerable research has been directed at modelling vehicles and the severity of collision interactions between vehicles using crash data. Unlike road safety simulation models, these models are cross-sectional in nature and do not replicated the crash process. However, they are extremely useful in highlighting some of the main factors influencing crashes and their severity.

Newtonian Mechanics models duplicate the physical dynamics of a crash. They have been used to develop numerical models to explore the relationship of crash characteristics and crash severity. These models tend to focus on the vehicle to vehicle interaction, describing it in considerable detail. Researchers (Evans and Frick, 1993; Joksch, 1993; Evans, 1994; Wood, 1997; Buzeman et al., 1998a,b; Wood and Simms, 2002) focused on crash severity from the crash analysis perspective, with crash information as the main predictor of crash severity outcome. Different combinations of crash information with human and vehicle characteristics have been used to estimate the severity of the crashes. The crash information used in these studies includes the mass of bullet and target vehicles, ΔV (change in velocity) of the crash, energy absorption of the colliding vehicles, impact speed, impact characteristics, angle of the crash and equivalent barrier speed. The main benefit of these models is to investigate the physical relationship between crash outcome and crash characteristics to obtain a better understanding of the factors influencing crash severity. However, these models do not have the capability of modelling the frequency of crashes for each severity level. The major disadvantages of these models are:

- they cannot show the effect of road, environment, traffic and trip characteristics on crash severity;

- they do not consider the crash frequency as a measure for safety modelling.

As a result, although numerical models using Newtonian Mechanics improve the understanding of the factors affecting crash severity they tend to under-represent the road and environmental characteristics influence on crash outcomes. In addition, these models could not investigate the effect of driving behaviour on the number and severity of crashes.

The physics of a crash is extremely important, but other factors like the driver, environment and road also contribute to crash outcomes. Researchers have used statistical models to explore the relationship of the main factors affecting safety with the number and severity of crashes. Three types of dependent variables have been used in statistical models. The first type of statistical models is crash count models. Lord et al. (2005), Kim et al. (2007) and Li et al. (2008) have utilised Poisson, Poisson-Gamma, Zero-Inflated, Hierarchical Binomial Logistic and Support Vector Machine models to model roads crash counts. They have considered the road and environmental factors as independent variables and developed models to investigate crash number or occurrence. Lord and Mannering (2010) conducted a comprehensive review on different statistical methods for crash count modelling. Crash severity models are the second type of statistical models. Researchers (Abdel-Aty and Keller, 2005; Caliendo et al., 2007; Wong et al., 2007; Quddus et al., 2009; Das and Abdel-Aty, 2010) have utilised Ordered Probit, Ordered Logit, Nested Logit and Regression Tree models to study the variables affecting crash severity. They have analysed the relationship of the road and environmental factors to the severity of crashes and used different defined categorical variables to represent the severity of crashes. Crash severity models contribute on understanding of the explanatory variables influencing different crash severity models. The third type of statistical models is the models developed to investigate both the number and severity of crashes. Ma et al. (2008) improved safety modelling using statistical analysis through developing a statistical model to investigate the relationship of the road and environmental factors to the number of crashes by severity level. They proposed a Multivariate Poisson-Lognormal Regression model to predict crash count for different severity levels. The statistical models improve the understanding of factors affecting the number and severity of crashes; however, current statistical models are not able to explore the effect of driving behaviour on the number and severity of crashes. Furthermore, these models do not explore the physical relationship between crash outcome and crash characteristics.

Sayed et al. (1994), Davis (2000, 2004, 2007), Elvik (2007) and Hauer (2010) question the ability of existing statistical and numerical models to reflect crash causality, indicating there is a need for more research to confirm the link between traffic conflict to risk and safety. However, these models do incorporate a number of variables traditionally not included in road safety simulation models. Some of these are driver descriptions and vehicle safety characteristics.

2.3.2. Simulation models including conflicts and crashes

Many of the simulation models discussed in the previous sections use existing simulation packages to model traffic behaviour. Several researchers (Bonsall et al., 2005 and Xin et al., 2008) suggest that existing simulation models are developed to preclude collisions and are not an accurate representation of the traffic 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. Many simulation models consider it as the time distance between the same points on consecutive vehicles. The model is calibrated and verified on two sets of vehicle trajectories. The first is a set of crash free trajectories collected at the Hokkaido University, Japan. The second is a set of trajectories on a high-crash section of the I-94 in Minneapolis, Minnesota, USA. The model has not been incorporated into commercial software packages.

Clearly the development of a road safety simulation model which relates to crashes must pull together a number of probabilistic 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:

$$P(y, x, u) = P(y|x, u) \times P(x|u) \times P(u) \tag{3}$$

Davis and Morris (2009), Davis et al. (2011) expand this relationship through four propositions relating to the model properties, focusing on each component of the model (see Table 1). Proposition 1 divided the initial events into minimum successful evasive actions. Proposition 2 demonstrated that the probability of a crash is related to the mix of events and the probability of successful evasion. Proposition 3 indicated tests used to identify the probability distributions of the initial events. Proposition 4 gave some conditions for the lower bounds of crash probability. Davis et al.'s (2011) model is explored through the use of the 100-Car Naturalistic Driving Study (Dingus et al., 2005) and some probabilistic and Markov Chain Monte Carlo formulations. They conclude that relating the propensity to link conflicts to the propensity for crashes requires a structural model of crash events, understanding how evasive actions relate to a range of conflict severities and the relative frequency of conflict severities.

Tarko (2012) extends Davis et al.'s (2011) ideas 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. He extends the direct relationship between the crash and factors affecting it to a continuum of four steps moving from traffic factors, through conflict, collision to 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 hypothesises, that safety events can be grouped in increasing severity and decreasing frequency. The important link connecting risky behaviour and the crash (Step 3) is quantified using the Generalise Parato distribution to link the other models. Simulation has not been used in this study but it is not a far step to see how it can be used for steps one and two. Step four can be estimated by existing techniques (Lord and Mannering, 2010; Savolainen et al., 2011; Washington et al., 2011). Corben et al. (2004) utilise a series of concentric circles to move from the traffic system to the person involved in a crash. This continuum was used to illustrate how the severity of a crash could be reduced at each level of interaction.

