Multi-model-based simulation in the reconstruction of road traffic accident

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Multi-Model Based Simulation in the Reconstruction of

Road Traffic Accident

By

Qiang (John) Zhao

A doctoral thesis submitted in partial fulfilment of the requirements for the
degree of Doctor of Philosophy

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Abstract

A Synthetic Traffic Simulation (ST-SIM) framework is constructed in this project. The framework provides a computer-based platform for traffic research, consisting of three modules: Driver Behaviour, Vehicle Dynamics, and Road Network modelling. Based on these models, ST-SIM can construct and simulate a broad range of traffic scenarios, including accidents. The research in this project has concentrated on the contribution of driver behaviour to the formation of normal traffic and traffic failure.

ST-SIM has been designed and implemented using Agent-based modelling techniques. The software has been validated using simulator based driver collision avoidance behaviour from TRL and applied to help the accident reconstruction work of On-The-Spot (OTS) team in the UK.

Keywords

Agent-based Traffic Simulation, Driver Decision Modelling, Accident Reconstruction, Synthetic Traffic Simulation (ST-SIM) framework
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1 Introduction

In Great Britain, based on data from National Statistics 2004 [1], there were 290,607 reported casualties on roads in 2003, which caused 3,508 people were killed, 33,707 were seriously injured and 253,392 were slightly injured. Among these, total number of road accidents involving personal injury in 2003 is 214,030 and 32,160 involved deaths or serious injury. The increasing road traffic problems raised the challenges to both academic researchers and engineers working in traffic investigation areas.

Traffic research covers the broad areas including Driver, Vehicle Dynamics/Kinematics, Road Network, and Traffic Flow study. In these areas, two common approaches applied by scientists are Macro-level and Micro-Level research. The Macro approach is the top-down method by observing the measurable behaviours of the systems in terms of aggregating or abstracting the system behaviours into quantified parameters. For example, the diagram based speed–flow, speed–density, and flow–density traffic analysis [24]-[30]. In Micro-Level, the overall traffic system is studied from its components models and the interactions among them. The traffic is presented by the key elements including Driver, Vehicle Dynamics, and Road Network. In the mean time, the development of computing technique in recent years has greatly promoted the Microscopic research in different areas. For examples, the driver research topics including Vision [2]-[5], Behaviour [6]-[8], and Decision modelling [9], the Component Based Vehicle Dynamics research including Steering [10], Braking [11]-[13] systems, and Tyre modelling [14], etc. In this project, the work focuses on the Microscopic research.

The research works in traffic normally covered several areas and required the studies of interactions among different subjects, for example, the driver behaviour study relating to the vehicle dynamics and road network situation [7]. The research works in Control Engineering, Artificial Intelligence (AI) and Ergonomics, etc, have partially provided the bridges between these gaps with the popular applied control analysis methodology in driver/vehicle control process [10] and driver behaviour models based on AI modelling [36]. These particular knowledge based investigation approaches applying scale and flexibility of research works are usually restricted by the special problems scenario. This raised the requirement to construct a general framework that can help bridge these areas for the traffic research work. In this project, based on the models developed by the author and previous researchers, it revealed the feasibility of using the multi-model based system that integrating the expertise knowledge from different areas to aid the traffic research. A traffic research platform-Synthetic Traffic SIMulation (ST-SIM) framework is constructed.
1.1 Project History

This project started since 1996 with support provided by the UK Highways Agency through the Vehicle Safety and Research Centre (VSRC) at Loughborough University. The construction of the framework began with the design of driver sub-models from Driver, Vehicle, and Road Network Modelling research area. In 1997, Wood, R. L., and Arnold, J. E developed the driver decision model applying rule-weight system to provide the qualitative decision references for the driver behaviour [9]. This model was implemented and validated in a perfect perception situation, which means the driver could perceive all the required traffic environment parameters during the simulation (e.g. positions and speeds of other vehicles, distance to the lane boundaries, etc.). To achieve the more realistic simulation circumstance (i.e. non-perfect perception situation of human driver), the development of driver perception models were necessary. In 1999-2002, Dumbuya, A D and Wood, R L designed the driver vision model [2] and proposed the Synthetic Driving Simulator (SD-SIM). The vision model successfully mimicked the image capture process; however, the distance estimation and speed estimation part were still based on the perfect perception. During 2002-2005, Zhao, Q J and Wood, R, L refined the distance and speed estimation parts of the vision model and constructed the simulation skeleton by adding in the new model components of Vehicle Dynamics and Road Network, the new framework is named as Synthetic Traffic Simulator (ST-SIM). The basic models of vehicle dynamic components are designed and implemented based on the theories from [107]. The road network model was created with reference to the finite element description methods [21]. In the mean time, by collaborating with Thomas, Pete and Julian, Hill in VSRC, the ST-SIM was applied to the accident reconstruction of On-The-Spot (OTS) investigation team’s work.

1.2 Research Aim and Objectives

Based on the investigation and development of models from different areas, the primary aim of this project is to aid the understanding of research work in traffic area by bridge the gaps of different research subjects with the multi-model based ST-SIM framework. Consequently, the research has following objectives:

1. Review the key elements in traffic research, identify the topics relate to current research hypothesis-construct the components model based ST-SIM framework for realistic traffic simulation.

2. Investigate the models in Driver, Vehicle Dynamics and Road Network research; reveal the feasibility to construct a cross area research platform for traffic investigation to enable multi-viewpoints research work.
   a) View from the driver’s aspect; describe the drivers’ basic psychology process in vehicle handling (i.e. perception-decision-action loop).
b) View from vehicle dynamics aspect; identify the key factors impact the vehicle's performance and their relationships with human and road network factors.

c) View from the highway designs aspect; investigate the road network design factors impacts on traffic flow and driver behaviour. For example, review the traffic signs in an 'roundabout to evaluate how their influent drivers' behaviour.

3. Review previous developed Driver Decision, and Driver Vision models in the project. Evaluate the models compatibility in the simulation framework by investigating the gaps among models and develop the interfaces to bridge them.

4. Design new models under the need of ST-SIM to fulfil the framework for the simulation.

5. Develop the computer based ST-SIM software.

6. Help the accident study based on the cases from OTS investigation work.

1.3 Problems and Research Scopes

To prevent losing focus point, we divide traffic research problems and research scopes in this project into three domains: Traffic Modelling Components Development, ST-SIM framework design, and using ST-SIM for traffic investigation. This section introduces them separately.

1.3.1 Traffic Modelling Components Development

Driver, Vehicle Dynamics, and Road Networks modelling system are the three main areas covered in this project. Previous version of driver decision and driver vision models have been developed for the framework; however, to construct ST-SIM (see Figure 1.3.1), model refinement and new model construction are still the main tasks in the preliminary stage of the project. Consequently, following works are presented in the model development domain:

1. **Road network module** includes road geometrical and traffic control objects models. A hierarchical road module is presented in section 3.2.3.2. ST-SIM framework, in Micro-Level, studies the interaction among road segment, vehicle, and driver decisions in a driver-oriented approach; it reveals the feasibility to investigate the driver-road network interaction by incorporating the driver decision/action models with the traffic environment, and other objects on road such as trees, pedestrians, and motorbikes, etc. can be added to the framework in further development.

2. **Vehicle dynamics module** includes the implementation of fundamental dynamic models of vehicle components (see section 2.5.6) and the Vehicle Steady State Handling Dynamics in section 3.2.2.

3. **Driver module** controls the vehicle and perceives the road information. It includes the vision, decision, and action models. A perception-decision-action loop based driver modelling context is proposed in section 2.5.2.
In this framework, based on the previous researcher developed driver vision and decision model, the author created road network and vehicle modules (the grey part), also refined the driver vision model to for distance and information capture. The dotted line part is where possible further modelling works can be done to fulfil the framework. For example, the driver action and vehicle control system are realized with direct change of object parameters such as steering angle, speed, and travelling direction, etc. This simplification will need to be replaced by more comprehensive driver behaviour or vehicle control models in future work.

1.3.2 Framework Design

In ST-SIM, the basic components models are developed to investigate the traffic system, the required knowledge base in different areas and implementation cost (e.g. computing time and hardware requirements) usually limited the research scope. In the design of ST-SIM framework, following two points need to be mentioned:

1. When constructing the simulation environment, the investigated problem often requires different areas knowledge to present the complex paradigm, the fundamental knowledge based models in each area is easier to fit in the framework comparing with the complex models for special scenario study. Hence, use fundamental models from different areas to provide a flexible simulation platform is the design theme of ST-SIM.

2. Newly developed model need to be compatible with other models in the framework. Here, the 'compatibility' means the newly developed model's capability to work together other models and does not require the change of their design. For ST-SIM, in implementation level, the compatibility of a model is represented by the required interfaces' that available to collaborate with other models in simulation. Hence, for simulation platform development, the Object-
Oriented design methodology [17] is adopted in the system analysis and design.

1.3.3 ST-SIM Application

ST-SIM provides the chance to investigate traffic problems from different viewpoints (i.e. driver, vehicle or road network focused investigation). Consequently, the applying area can be summarized in following three scopes:

1. Investigate the driver psychology and behaviour in relation to personal characteristics (e.g. driver experience, age, and gender, etc.). A broad context of driver model in perception-decision-action loop exposed the driver's behaviours relating to his/her personal character (see section 3.2.1.3).
2. Provide a tool to help the traffic accident reconstruction work of OTS team in Loughborough University.
3. Analyze the driver's reaction to variant road situations for the optimization of road network design. The Micro-Level research for certain road segment to identify the key factors (e.g. traffic light, speed limitation, or stop sign, etc) influencing drivers' behaviour.
4. Analyze the driver's behaviour in react to different vehicle dynamic performance to aid for vehicle design.

1.4 Research Contributions

This project constructs the ST-SIM simulation framework and applies it to traffic research work. In details, its research contributions cover two scopes:

1. In framework construction, this project reviewed the knowledge in driver decision, vehicle dynamics, and road network simulation. The finished work includes:
   a. Design and develop road network model (see section 3.2.3).
   b. Refine the driver vision model for object information extract (see section 3.2.1.1).
   c. Re-design the driver decision model in a broader driver psychology and behaviour context (see section 3.2.1.3) for ST-SIM development.
   d. Design the fundamental vehicle dynamics models for the framework (see section 3.2.2).
   e. Based on above components models, design and develop ST-SIM platform for traffic simulation.
   f. Implement the simulation framework with computer-based techniques (see Chapter 4).
2. In application, the ST-SIM is used to simulate the traffic scenario with basic model components. It constructs the virtual traffic scenario for the evaluation of different factors. To be focus, the research concentration in this project is the driver decision process that is
influenced by the environment factors (e.g. road or other vehicles) and driver personal characteristics (e.g. driving experience). Two applications have been realised:

a. The and collision avoidance behaviour in TRL simulator [19] experiment

b. Evaluate environment factors effect in the accident reconstruction case of OTS.

1.5 Outline of the Thesis Structure

The content of this thesis is presented in five chapters:

Chapter 2 is the knowledge literature. It identifies the research areas covered in this project and introduces the current research scope in each area.

Chapter 3 presents the detailed system analysis and design of ST-SIM. The design and analysis for each model component and the interfaces in the framework is presented.

Chapter 4 describes the techniques used in the ST-SIM framework development and the details of the framework implementation. The core computing techniques applied in the framework are introduced in aspects of system design with Rational Rose, algorithms realization with C++, Graphic User Interface (GUI) development with MFC, and 3D Scene generation with VRML.