A further attempt to develop the crash continuum described by Tarko (2012) was undertaken by Sobhani et al. (2011a, 2013b). Sobhani et al. (2013c) 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. This is somewhat akin to the surrogate safety models described above. 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. Sobhani et al.'s (2011b) model is essentially a hybrid model which uses simulation as the overall framework and embeds several numerical and statistical models which measure crash likelihood and severity. The explanatory variables (independent variables) used in Sobhani et al. (2011a,c) relate to road and environmental characteristics, human factors, vehicle type and specific crash information. The road and environmental characteristics include factors like road, weather, traffic and trip characteristics. Human factors include demographics, behaviour, 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. Sobhani et al.'s (2013b) final simulation model was built around the kinetic energy framework developed by Corben et al. (2004), which took in all levels of the safety system from the road system, through the traffic, vehicle and driver dimensions. VISSIM (2007) was used to model critical conflicts. A Log-Gamma regression equation was used to estimate the expected speed change (ΔV_s) of the vehicles involved in the critical conflicts. The significant variables were mass-ratio and a combination of driver reaction and definition of classified vehicles (DCA). The expected kinetic energy (KE_s) is a function of (ΔV_s), The injury severity score (ISS) of the conflict was measured using a Multiple Linear Regression Equation and was a function of the kinetic energy and the impact type of the expected crash. The model was calibrated and validated using video data of an intersection in Melbourne, Australia, crash data from the ANCIS data base (Logan et al., 2006) and police crash data from (CRASHSTATS, 2013).

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 Sicking (2003) developed a simulation program to investigate these crashes called the Roadside Safety Analysis Program (RSAP). 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 consists of four modules. The first is the encroachment module. This model uses data on the roadway characteristics and traffic conditions to estimate and encroachment probability and hence frequency. It uses data on tyre 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, in module two. 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, module three, takes the data on the crash and determines a probability of injury based on historical police-reported crash data. The fourth model calculates incremental benefits and costs associated with the crash outcomes and potential countermeasures to determine the best priority for treatments. The model is calibrated using data on vehicle encroachments, crash statistics and road side information.

2.3.3. Discussion

The explicit modelling 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 behaviour or lack of behaviour (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 manoeuvres. 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 behaviour of the driver prior and during the crash. This aspect is the main thrust of the next section of the paper.

3. Related developments which may influence the future of road safety simulation models

The paper to this point has focused on developments in road safety simulation models. These are substantial and we are in the situation where many of these developments are being incorporated into transport network evaluation systems. There are, however, a number of developments taking place at the present time that could drive future development in road safety simulation modelling. This paper will discuss three of these: the developments in the data used to develop, calibrate and validate these models; the interfacing between driver simulators and road safety simulation models and the introduction of machine learning into model development.

3.1. Data sources used in calibration, verification and validation of models

Road safety simulation models utilise theory and data to develop their structure. The model structure, in turn, provides the framework for incorporating data from many sources into a representation of the traffic system. This is done through the calibration, verification and validation of the model and its components. Several forms of data are used to develop these models. This section will review this data in the light of how it impacts the model development and implementation.

The most common data set used in the development, verification and/or validation of models of safety is crash data. This data can be collected by law-enforcement agencies during or after visiting a crash sites (FHWA, 2003; Dijkstra et al., 2010; Dijkstra, 2012; CRASHSTATS, 2013). This data can provide information on the crash type, the people involved and the characteristics of the road and environment. These data sets are extremely useful but rarely provide detailed information on the crash process and the overall conditions during the crash. This information is at best estimated second hand. More detailed crash data, such and the ANCIS (Logan et al., 2006) and National Automotive Sampling System (NASS, 2013) data sets, can be collected at or after the event at the accident site and/or from post accident data sources (e.g. hospital data). Crash data has been used in the estimation of road safety simulation models (Sobhani et al., 2011b). This data provides detailed information on the crash event and the people involved, however, the data is collected after the event and no direct observation of the event is possible. Furthermore, crash data, by definition, does not collect information on near crashes and conflicts so the factors turning a conflict into a crash cannot be determined directly. This data has not been greatly utilised in the development of road safety simulation models because it does not directly measure crash causality (Sayed et al., 1994; Davis, 2000, 2004, 2007; Elvik, 2007; Hauer, 2010).

The next data set commonly used in road safety simulation models is observational data of traffic situations from the roadside. This can be collected by direct observation of conflict and crash situations by trained observers or via the use of video. Improvements in this technology have been one of the main reasons for the increase in road safety simulation model development in the last decade. Cunto and Saccomanno (2008), Archer and Young (2009, 2010a,b,c), Sobhani et al. (2012), Tageldin et al. (2013) and Astarita et al. (2012a,b) used fixed video data to look at behaviour of drivers at and approaching intersections. This approach provides a considerable data set with repeat behaviour and provides a useful overall measure of drivers' behaviour. Many of the simulation studies focus on locations like intersections, parking lots or specific road lengths where it is easy to use video to monitor movement. Conflicts and crashes on routes may involve fixed objects, run-of-road and cross centre line situations which are not so easily defined in terms of surrogate safety measures like time-to-collision. Fixed on-route video is limited in that it has difficulty providing descriptive data on drivers (age, gender, alcohol levels, etc.); detailed descriptions of safety equipment in the car (e.g. seat belt use, air bag provision, etc.); and is limited in terms of location and length of road it can consider since it cannot roam the traffic system collecting data. This data could be collected using the crash data collection techniques described previously but this has rarely undertaken. However, there is considerable potential for integrating data collected externally to the vehicle and crash data in model development to replicate the crash continuum (e.g. Sobhani et al., 2013b)