Chapter 5 validates the ST-SIM in traffic research and investigation work. It provides two scenarios for the framework application. Driver collision avoidance behaviour and the OTS traffic accident reconstruction.

Chapter 6 summarizes the thesis by concluding the research and implementation work in the project and the proposal for future works is presented.
2 Traffic Simulation and Modelling Areas Review

2.1 Introduction

Various types of models are used to help understand traffic and driving. In general terms, a model can be thought to have many qualities, two of which that are particularly relevant here are: 1) its usefulness to describe and 2) its ability to predict. It is possible to have a model that describes a system or process very well, but is not useful for making predictions about how the system or process may perform in various circumstances. It is also possible for a model to be only a weak, poorly accurate, or perhaps abstract description of a system, but be capable of predicting how the modelled system may behave. In contrast, a more comprehensive model is likely to have both qualities.

Previous research into traffic modelling has produced descriptive models, e.g. the ‘Fundamental Diagrams’, obtained from observation of real traffic, and also predictive models of mechanisms for traffic flow. Fundamental diagrams summarise the interaction of important macroscopic traffic flow parameters, such as traffic density, speed and flow rate. They can also provide a convenient benchmark for assessing and comparing the performance of predictive models.

In contrast, a number of traffic simulation techniques have been developed in which vehicles are treated as 'particles of flow'. Traditionally, each result in relatively abstract models representing traffic flow in terms of various macro- and microscopic fluid flow phenomena. Although these approaches have tended to be restricted in their capabilities when compared with the results of real-world traffic measurements and/or experiments, models developed for carefully specified scenarios have produced useful results that have informed road and traffic control development. However, since these approaches provide an abstract description of traffic flow, it has not been possible to incorporate significant detail of driver behaviour and this has developed separately around various aspects of driver psychology.

Models developed in the driver psychology area are generally descriptive, promoting various debates concerning the realism with which they represent either specific or general driving behaviour. There is little evidence that these models have been used in a predictive way, due partly to their qualitative nature and to their relative isolation from other elements of traffic behaviour and infrastructure.
In contrast, providing an alternative approach to macro- and micro traffic flow models, agent based modelling offers a framework in which drivers, vehicles and elements of the traffic environment can interact. Depending on their focus, agent based models can accommodate many levels of detail, including driver behaviour, vehicle dynamics and vision mediated vehicle interaction.

Despite wide ranging developments, little modelling effort has been applied to the analysis of road traffic accidents. In part, this is due to model development focusing on 'normal' driving and recognition that accidents represent the failure of 'normal' circumstances. In practice, accident investigation relies on the development of expert opinion supported, in some cases, by software that can simulate the dynamics of vehicle impact.

In the context of these broad ranging developments, the work reported here is unique in that it explores road traffic simulation using agent based modelling, incorporating driver decision making and aspects of driver psychology, to investigate driver behaviour, this chapter reviews each area from a modelling perspective, setting the context for the development of ST-SIM.

### 2.2 Fundamental Diagrams

This section is concerned with real-world traffic flow experiments that have provided useful means of validating simulation methods. In traffic research, the interested factors include:

- rates of traffic flow (vehicles per unit time);
- speeds (distance per unit time);
- travel time over a known length of road (or sometimes the inverse of speed);
- occupancy (percent of time a point on the road is occupied by vehicles);
- density (vehicles per unit distance);
- time headway between vehicles (time per vehicle);
- spacing, or space headway between vehicles (distance per vehicle);
- concentration (measured by density or occupancy)

The experimental results of above parameters have been conveniently summarized in a number of Fundamental Diagrams:

- **Speed-Flow Diagram**

The Speed-Flow diagram is commonly used to represent the relationship between traffic flow...
speed and flow rate. Figure 2.2.1 shows the generalization of empirical results accepted by the Highway Capacity Manual [24], the sample period was set as 15mins and the flow rate was measured as passenger car per hour per lane (pcphpl).

Figure 2.2.1 Speed-Flow accepted for Highway Capacity Manual [24]

- Speed-Density Diagram
This diagram models the relationship between traffic flow density and its flow speed. Figure 2.2.2 shows the data of [25] from the Lincoln Tunnel experiment. The curve represents a "least squares fit" to the data.

Figure 2.2.2 Speed (km/hour) Versus Vehicle Concentration (vehicles/km) [25]

- Flow-Density Diagram
The Flow-Density diagram reveals the relationship between vehicle flow rate and traffic flow density in a specified time interval. As shown in Figure 2.2.3, Wolfgang Knospe and his
colleagues [26] used it to compare the performance of different traffic flow models.

Figure 2.2.3 Comparison of the Flow-Density diagram of the NaSch [27], the VDR [27], the TOCA [29], and the ER [30] model (Note: J-Vehicle Flow rate, \( \rho \) -Traffic Flow density).

2.3 Macroscopic Traffic Simulation

Macroscopic traffic simulation was first proposed by Lighthill and Whitham (LW model) in 1955 [23], representing traffic flow between junctions on a road network as a compressible fluid that circulates in a network of pipes or links connected by joints. Assuming a network of \( p \) links, in its basic form, the LW model assumes that traffic is described for each link \( (L_m) \ m=1,...,p \) in terms of average speed \( v_m \); rate of flow \( q_m \) and density \( d_m \) according to:

- the vehicle conservation equation: \( \frac{\partial q_m(x,t)}{\partial x} + \frac{\partial d_m(x,t)}{\partial t} = 0, \ m=1,...,p \) \hspace{1cm} (2.1)

- the dimensional consistency relation: \( q_m(x,t) = d_m(x,t) \cdot v_m(x,t), \ m=1,...,p \) \hspace{1cm} (2.2)