Given the impact of improvements in video data collection and analysis on the development of road safety simulation models, based on surrogate safety measures, possibly the next quantum step in these 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. As noted within a recent special issue in this Journal (Accident Analysis and Prevention), Lenné (2013) notes that the recent development in technology are now supporting the most cost-effective conduct of naturalistic studies. To collect this data advanced instrumentation (e.g. video cameras, vehicle sensor, global positioning systems etc.) were installed in vehicles (Dingus et al., 2005; Campbell, 2012). The in-vehicle data was supplemented by, driver statistics like genders, education, occupation, driver experience, visual acuity, speed selection, seat belt use, and eye movements were also collected along with environmental information like weather condition, surface condition, traffic density, kind of locality, and road alignment. A data set is collected using the instrumentation put in the vehicle to monitor the behaviour of drivers and the situations that take place (e.g. conflict, crash avoidance, crash). Several research groups (Guo et al., 2010; Wu and Jovanis, 2012a,b) have used the naturalistic data set to develop machine learning models of driver behaviour in conflict situations. These models will be discussed latter in this section. These data sets offer considerable opportunity in coming to grips with behaviour of drivers on the road. This data can be associated with the data collected from video located at particular locations and crash event recording to improve simulation of the events that occur during driving and improving the quality of simulation models.

The quality of the simulation models of safety relies on the quality of the data used to calibrate and validate them. Data from crash investigations, police crash records, videos, naturalistic data collection studies and driver simulators have been used to develop and underpin the calibration and validation of these models. All these approaches have their strengths. Crash data sets provide considerable insight into the characteristics of a crash however, they do not provide direct measures of driver behaviour. The use of fixed point videos to measure provides a useful data set on driver behaviour. However they are often limited in the scope of data they can collect. For instance, conflicts and crashes on routes may involve fixed objects, run-off-road and cross centre line situations which are not so easily measured by fixed video cameras. Fixed on-route video is also limited in that it has difficulty providing detailed data on the drivers. In-vehicle or naturalistic data offers considerable potential in looking at the crash and conflict situation in the immediate vicinity of an event. These data sets provide considerable insight into the characteristics of a crash however, it is time consuming to collect and may not provide information to satisfy full experimental designs. Naturalistic data does however provide the opportunity for the next quantum step in roads safety simulation model development.

In summary, each of these data sets contributes to the theoretical development, calibration, verification and validation of road safety simulation models and they should be used appropriately. The extension of this data set to an increased number of driver events is likely to increase our knowledge of the relationship between driver behaviour and crashes and improve the behavioural base of simulation models.

3.2. Driver simulators

Road safety simulation models provide the potential of quantifying the level of safety in a transport network quickly and easily. However they must be calibrated and validated. Traditionally, this is undertaken through a process of data collection, model parameter estimation, verification and validation using real world data (Young et al., 1989). Field data, like naturalistic data, provides a rich data source related to real world experience, however, it is time consuming to collect and may not provide information to satisfy a full experimental design. The use of stated preference data in the development of road safety simulation models is an area of potential opportunity. A rapidly advancing technology which may be able to complement field data on road safety is the utilisation 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.

Driver simulators have been used to provide information on behaviour of drivers in particular situations. Mitsopoulos-Rubens and Lenné (2012) have utilised driver simulators to look at gap acceptance for drivers facing motorcyclists with different levels of driving experience and with motorcycles showing utilising low levels of headlight beams. They used a Generalised Estimating Equation (GEE) approach to compare the behaviour of the drivers in terms of accepted gap, and approach, intermediate and completion phase of the manoeuvre. Lenné et al. (1997) focused on the impact of time of day variations on driver performance. Tarko (2012) details a driver simulator experiment that looks at drivers keeping in their lane and speed selection. They found it had a particular impact on the fluctuation of speeds.

Driver simulators offer considerable flexibility in the collection of data which is relevant to the situation and allows data to be collected efficiently and effectively. Although such data has been used in traffic simulation model development (Koutspoulos et al., 1994; Sarvi et al., 2004; Sarvi and Kuwahara, 2008) the authors could find no evidence that such data has been used in the development of road safety simulation models.

Although such data sets are extremely useful, it is necessary to ensure the data truly represents the actual conflict situation studied. This requires verification and validation of the simulator results using real work fixed video, naturalistic and/or crash data sets. Furthermore, ethics and participant safety consideration may preclude particular experimental types being undertaken.

3.3. Machine learning approaches

The preceding sections have focused on traditional discrete event traffic simulation models. These models involve the development of algorithms to replicate driver behaviour and the connection of these algorithms to mimic the traffic interaction process. Future development in data collection technology are likely to provide considerable amounts of data which cannot easily be analysed by hand nor incorporated into the models in a satisfactory fashion. An approach which may assist in traversing this chasm is the use of machine learning or artificial intelligence in developing road safety simulation models. Such techniques as neural networks and fuzzy logic utilise a computer system which accepts input describing the driver's behaviour and relates it to the output variables, conflict and/or crash. Some applications of these to safety simulation are discussed here.

Initial applications do not look at the dynamics of the traffic system but rather look at the driver, vehicle, road environment and develop machine representation of this system. These approaches have been preferred to linear regression studies due to the inherent non-linearity of the approach. Hassan and Abdel-Aty (2001) used Multilayer Perceptron (MLP) and Fuzzy Adaptive Resonance Theory from the MATLAB toolbox to replicate two vehicle accidents with three levels of severity (no injury, possible/evident injury (minor injury) and disabling injury/fatality). Variables representing the driver, vehicle and road and physical environment were input into the neural network, The models was applied to accident data from Central Florida. Training involved over 2000 cases. Comparison of the predictability of the models showed approximately a 12% improvement on a probit model calibrated and applied to the same data sets.