- the fundamental relationship: \( q_m(x,t) = F(d_m(x,t)), \ m=1,...,p \) \hspace{1cm} (2.3)

where \( x \) is distance along the m'th link, \( t \) is time and \( F \) is a (usually non-linear) function representing the relationship between flow rate and changes in flow density caused by vehicles leaving or joining at locations along the specified link.
Chapter 2 Traffic Simulation and Modelling Areas Review

The LW model is inspired by the conservation laws of fluid dynamics [31]; it assumes that vehicles are particles in a continuum, which ignores the dynamic interaction between vehicles and gives qualitative consistency with the traffic flow phenomena. Building on the LW model, Payne [32] accounted for driver reaction time $\tau$ in the traffic flow by adding in a dynamic Mean speed function:

- the vehicle conservation equation: $v_m(x, t + \tau) = M\left(d_m(x + \Delta x, t)\right) \quad (2-4)$

$M$ defines the function representing the effect of traffic density (at a distance $\Delta x$ in front of the subject driver) on the subject vehicle velocity. This model improves the quantitative accuracy of traffic simulation but is criticized for poor performance in scenarios involving vehicles joining or leaving the main flow [33]. In more recent research, Coscia [34] proposed that a driver’s speed after their reaction time $\tau$ should be based on the traffic density at an earlier time of the actual traffic conditions as:

$$v_m\left(\bar{d}_m\right) = N\left(d_m(x, t - \tau)\right) \quad (2-5)$$

where $\bar{d}_m$ is the average density at time $\tau$ and $d_m = \left(\bar{d}_m\right)_{\tau=0}$ as $\tau \to 0$.

$N$ defines the function representing the effect of traffic density at time $t - \tau$ on subject vehicle’s speed.

To solve the conservation equations in (2-1) with (2-5), Coscia proposed a relationship between vehicle speed and traffic density based on the experimental results of [35]:

$$\bar{d}_m \leq d_c : v_m = 1, q_m = d_m \quad (2-6)$$
$$\bar{d}_m \geq d_c : v_m < 1, q_m = \varphi(d_m) \quad (2-7)$$

where:

$$q_m = \varphi(d_m) = d_m \exp\left\{-\alpha \frac{\bar{d}_m - d_c}{1 - d_m}\right\} \quad (2-8)$$

Here, $d_c$ is the critical density at the boundary of congestion and free flow traffic sampled from the experiment data set. This practical approach describes the instability properties, which are experimentally observed in congested traffic flow such as 'stop-go' phenomena. However, arguments still exist concerning moving boundary evolution separating free and congested flow.
and the variability of reaction time between drivers [35].

Macroscopic models now are commonly used in traffic research topics such as traffic state estimation [37] traffic noise investigation [38] and traffic control [39]. However, the highly abstract description of traffic flow in above approach ignores the difference of individual driver behaviour, vehicle performance, and the mutual interactions among road users. The Microscopic simulation proposed by other researchers is introduced in next section.

## 2.4 Microscopic Traffic Simulation

Three theories have traditionally dominated microscopic traffic research:
- Vehicle-Following
- Cellular-Automata
- Three Phase Traffic

### 2.4.1 Vehicle Following Model

The Vehicle Following theory assumes that the behaviour of each driver in a traffic stream is primarily influenced by the actions of the vehicle in front. According to Newell [40], the Vehicle Following model investigates how the trajectory $x_n(t)$ of the $n$th vehicle, at time $t$, depends on the trajectory $x_{n-1}(t)$ of the $(n-1)$th vehicle when the $n$th vehicle is following the $(n-1)$th vehicle (which is following the $(n-2)$th vehicle, etc.). Gipps [41] summarises the fundamental equation of Vehicle-Following as:

$$a_n(t + \tau) = l_n \frac{[v_{n-1}(t) - v_n(t)]^k}{[x_{n-1}(t) - x_n(t)]^m}$$

(2-9)

where vehicle $n-1$ is followed immediately by vehicle $n$ with:
- $\tau$ - reaction time (s)
- $x_n(t)$ - location of vehicle $n$ at time $t$ (m)
- $v_n(t)$ - speed of vehicle $n$ at time $t$ (m/s)
- $a_n(t + \tau)$ - acceleration of vehicle $n$ at time $t + \tau$ (m/s²)
- $l_n, k, m$ - empirical based parameters, estimated from observations
A number of studies have explored this model, mainly concerned with the effect of $\tau$ on flow stability; i.e. amplification of disturbances propagating through traffic flow. One of the limitations of this model is that no direct relationships have been revealed between estimated parameters and identifiable driver or vehicle characteristics. In his related work [41], Gipps proposed to constraint the driver's behaviour with safety requirements for acceleration and deceleration in reference to driver's desired speed. This model considered driver preference (i.e. desired speed) in traffic follow and provided an opportunity for vehicle characteristics (e.g. engine torque) to influence vehicle behaviour. Also, this model is calibrated using a Normal distribution of vehicle acceleration samples but no further explanation is given for the estimations of related parameters such as driver preferences in different scenarios. In 2002, Newell [40] developed a simplified model that accounted for the car following behaviour on a homogeneous highway segment (i.e. the segment geometry and traffic volume are constant within the investigation time). Newell assumes the driver's preferred forward distance $S_n$ is proportional to vehicle speed $v_{mn}$, the trajectory $x_n(t)$ can be represented as shown in Figure 2.4.1. The $n$th vehicle follows the same trajectory as the $(n-1)$th vehicle except for a translation in space $d_n$ and time $\tau_n$, as shown in Figure 2.4.2.

![Figure 2.4.1 Relation between spacing and velocity of a single vehicle [40]](image)
In Figure 2.4.2, following the speed change of vehicle n-1, it takes time $\tau_n$ (i.e. the comfortable reaction time) for vehicle n to achieve the corresponding preferred forward distance $S_n$. Vehicle n’s trajectory relating to front vehicle n-1’s trajectory as:

$$x_n(t + \tau_n) = x_{n-1}(t) - d_n$$  \hspace{1cm} (2-10)

At the same time, supposing that vehicle n can exactly follow vehicle n-1’s trajectory, $x_n(t + \tau_n)$ can be represented as:

$$x_n(t + \tau_n) = x_n(t) + \tau_n v_n(t + \tau_n)$$  \hspace{1cm} (2-11)

and:

$$x_n(t + \tau_n) \equiv x_n(t) + \tau_n v_n(t) + \tau_n \tau_n \alpha_n(t)$$  \hspace{1cm} (2-12)

Here $\tau_n$ is introduced in as the ‘relaxation time’ needed for the driver to achieve the required average speed with acceleration $\alpha_n$ during $\tau_n$ for vehicle n to maintain the preferred forward distance $S_n$. Substituting (2-11) into (2-10) gives

$$v_n(t + \tau_n) = \frac{1}{\tau_n} \left[ x_{n-1}(t) - x_n(t) \right] - \frac{d_n}{\tau_n}$$  \hspace{1cm} (2-13)

Then taking the derivative of (2-12) with respect to $t$ gives:

$$\alpha_n(t + \tau_n) = \frac{1}{\tau_n} \left[ v_{n-1}(t) - v_n(t) \right]$$  \hspace{1cm} (2-14)

Finally, substituting (2-12) into (2-10) gives

$$T_n \alpha_n(t) = \frac{1}{\tau_n} \left[ x_{n-1}(t) - x_n(t) \right] - \frac{d_n}{\tau_n} - \nu_n(t)$$  \hspace{1cm} (2-15)
Equations (2-13) and (2-14) enable the \( n \)th driver to choose their velocity and acceleration based upon the value of the ‘relaxation time’ \( T_n \). Equation (2-15) alternatively allows the \( n \)th driver to choose the acceleration proportional to his deviation from the current forward distance with a "relaxation time" \( T_n \).

These models can be applied to homogenous traffic with negligible overtaking; however, supplementary rules must be set up for inhomogeneous traffic subject to traffic signals or on/off stream bottlenecks. This inhomogeneities problem of traffic flow was amended by Zhang [42], based on the model proposed by Pipes [43], Zhang introduced the concepts of gap-distance (i.e. distance separation between the rear of the leader and the head of the follower) and gap-time (i.e. the time that the follower needed to travel the gap-distance). In this model, the driver’s behaviour is decided in relation to achieving the desired gap time. It declares that the desired gap time should depend on both gap distance and traffic phase (i.e. acceleration, deceleration, and free-flow/coasting phases). Hence, the description of capacity drop by Edia [44] and hysteresis by Newell [45] phenomena in multiphase vehicular traffic flow could be represented by variations of driver desired gap time and distance in different traffic phases.

### 2.4.2 Cellular Automata (CA) Model

The CA model was first proposed by Nagel [27] and named as NaSch model. The basic concept of the CA model is to represent the road lane as a lattice, so that each cell of the lattice can either be occupied by a vehicle or empty. Also, the units of velocity and distance are defined in terms of cells. Vehicle movement is simulated by updating cell states in discrete time-steps, with each new cell state depending only on its own present value and that of its neighbours’ [30]. The discrete spatio-temporal characteristics of the CA approach provide the possibility of simulating large traffic networks faster than real-time [47]. This model involves a minimum set of state-update rules for the vehicles in the traffic flow, together with a controlled element of randomly selected speed change to represent uncertainty within the traffic flow [47]:

1) **Acceleration**: if the velocity \( v \) of a vehicle is lower than \( v_{\text{max}} \) and if the distance to the next car ahead is larger than \( v+1 \), the speed is increased by one \( [v = v + 1] \).

2) **Slowing down** (due to other cars): if a vehicle at site \( i \) sees the next vehicle at site \( i+j \) (with \( j \leq v \)), it reduces its speed to \( j-1 \) \( [v = j-1] \).

3) **Randomization**: with probability \( P_{\text{dec}} \), the velocity of each vehicle (if greater than zero) is decreased by one \( [v = v-1] \).
4) **Car motion**: each vehicle is advanced $v$ cells.

By tuning the two free parameters (i.e. $v_{\text{max}}$ and $P_{\text{dec}}$) [27], the NaSch model is able to reproduce the flow-density diagrams outlined in section 2.2 [48]. Building on the NaSch model, researchers have proposed various developments [28]-[30], [49]-[52]. For example, one of the limitations of NaSch model is that no clear relationship is given between vehicles’ acceleration, its speed, and the driving situation (i.e. headway) due to the cell status is only decided by the states of the neighboured cells. This is unrealistic considering the driver’s variable foreseen distance and variable preferred speed in different traffic situations. Takasihi [53] proposed to establish a more realistic relationship between vehicle acceleration and speed by the integration of headway distance. His simulation work generated increasing propagation of traffic jams with the vehicles’ increasing ability to accelerate. However, no experimental data are presented for the validation of his simulation results. Emmerich [46] extended the NaSch model by introducing updated rules to better fix the flow-density diagram with the proposition that vehicles’ acceleration should be related to both the forward distance and to its previous speed. The change is that the vehicle status now is updated in the opposite direction of the moving flow, which means the updated vehicle’s status will count in the previous vehicle’s motion (i.e. the driver’s anticipation of the front vehicle’s motion based on its speed). Emmerich also claimed vehicle deceleration should be related to its speed via a preferred speed look up table, such as that in Figure 2.4.3. This is setup to determine the driver’s preferred speed as a function of their current speed and the forward distance. As shown in Figure 2.4.3, a vehicle with velocity $j$ and forward distance $i$ reduces its speed to $M_{j,i}$. (Note: following the CA model convention, distance and speed are defined with the unit ‘cell’).