The collection of in-vehicle data on driver behaviour (Dingus et al., 2005) offers an opportunity to use Machine Learning models to look at car-following and evasive behaviour at a higher level of detail. Chong et al. (2013) use the naturalistic data set collected at Virginia Tech to explore car-following and safety critical events. They develop a fuzzy logic model of car-following with the state layers of relative distance, relative speed and vehicle speed. The state variable is linked to two nodes to form fuzzy sets. The fuzzy rules are developed in the third layer of the model. The action and critical layer, fourth layer, defines discrete action sets that include a limited number of actions. Continuous actions are generated by weighting these discrete actions. They consider truck crash and near crashes events in their study of safety critical events. The study contained 14,500 driving data hours, 735,000 mi travelled, 15 police reports, 67 non-police reported crashes and 761 near crash reports. Data was collected on car-following situations. Crashes were defined as any contact with another object. Near-crashes were defined as any circumstances that required a rapid evasive manoeuvre. Only following vehicles were used in the study. Specifically, one of longitudinal decelerations equal to −0.2 g, forward time to collision of less than or equal to 2 s, swerve greater than or equal to 2 rad/s^2, lane tracking status abort (lane change), critical incident button and analyst identification were used to identify a critical action. These processes were replicated using a fuzzy logic formulation as the driver simulator and to replicate truck driver behaviour. The models were cross validated by using the driver behaviour for one driver in another driver's situation. The model was found to perform well.

3.4. Discussion

This section of the paper has explored three areas of technological development which may influence the future development and use of road safety simulation models. Developments in data collections technology have enabled data to be collected on the driving process and will enable the calibration and validation of new road safety simulation models. Driver simulators are developing a realistic virtual driver environment which will enable the exploration of changes to vehicle technology, driver's involvement in the navigation process and traffic systems components to be investigated rapidly and cheaply. Further developments in machine learning will enable new road safety simulation models to be developed and/or updated quickly and perhaps one day on-line.

4. Conclusions

This paper reviews developments in the area of road safety simulation models. It focuses on stochastic numerical models of traffic behaviour 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 behaviour and character of each of these systems components. The stochastic nature of these models requires accurate measures of the variations in behaviour of drivers and vehicles. These models were first seen in the 1970s when computer technology developed to the stage where traffic micro-simulation 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 behaviour of drivers; and developing surrogate safety measures. Many studies have utilised existing traffic simulation approaches and software (VISSIM, 2007; PARAMICS, 2002a,b; AIMSUM, 2007). They calibrate or changing parameters to better represent the dynamics of traffic behaviour. These models appear to provide a flexible enough platform for the modelling of safety and the developers appear amenable to assisting developers in their pursuits. The basic theory behind the traffic models appears to be flexible enough to allow improvements. These models have been developed to look at the capacity of the transport system and its performance in terms of delay, travel time etc. Road Safety simulation models required refinements to these traffic simulation models to more accurately measure driver behaviour and conflicts. 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 analysing 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.

There are a number of new developments in the theory underlying the models. These will focus on:

- *The crash as the measure of performance:* The "sustainable safety" (Koornstra et al., 1992; Wegman and Aarts, 2006) approach to safety focuses on the functionality of the road system and the forgiveness principle. It recognises this limitation in crash analysis and looks for the major factors which will commonly be involved in a casualty and sets about eliminating them. It is clear from this review of safety measures that there is no one measure which will link driving environment, events, behaviour and/or crashes to provide a single measure of the safety for all parts of the road system. The probabilistic nature of the process leading to a crash has the potential for compensating components, with a set of circumstances which would normally lead to a severe crash being circumvented by the contribution of one small anomaly. Road safety simulation models may be able to quantify this probabilistic link between the factors contributing to a crash. Exploration of the crash continuum (traffic flow, conflict, severe conflict, crash, severe crash) may provide a basis for such studies. This however requires new data sets, techniques for synthesising the data and model frameworks. The main measure of performance, the crash, still requires some theoretical and numerical improvement in the models for them to indicate the combination of factors that result in it. Few models have attempted to look at the link between conflict and crashes in detail but there is some evidence this interface will be crossed in the near future.

- *The theory behind driver behaviour in crashes:* Clearly an important area of research is the total traffic system or network. The relationship between behaviour on links and midblock locations combined with the character and diversity of intersection driver behaviour is required to obtain a holistic view of driver behaviour and safety on traffic networks. Detailed understanding of car-following, lane-changing, merging, route choice behaviour and driver characteristics is required if this area of research is to develop.
- *A more detailed representation of the vehicle and conflict situations:* Most of the simulation models reviewed consider a vehicle as a point moving along a trajectory, most commonly the lane centreline. The surrogate safety measures developed using this approach appeared to provide a tool for measuring the safety impacts of driver behaviour in safety modelling. However, refinements in these measures, take into account the size and dimension of a vehicle and its turning movement at intersections are necessary. and
- *A generalisation of the models to look at more crash and vehicle types:* To date the models have focused primarily of vehicular traffic that is cars and heavy vehicles. There is a need to broaden this to look at crashes that involve different vehicle types: the pedestrian, buses, bicycles, motorbikes, and trams.

New technology in computer systems, information technology and data collection are likely to facilitate the next stage in the developments of road safety simulation models. This will occur in a number of areas. Most of the studies have focused on areas where video imaging can be used to provide data to calibrate and validate the models. These are parking lots, intersections and selected road links. 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 traffic characteristics. Further, developments in technology are allowing driver simulators and machine learning to improve and develop the models. Neural networks and fuzzy logic have also been used to relate driver behaviour and safety. No doubt new models of traffic behaviour will be developed and it is hoped these will also allow for the integration of safety measures into them.

References

Abdel-Aty, M., Keller, J., 2005. Exploring the overall and specific crash severity levels at signalised intersections. Accident Analysis and Prevention 37 (3), 417–425.