\[
M = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 1 & 1 \\
0 & 1 & 2 & 2 & 2 \\
0 & 1 & 2 & 3 & 3 \\
0 & 1 & 2 & 3 & 4 \\
0 & 1 & 2 & 3 & 5 \\
\end{pmatrix}
\]

*Figure 2.4.3 Preferred speed look up table for CA model [46]*

These amendments provided the opportunities to generate better flow-density diagrams for CA models as shown in [48]. Furthermore, Rickert and his colleagues [54] expanded the NaSch model to the two-lane situation where a lane change model is represented by extra rules added in CA model. They analyzed flow related parameters (e.g. flow density, speed, etc.) in relation with the lane change model but did not match with the empirical result in lane change frequency and “density inversion” phenomena observed in [55][56]. A more ‘secure’ approach is proposed in
May's work [56], by introducing a ban on overtaking on the right side (based on the German road system). May considered the impact on the vehicles in the destination lane by the extra rule set based on the distance detection to the following vehicle. With this model, a qualitative lane usage-density relationship is identified. In more recent research, the impact of driver behaviour on traffic flow is identified as the amending explanation for the newly appeared Three-Phase traffic flow theory with CA point of view [50] [51]. Knospe[51] pointed out the human anticipation may influence the stability of traffic phase and even reproduce the empirically observed phase. The incorporation of driver perception is introduced by the adaptation of random parameter $p_{dec}$ and related update rules based on the preceding vehicle brake light status and the definition of interaction range. The modelling result was qualitatively in accordance with empirical results of microscopic traffic states that shown in [51].

2.4.3 Three-Phase Traffic Theory

Between 1996-2000, Kerner proposed the theory of Three-Phase Traffic Flow [57]-[66]. He proposed that the traffic flow should have three phases:

1. Free flow.
2. Synchronized flow.
3. Wide moving jam.

(2) and (3) represent different states of congested traffic. As shown in Figure 2.4.4, free flow represents increasing flow rate with increasing flow density, up to the limit, $F$, where the flow density reaches its maximum (i.e. the road segment capability). Synchronized flow is introduced based on the tendency for speed synchronization in different lanes of the road segment as traffic congestion develops. Synchronized flow is associated with a fixed front (i.e. where vehicles escape from the congestion) into the downstream the traffic flow. The Wide moving jam is where the vehicle speed is zero and the jam propagates through the traffic with constant speed in the upstream direction of traffic flow. Here, Kerner hypothesized that steady state synchronized flow covers a two-dimensional (2D) region (see Figure 2.4.4) in the flow-density plane and there was no additional fundamental diagram for steady state synchronized flow. Physically, this may be interpreted as variable synchronized speed and density in the traffic flow, rather than a fixed relationship.
Kerner claimed that in traffic flow, the phase transition may only happen in the sequence of Free flow-Synchronized flow-Wide moving jam (F-S-J) instead of a transition from Free-flow to a sequence of spontaneous wide moving jams. The crucial point in the theory is the identification of a two-dimensional region of equilibrium speeds in different synchronization flow states with different rules of vehicle motion. In comparison with the CA models, Kerner and his colleagues proposed the KKW model [67], which integrated collision avoidance and speed related synchronization gaps into three-phase traffic theory. At the qualitative level, this model reproduced the congested patterns on a homogeneous one-lane road and the on-ramps (i.e. entrance to the main road or motorway).

Since Three-Phase theory explained the empirical features of congested traffic patterns over the highway bottleneck [66], Kerner claimed this theory was a behaviour fundamental behavioural characteristics of drivers observed on highways. However, the hypothesis of all drivers having the same characteristics and all vehicles having the same parameters ignored the difference among human behaviour and vehicle performance. The drivers’ behaviour-related factors, such as accuracy of distance and speed estimations are not considered. It remains doubtful that, with the exclusion of these ‘neglectable’ [66] factors in relating to differences in driver and vehicle characteristics, current traffic flow theories can adequately explain the fundamental observed features of traffic flow. Furthermore, the influence from environment factors such as traffic controls, accidents, and road conditions all lead to additional difficulty when explaining how the Synchronized flow transits to Wide moving jam.

2.4.4 Agent Based Simulation

Agent-Based simulation is the computer modelling methodology that gives the modelled entity the knowledge and intelligence to decide and behave in response to varying real circumstances. It has
been used in financial market, logistics, and other business modelling areas as introduced in [68] [69]. In Microscopic traffic research, Agent-based simulation naturally fits in the requirements of modelling drivers and vehicles. It has been applied in different simulation frameworks with its self-encapsulated decision and action capabilities. Examples of agent based modelling include:

In [70], Hussein used agents to model the behaviour of individual drivers under the influence of real-time traffic information. His work identifies the parameters that define each driver's characteristics based on survey data of real drivers. The results are applied to the agents route choice behaviour. In his paper, discrete choice modelling techniques and the Multinomial Logit models [71] are used to model drivers' responses and identify the parameters influencing their route choice. Discrete choice models assume that the probability of an individual choosing a given option from a finite set of alternatives is a function of the context variables (e.g. the individual's socio-economic characteristics) and the relative attractiveness of the option under consideration [71]. The attractiveness of the alternatives is described and quantified by a utility function, which individuals typically seek to maximise. To determine if an alternative will be chosen, the value of its utility is compared with the utility of the alternative options and transformed into a probability value between 0 and 1. For each form of information provided, e.g. quantitative delay, predictive and prescriptive delay in the trip, a Multinomial Logit model [71] is developed to determine the socio-economic and context variables that are most significant in influencing driver compliance for that type of information.