Aghabayk, K., Sarvi, M., Forouzideh, N., Young, W., 2013. Modelling heavy vehicle car-following behaviour in congested traffic conditions. Journal of Advanced Transportation, In Press.

AIMSUM, 2007. AIMSUN NG Manual. Transport Simulation Systems, Barcelona, Spain.

Alhajyaseen, W.K.M., Asano, M., Nakamura, H., Tam, D.M., 2013. Stochastic approach for modelling the effects of intersection geometry on turning vehicle paths. Transportation Research 32C, 179–192.

Amundson, F.H., Hyden, C., 1977. Proceedings of the First Workshop on Traffic Conflict , Institution of Transport Economics, Oslo/Lind Institute of Technology, Oslo, Norway.

Archer, J., 2005. Indicators for traffic safety assessment and prediction and their application in micro-simulation modelling: a study of urban and suburban intersections. In: Doctoral Dissertation. Department of Infrastructure, Division for Transport and Logistic (TOL), Centre for Transport Research, Royal Institute of Technology, Stockholm, Sweden.

Archer, J., Young, W., 2009. Signal treatments to reduce heavy vehicle crash risk at metropolitan highway intersections. Accident Analysis and Prevention 41, 404–411.

Archer, J., Young, W., 2010a. The measurement and modelling of proximal safety measures. Proceedings of the Institution of Civil Engineers 163 (4), 191–201, Transport Journal.

Archer, J., Young, W., 2010b. A traffic micro-simulation approach to estimate safety at unsignalised intersections. In: Proceedings of Transportation Research Board Annual Meeting, Washington, USA, pp. 1–19.

Archer, J., Young, W., 2010c. Signal treatments to reduce the likelihood of heavy vehicle crashes at intersections: a micro-simulation modeling approach. Journal of Transportation Engineering (ASCE) 136 (7), 632–639.

Asmussen, E., 1984. International Study of Traffic Conflict Techniques. Springer-Verlag, Berlin.

Astarita, V., Giofre, V., Guido, G., Vitale, A., 2012a. Calibration of a new microsimulation package for the evaluation of traffic safety performance. In: Proceedings of Energy Efficient Transportation Networks 2012, 15th Edition of the Euro Working Group on Transportation, Paris, September 2012.

Astarita, V., Guido, G., Vitale, A., Giofre, V., 2012b. A new microsimulation model for the evaluation of traffic safety performance. Trasporti Europei 51, 1–16.

Bonsall, P., Liu, R., Young, W., 2005. Modelling safety-related driving behaviour—impact of parameter values. Transportation Research 39A, 425–444.

Brackstone, M., McDonald, M., 1999. Car-following: a historic review. Transportation Research, Part F: Traffic Psychology and Behaviour 11 (6), 181–196.

Buzeman, D.G., Viano, D.C., et al., 1998a. Car occupant safety in frontal crashes: a parameter study of vehicle mass, impact speed, and inherent vehicle protection. Accident Analysis and Prevention 30 (6), 713–722.

Buzeman, D.G., Viano, D.C., et al., 1998b. Injury probability and risk in frontal crashes: effects of sorting techniques on priorities for offset testing. Accident Analysis and Prevention 30 (5), 583–595.

Caliendo, C., Guida, M., et al., 2007. A crash-prediction model for multilane roads. Accident Analysis and Prevention 39 (4), 657–670.

Campbell, K.L., 2012. The SHRP 2 natrualistic driving study: addressing driver performance and behaviour in traffic safety. TR News 282 (September), 30–35.

Chandler, R.E., Herman, R., Montroll, E.W., 1958. Traffic dynamics: studies in car following. Operations Research 6 (2), 165–184.

Chong, L., Abbas, M.M., Flintsch, A.M., Higgs, B., 2013. A rule-based neural network approach to model driver naturalistic behaviour in traffic. Transportation Research 32C, 207–223.

Cooper, D.F., Ferguson, N., 1976. Traffic studies at T-junctions—a conflict simulation model. Traffic Engineering and Control 17, 306–309.

Cooper, P., 1980. Analysis of Roadside Encroachments—Single Run-of-road Accident Data Analysis for Five Provinces. B.C. Research, Vancouver, BC, March.

Corben, B., Senserrik, T., Cameron, M., Rechnitzer, C., 2004. Development of a Visionary Research Model: Application to the Car/Pedestrian Conflict. Monash University Accident Research Centre (MUARC), Melbourne.

CRASHSTATS, 2013. Victorian Crash Data Base, http://www.vicroads.vic.gov.au/Home/SafetyAndRules/AboutRoadSafety/StatisticsAndResearch/CrashStats.htm (sighted 9/8/13).

Cunto, F.J.C., 2008. Assessing safety performance of transportation systems using microscopic simulation. In: Ph.D. Thesis. Department of Civil Engineering, University of Waterloo, Waterloo, ON.

Cunto, F.J.C., Saccomanno, F., 2007. Microlevel traffic simulation method for assessing crash potential at intersections. In: Proceedings of the 86th Annual Meeting of the Transportation Research Board, Washington, DC.

Cunto, F., Saccomanno, F.F., 2008. Calibration and validation of simulated vehicle safety performance at signalised intersections. Accident Analysis and Prevention 40 (3), 1171–1179.

Darzentas, J., Cooper, D.F., Storr, P.A., McDowell, M.R.C., 1980. Simulation of road traffic conflicts at T-intersections. Simulation 34, 155–164.

Das, A., Abdel-Aty, M., 2010. A genetic programming approach to explore the crash severity on multi-lane roads. Accident Analysis and Prevention 42 (2), 548–557.

Davis, G.A., 2000. Accident reduction factors and causal inference in traffic safety studies: a review. Accident Analysis and Prevention 32 (1), 95–109.

Davis, G.A., 2004. Possible aggregation biases in road safety research and a mechanism approach to crash modelling. Accident Analysis and Prevention 36 (6), 1119–1127.