In [72], the Intelligent TRAnsport System (SITRAS) utilized driver agents with lane changing/merging knowledge and behaviour processes to simulate the driver (see Figure 2.4.5). The Car-Following model algorithms are used to calculate vehicle speed variance.
Figure 2.4.5. Summary flowchart of the lane changing process in SITRAS [72]

SITRAS is used to simulate the lane changes caused by accident or congestion in the traffic flow. It uses the definition 'courtesy' of drivers in the target lane of the subjective driver to decide if they refused or accepted the subject driver’s lane change request. Here 'courtesy' is implemented by evaluating each of the vehicles in the simulation based on several factors such as the speed, position and driver type.

Another sample is the agent-based Transportation Analysis and SIMulation System (TRANSIMS) that is developed in [73]. It is an agent-based simulation system capable of simulating the movements of person and vehicle through the transportation network of metropolitan area with the modules shown in Figure 2.4.6.

Figure 2.4.6 TRANSIM design [73]

By changing the agents' behaviour (e.g. route plans), this framework solves the problem of consistency between different modules. For example, plans depend on congestion, but congestion depends on plans; this problem solved by using systematic relaxation, that is, make preliminary
plans, running the traffic micro-simulation, adapting the plans, running the traffic micro-simulation again until consistency between modules is reached. During each iteration, a certain percentage of a driver's route is changed due to the congestion and the system will loop until a driver may achieve no obvious advantage by further trying to change their route. In this framework a micro-level queue model [74][75] similar to CA model (see section 2.4.2) is applied to simulate vehicle movement in the traffic flow.

Dynamic Route Assignment Combining User Learning and microsimulation (DRACULA), Figure 2.4.7 [76], is developed at Leeds university and extended in 2002 to support an agent based traffic model[77]. It uses a driver reasoning mechanism based on a Beliefs, Desires, and Intentions (BDI) architecture [78]. This approach enabled the agent-based framework to evaluate the Intelligent Transportation Systems (ITS) performance in three commuter scenarios by applying its impact on the BDI model parameters:

1. The driver has no contact with traffic information before the trip
2. The driver has contact with the traffic information before the trip,
3. The driver has contact with the traffic information during the trip

![Diagram of the simulation process of DRACULA framework]

Summarizing the above samples, agent based simulation provides a vital tool to model the driver in traffic simulation to identify the factors that influencing the drivers' decision (e.g. route choice, departure time, etc.) However, in above approaches, the drivers have perfect traffic information
retrieval via the agent communication. This assumption ignored the fact that the ITS or the surrounding objects influence the subjective driver via human perception layer. This layer exposed new investigation areas for driver modelling. For example, when a driver makes a lane change manoeuvre, detection of the target lane traffic is influenced by perceived forward distance, relative speed, and current speed limitation, etc. Visual modelling system is required to investigate the traffic information retrieval of human driver. Partially in response to this, ST-SIM presents a multi-model based simulation framework encapsulating a simple vision model (see section 3.2.1.1) to capture traffic situation parameters for driver decision process.

2.5 Multi-Model Based Simulation

2.5.1 Introduction

This section explores various approaches of modelling or explaining different aspects of driver behaviour. It provides a broad knowledge context for ST-SIM driver model re-development. In doing this, it is useful to summarize the driver model in ST-SIM (discussed in more detail in section 3.2.1).

2.5.2 The Current ST-SIM Driver Model

Driver behaviour can be investigated in many ways and ST-SIM is developed to provide an open framework, in which different behavioural models can be developed, assessed in the context of ST-SIM traffic scenarios, and used to support other ST-SIM scenarios in which, for example, vehicle behaviour or junction design may be the major focus. ST-SIM currently employs a simple agent-based approach corresponding to the Weak agent definition proposed in [80], so that ST-SIM agents demonstrate the following characteristics:

- **Autonomy**: agents operate without the direct intervention of humans or others, and have some kind of control over their actions and internal state
- **Social ability**: agents interact with other agents and possibly humans
- **Reactivity**: agents perceive their environment and respond in a timely fashion to changes that occur in it
- **Pro-activeness**: agents do not simply act in response to their environment; they are able to exhibit goal-directed behaviour by taking the initiative.
These characteristics are enabled in ST-SIM agents through their repeated performance of a *Perceive – Decide – Act* loop. This is shown in Figure 2.5.1, which also shows how ST-SIM drivers interact with their vehicle and the traffic environment.

![Figure 2.5.1 Current driver model in ST-SIM](image)

To provide a context for discussing driver behaviour models developed elsewhere, the following paragraphs summarize the perceive, decide and act stages of ST-SIM driver behaviour.

**Perceive**
Although all of our senses influence our behaviour, vision and touch (the perception of force) are fundamental to driving, with hearing also making some contribution. The driver model in ST-SIM currently implements two forms of vision model, termed 'perfect' and 'realistic', that enable a driver to perceive the environment around their vehicle and also to perceive their own vehicle speed. Perfect vision simply involves sharing of data, so that a driver can know the exact (depending on calculation accuracy) position, velocity, and acceleration of objects in their environment. Perfect vision is also used to mimic a dashboard speed display. Realistic vision is based on ray tracing and, in the development of ST-SIM, is thought of as a filter that introduces an element of real-world uncertainty into perception of the environment around the driver’s vehicle. The interface between a driver and their vehicle has been developed in a sufficiently general way that it can also model the transfer forces and sound from the vehicle to the driver, aiming to provide comprehensive perceptual capabilities in the future.

**Decide**
The Decide step is the key area where driver behaviour can be expressed in various levels of detail. ST-SIM currently uses the rule based decision model developed in [9], in which six rules enable
drivers to try achieving their goals and preferences. These rules are responsible for determining the meaning of perceived information and formulating an appropriate action. By modifying various rule parameters, it is possible to prescribe a wide range of driver 'attitudes' or driving styles.

**Act**

This implements the fundamental tasks of changing vehicle speed and direction.