Davis, G.A., 2007. On the plausibility of using simulation to model left-turn cross-path crashes. In: Proceedings of 86th Annual Meeting of Transportation Research Board, Washington, USA.

Davis, G.A., Morris, P., 2009. Statistical versus simulation models in safety. Transportation Research Record: Journal of The Transportation Research Board 2102, 93–100.

Davis, G.A., Hourdos, J., Xiong, H., Chatterjee, I., 2011. Outline for a causal model of traffic conflicts and crashes. Accident Analysis & Prevention 43 (6), 1907–1919.

Dedes, G., Wolf, S., Grejner-Brzezinska, D., Guenther, D., Heydinger, G., Mouskos, K., Park, B., Toth, C., Wang, X., 2011. A simulation design of an integrated GNSS/INU, vehicle dynamics, and microscopic traffic flow simulator for automotive safety. In: Proceedings of Third International Conference on Road Safety and Simulation, Indianapolis, IN.

Dijkstra, A., 2012. Assessing the safety of routes in a regional network. Transportation Research 32C, 103–115.

Dijkstra, A., Marchesesini, P., Bijleveld, F., Kars, V., Drolenga, H., 2010. Do calculated conflicts in microsimulation models predict number of crashes? Transportation Research Record 2147, 105–112.

Dingus, T.A., Klauer, S.G., Neale, V.L., Petersen, A., Lee, S.E., Sudweeks, J., Perez, M.A., Hankey, J., Ramsey, D., Gupta, S., Bucher, C., Doerzaph, Z.R., Jermeland, J., Knipling, R.R., 2005. The 100-car naturalistic driving study, phase II: results of the 100-car field experiment. In: DOT HS 810 593. NHTSA, US Department of Transportation.

Elvik, R., 2007. Operational criteria of causality for observational road safety evaluation studies. Transportation Research Record: Journal of Transportation Research Board 2010, 74–81.

Evans, L., 1994. Driver injury and fatality risk for two-car crashes versus mass ratio inferred using Newtonian mechanics. Accident Analysis and Prevention 26 (5), 609–616.

Evans, L., Frick, M.C., 1993. Mass ratio and relative driver fatality risk in two-vehicle crashes. Accident Analysis and Prevention 25 (2), 213–224.

FHWA, 2003. Surrogate safety measures from traffic simulation models. In: Federal Highway Administration, FHWA-RD-03-050. U.S. Department of Transportation, McLean, VA.

FHWA, 2004. Traffic analysis tool box volume III: guidelines for applying traffic microsimulation modelling software. In: Federal Highway Administration Final Report FHWA-HRT-04-040. U.S. Department of Transportation, McLean, VA.

FHWA, 2006. NGSIM Lankershim Data Analysis: Summary Report. FHWA, On http://www.ngsim.fhwa.dot.gov (accessed on November 15, 2007).

FHWA, 2008. Surrogate safety assessment model and validation. In: Final Report, FHWA-RD-03-051. Federal Highway Administration, U.S. Department of Transportation, McLean, VA.

Fristzsche, H., 1994. A model for traffic simulation. Traffic Engineering and Control 35 (5), 317–321.

Getman, D., Head, L., 2003. Surrogate safety measures from traffic simulation models. Transportation Research Record: Journal of Transportation Research Board 1840, 104–115.

Gipps, P.G., 1981. A behavioural car-following model for computer simulation. Transportation Research 15B, 105–111.

Guo, F., Klauer, S.G., Hankey, J.M., Dingus, T.A., 2010. Near crashes and crash surrogate for naturalistic driving studies. Transportation Research Record: Journal of Transportation Research Board 2147, 66–74.

Goh, K., Currie, G., Sarvi, M., Logan, D., 2013. Exploring bus lane safety impacts using traffic microsimulation. In: Proceedings of Australian Transport Research Forum, Brisbane, Australia, pp. 1–17.

Hassan, T.A., Abdel-Aty, M.A., 2001. Development of artificial neural networks models to predict driver injury severity in traffic accidents at signalised intersections. Transportation Research Board 1748, 6–13.

Hayward, J., 1972. Near-miss determination through use of a scale of danger. Highway Research Record 384, 24–34.

Hauer, E., 1982. Traffic conflicts and exposure. Accident Analysis and Prevention 14 (5), 359–364.

Hauer, E., 1997. Observational Before–After Studies in Road Safety. Pergamon, Oxford, UK.

Hauer, E., 2010. Cause, effect and regression in road safety evaluation: a case study. Accident Analysis and Prevention 42 (4), 1128–1135.

Heinrich, H., 1959. Industrial Accident Prevention: A Scientific Approach. McGraw Hill, New York, NY.

Hodge, G.A., Richardson, A.J., 1978. A study of intersection accident exposure. Proceedings of the Australian Road Research Board 9 (5), 151–160.

Huguenin, F., Torday, A., Dumont, A., 2005. Evaluation of traffic safety using microsimulation. In: Proceedings of the Fifth Swiss Transport Research Conference—STRC, Ascona.

Hyden, C., 1987. The Development of a Method of Traffic Safety Evaluation: The Swedish Traffic Conflict Technique. Department of Traffic Planning and Engineering, Lund University, Lund, Sweden.

Hyden, C., Linderholm, L., 1984. The Swedish traffic-conflict technique. In: Asmussen, E. (Ed.), International Study of Conflict Techniques. Springer-Verlag, Berlin, pp. 133–139.

Joksch, H.C., 1993. Velocity change and fatality risk in a crash—a rule of thumb. Accident Analysis and Prevention 25 (1), 103–104.

Kim, D.-G., Lee, Y., et al., 2007. Modeling crash outcome probabilities at rural intersections: application of hierarchical binomial logistic models. Accident Analysis and Prevention 39 (1), 125–134.

Koornstra, M.J., Mathijseen, M.P.M., Mulder, J.A.G., Roszbach, R., Wegman, F.C.M., 1992. Naar een duurzaam veilig wegverker (Towards a sustainable safe traffic system). In: Nationale Verkeersveiligeidsverkenning voor de jaren 1990/2010. SWOV, Leidschendam.

Koutspoulos, H.N., Lotan, L., Yang, Q., 1994. A driver simulator and its application for modelling route choice in the presence of information. Transportation Research Part C: Emerging Technologies 2C (2), 91–107.

Laureshyn, A., Svensson, A., Hyden, C., 2010. Evaluation of traffic safety, based on micro-level behavioural data: theoretical framework and first implementation. Accident Analysis and Prevention 42 (6), 1637–1646.

Lenné, M.G., 2013. The contribution of on-road studies of road user behaviour to improving road safety. Accident Analysis and Prevention 58, 158–161.

Lenné, M., Trigg, T.J., Redman, J.R., 1997. Time of day variations in driving performance. Accident Analysis and Prevention 29 (4), 431–437.

Levison, W.H., 1998. Interactive highway safety design model: issues related to driver modelling. Transportation Research Record 1631, 20–27.

Li, X., Lord, D., et al., 2008. Predicting motor vehicle crashes using Support Vector Machine models. Accident Analysis and Prevention 40 (4), 1611–1618.

Logan, D.B., Scully, J., Sharwood, L.N., Xafis, V., Fidles, B., 2006. ANCIS—progress report, July 2003–December 2005. In: Report No. 247. Monash University Accident Research Centre (MUARC), Melbourne.

Lord, D., Mannering, F., 2010. The statistical analysis of crash-frequency data: a review and assessment of methodological alternatives. Transportation Research Part A: Policy and Practice 44A (5), 291–305.

Lord, D., Washington, S.P., et al., 2005. Poisson, Poisson-Gamma and Zero Inflated Regression Models of motor vehicle crashes: balancing statistical fit and theory. Accident Analysis and Prevention 37 (1), 35–46.

Mak, K.K., Sicking, D.L., 2003. Roadside safety analysis program (RSAP)—Engineering Manual. In: National Cooperative Highway Research Program Report 492. Transportation Research Board of the National Academies, Washington, USA.

Ma, J., Kockelman, K.M., et al., 2008. A multivariate Poisson-lognormal regression model for prediction of crash counts by severity, using Bayesian methods. Accident Analysis and Prevention 40 (3), 964–975.

McDowell, M.R.C., Wennell, J., Storr, P.A., Darzentas, J., 1983. Gap acceptance and traffic conflict simulation as a measure of risk. In: Special Report 776. Transport and Road Research Laboratory (TRRL), pp. 1–27.

Mehmood, A., Saccomanno, F., Hellinga, B., 2001. Simulation of road crashes by use of simulation dynamics. Transportation Research Record 1746, 37–46.

Mitsopoulos-Rubens, E., Lenné, M., 2012. Issues in motorcycle sensory and congnitive conspicuity: the impact of motorcycle low-beam headlights and riding experience on drivers' decisions to turn across the path of motocycles. Accident Analysis and Prevention 49, 86–95.

NASS, 2013. National Automotive Sampling System. NASS, http://www.nhtsa.gov/NASS (sighted 9/8/13).

PARAMICS, 2002a. Paramics modeller reference V3. In: Internal Report. PARAMICS, www.paramics-online.com/techsupport/docum.htm.

PARAMICS, 2002b. Paramics systems overview V3. In: Internal Report. PARAMICS, www.paramics-online.com/techsupport/docum.htm.

Panwai, S., Dia, H., 2005. Comparative evaluation of microscopic car-following behaviour. IEEE Transactions on Intelligent Transportation Systems 6 (3), 314–325.

Perkins, S.R., Harris, J.I., 1967. Traffic Conflict Characteristics: Accident Potential at Intersections. General Motors Corporation, Warren, MI.

Perkins, S.R., Harris, J.I., 1968. Traffic conflict characteristics: accident potential at intersections. In: Highway Research Record., pp. 225.

Pirdavani, A., Brijs, T., Bellemans, T., Wets, G., 2010. Evaluation of traffic safety at unsignalised intersections using microsimulation: a utilisation of proximal safety indicators. Advances in Transportation Studies 22A, 43–50, An international Journal.

Pirdavani, A., Brijs, T., Bellemans, T., Wets, G., 2011. A simulation-based traffic safety evaluation of signalised and unsignalised intersections. In: Working Paper. Transportation Research Institute (IMOB), Hasselt University, Diepenback, Belgium.

Quddus, M.A., Wang, C., et al., 2009. The impact of road traffic congestion on crash severity using ordered response models. In: 88th Transportation Research Board Annual Meeting, Washington, USA.

Sarvi, M., Kuwahara, M., Ceder, A., 2004. Freeway ramp merging phenomena in congested traffic using simulation combined with a driver simulator. Computer-Aided Civil and Infrastructure Engineering 19 (5), 351–363.

Sarvi, M., Kuwahara, M., 2008. Using ITS to improve the capacity of freeway merging sections by transferring freight vehciles. IEEE Transactions on Intelligent Transportation Systems 9 (4), 580–588.

Sayed, T., Brown, G., Navin, F., 1994. Simulation of traffic conflicts at unsignalised intersections with TSC-Sim. Accident Analysis and Prevention 26 (5), 593–607.

Savolainen, P.T., Mannering, F.L., Lord, D., Quddus, M.A., 2011. The statistical of highway crash-injury severities: a review and assessment of methodological alternatives. Accident Analysis and Prevention 43 (5), 593–607.

Sobhani, A., Young, W., Logan, D., Bahrololoom, S., 2011a. A kinetic energy model of two vehicle crash injury severity. Accident Analysis and Prevention 43 (3), 741–754.

Sobhani, A., Young, W., Sarvi, W., 2011b. A simulation based approach to assess the safety performance of road locations. In: Proceedings of Third International Conference on Road Safety and Simulation, Indianapolis, IN, 14–16 September 2011.

Sobhani, A., Young, W., Logan, W., 2011c. Exploring the relationship of conflict characteristics and consequent crash severity. In: Proceedings of 34th Australasian Transport Research Forum, Adelaide, Australia, 28–30 September 2011.

Sobhani, A., Young, W., Sarvi, M., Bahrololoom, S., 2012. Calculating time-to-collision for analysing right turning behaviour at signalised intersections. In: Proceedings of 35th Australasian Transport Research Forum (ATRF 2012), Perth, Australia, 26–28 September 2012.

Sobhani, A., Young, W., Sarvi, M., Bahrololoom, S., 2013a. Using a simulation based road safety index to assess risk of turning behaviour at signalised intersections. In: Proceedings of World Conference in Transport Research, Rio de Janeiro, pp. 1–15.

Sobhani, A., Young, W., Sarvi, M., 2013b. A simulation based approach to assess the safety performance of road locations. Transportation Research 32C, 114–158.

Sobhani, A., Young, W., Bahrololoom, S., Sarvi, M., 2013c. Calculating time-to-collision for analysing right turning behaviour at signalised intersections. Road & Transport Research 22, 49–61.

Svensson, A., Hyden, C., 2006. Estimating the severity of safety related behaviour. Accident Analysis and Prevention 38, 379–385.

Tageldin, A., Sayed, T., Zaki, M.H., Azad, M., 2013. A safety evaluation of an adaptive traffic signal control system using computer vision. In: Fourth International Conference on Road Safety and Simulation, Rome, Italy.
Tarko, A.P., Davis, G., Saunier, N., Sayed, T., Washington, S., 2009. Surrogate measures of safety. In: White Paper ANB20(3) Subcommittee on Surrogate Measures of Safety ANB20 Committee on Safety Data Evaluation and Analysis Contributors. Transportation Research Board.
Tarko, A.P., 2012. Use of crash surrogates and exceedance statistics to estimate road safety. Accident Analysis and Prevention 45, 230–240.
Traffic Safety by Sweden, 2013. The Zero Vision Approach to Road Safety, Referred to http://www.visionzeroinitiative.com/ 17th November 2013.
Tingvall, C., Haworth, N., 1999. Zero vision: an ethical approach to safety and mobility. In: Paper Presented to the Sixth ITE International Conference Road Safety & Traffic Enforcement: Beyond 2000, Melbourne, 6–7 September 1999.
Van der Horst, A.R.A., 1991. Time-to-collision as a cue to decision making in braking. In: Gale, G. (Ed.), Vision in Vehicles III. North-Holland, New York, pp. 19–26.
VISSIM, 2007. VISSIM 4.30 User Manual. Planning Transport Verkehr AG, Germany.
Washington, S., Karlaftis, M., Mannering, F., 2011. Statistical and Economic Methods for Transportation Data Analysis, second ed. Chapman and HAll/CRC, Boca Raton, FL.
Wegman, F., Aarts, L. (Eds.), 2006. National Road Safety Outlook for 2005–2020. SWOV, Leidschendam.
Wiedemann, R., 1974. Simulation des Strassenverkehrsfluss. Institute fur Verkehrswesen der Universitat Karlsruhe, Karlsruhe, Germany.
Wiedemann, R., Reiter, U., 1992. Microscopic traffic simulation: the simulation system MISSION, background and actual state. In: CEC Project ICARUS (V1052) Final Report, Vol.2, Appendix A. CEC, Brussels.
Wong, S.C., Sze, N.N., et al., 2007. Contributary factors to traffic crashes at signalised intersections in Hong Kong. Accident Analysis and Prevention 39 (6), 1107–1113.
Wood, D.P., 1997. safety and the car size effect: a fundamental explanation. Accident Analysis and Prevention 29 (2), 139–151.
Wood, D.P., Simms, C.K., 2002. Car size and injury risk: a model for injury risk in frontal collisions. Accident Analysis and Prevention 34 (1), 93–99.
World Bank, 2013. The Safe System Approach to Road Safety, Referred to http://go.worldbank.org/6WPLVTMKS0 (17th November 2013).
Wu, K., Jovanis, P., 2012a. Crashes and crash-surrogate events: exploring modeling with naturalistic driving data. Accident Analysis and Prevention 45, 507–516.
Wu, K., Jovanis, P.P., 2012b. Defining and screening crash surrogate events using naturalistic driving data. In: Third International Conference on Road Safety and Simulation, September 14–16, 2012, Indianapolis, IN, pp. 1–13.
Xin, W., Hourdos, J., Michalopoulos, P., Davis, G., 2008. The less-than-perfect driver: a model of collision-inclusive car-following behaviour. Transportation Research Record: Journal of the Transportation Research Board 2088, 126–137.
Yang, Q., Koutsoupoulos, H.N., 1996. A microscopic traffic simulator for evaluation of dynamic traffic management systems. Transportation Research 4C, 113–129.
Young, W., Archer, J., 2009. Traffic microsimulation modelling to study a traffic signal incident reduction function. Journal of the Transportation Research Board 2103, 80–87.
Young, W., Taylor, M.A.P., Gipps, P.G., 1989. Microcomputer in Traffic Engineering. Research Studies Press, Taunton, England.
Yue, W.L., Young, W., 1992. Measuring the level of conflict in parking lots. In: Proceeding of Third Parking Congress, Melbourne, Australia.
Yue, W.L., Young, W., 1993. Good management in parking: minimising the conflicts in parking lots. ITE Journal 63 (3), 434–439.
Yue, W.L., Young, W., 1998a. Using PARKSIM2 to measure safety in parking lots. Journal of the Institute of Engineers Singapore 38 (5), 10–20.
Yue, W.L., Young, W., 1998b. Safety in parking lots: an overlooked area. In: First Asia Pacific Conference on Transportation and the Environment, Singapore.