### 2.5.3 Driving task models

It is generally accepted that driving can be divided into a three-level hierarchy of tasks [88], as shown in Figure 2.5.2. The top level describes Strategic, relatively low frequency tasks, such as route planning. The middle level involves more frequent Manoeuvring tasks, such as overtaking and junction negotiation, and the lowest level is concerned with relatively high frequency Control tasks, such as speed and steering adjustments.

![Figure 2.5.2 The minimal Hierarchical Driving Task Model](image)

In the strategic level, the driver's tasks are concerned with specification and monitoring of trip goals (e.g. shopping, go to office, or pick up friend, etc), leading to decisions concerning specification/selection of, for example, depart time, route choice, and travelling tools selection. Models of driver/traffic behaviour at this level include as [77][70], introduced in section 2.4.4, involving the use of intelligent agents to evaluate the impact of ITS on driver decisions. Modelling at the Manoeuvring level is exemplified by are [72], which used agent simulation to investigate drivers' lane change and merging behaviour, and [81], which used DRACULA to investigate...
unsafe, driving (also see section 2.4.4). At the control level, Macadam [82] reviewed the human driver modelling and demonstrated the basic control tasks-lateral/longitudinal position and headway maintain. Among the human attributes such as visual, auditory, and tactile and so on along with physical constraints like stability and comfort driving, it is noticeable due to the complexity of variant driving scenario, the driver modelling often specific to optimal driver performance like racing drive or focus on the certain provision of human attribute and driving constraints. While artificial intelligence methods such as neural networks, and genetic algorithms based modelling works are often lack of direct connection to the driver characteristics made these methods and their results hard to interpret [83].

At the most simple level, suggested in Figure 2.5.2, two points should be noted about the philosophy of thinking about driver behaviour in terms of hierarchical models. Firstly, they describe driving as a control system, involving feedback, and executive monitoring of lower level tasks and, secondly, they need not involve any psychological influences on driver behaviour.

In an attempt to include psychological factors Botticher [84] augmented the basic 3-level control model by including elements of perception, motivation, expectation, judgement, and emergency behaviour. This is an important model in that it highlights the need to explain how psychology and task performance interact. However, despite its complexity, it lacks detail within its elemental psychological processes and communication between processes is limited to binary signals. Also, there seems to be no easy way for the model to integrate any of the alternative driver behaviour models discussed later in this chapter.

In comparison to Figure 2.5.2, the driver model currently implemented in ST-SIM operates at the Control level, with manoeuvring tasks emerging as a consequence of interactions between drivers rather than being programmed. However, the ST-SIM driver model does not contain any Strategic tasks that are suggested in Figure 2.5.2.

Generally, hierarchical models are valuable in describing types of driving tasks and their relationships. However, the associated control system approach demands a complete description of all tasks at all levels. The absence of any task definition in the model means that there are real-world circumstances that the model cannot describe or predict. This is demonstrated by the identification of 45 major and 1700 lower level tasks in [85] [86] as an attempt to document driving. Despite the scale of this effort, there can never be a guarantee that the resulting model will reflect all circumstances and its real value should probably be seen as taxonomy of driving tasks rather than a complete model of their coordinated use.
2.5.4 Driver behaviour models

Keskinen [87] provides a well-structured review of driver behaviour models, suggesting that the following major theories of driving have been established:

- The Risk Compensation Model [95]
- The Risk Threshold- and Zero Risk Models [94]
- The Threat Avoidance Model [97]
- The Task Capability Interface Model [98]
- The Theory of Planned Behaviour [99]

2.5.4.1 The Risk Compensation Model

The core element of this model is that people conduct their lives aiming to achieve an approximately constant personal level of risk. The Risk Compensation Model proposes that, for any task or activity, an individual will aim to find an optimum balance between the benefits and costs of risky and safe behaviour, as exemplified in Table 2.5.1 for driving.

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Risky behaviour</strong></td>
<td>Accidents, prosecution for a driving offence, higher fuel and/or insurance costs</td>
</tr>
<tr>
<td>Reducing travel time by speeding,</td>
<td></td>
</tr>
<tr>
<td>increased thrill, perceptions of</td>
<td></td>
</tr>
<tr>
<td>competence</td>
<td></td>
</tr>
<tr>
<td><strong>Safe behaviour</strong></td>
<td>Being late, boredom and/or frustration, increased physical discomfort</td>
</tr>
<tr>
<td>Lower fuel and/or insurance costs,</td>
<td></td>
</tr>
<tr>
<td>perceptions of competence, fewer</td>
<td></td>
</tr>
<tr>
<td>accidents</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.5.1 Expected benefits from risky and safe behaviour [95]

From the Author's point of view, it appears that the Risk Homeostasis model makes no distinction between actual calculated risk and an individual driver's subjective perception of risk. Also, the model appears to be egocentric, making no reference to risk posed to or by other drivers.

2.5.4.2 The Risk Threshold- and Zero Risk Models

The main difference between the previous Risk Compensation model and the Risk Threshold model is that in the latter the driver makes no change to their behaviour until they judge that their risk has exceeded a personal threshold. To achieve this, the Risk Threshold model also introduces
safety margins based on the time separation and/or spatial distance between the driver and a hazard. The driver manipulates their risk by controlling these safety margins. The success of this approach depends on the accuracy of driver's subjective perception of risk, which is strongly influenced by their motives and previous driving experience.

The Risk Threshold model is concerned with how drivers recognise the need to change their behaviour. However, the model begs the question of where does the driver's behaviour originally come from? This is also related to motives and the development of driving experience. According to this model, each time a new potential hazard is encountered, a driver will decide how to manipulate their safety margins to control their risk over a period involving various hazards; they will build a repertoire of driving skills that will keep them safe, i.e. subject to zero risk. Exposure to new hazardous situations is an important part of learning to drive, so it would be expected that the Risk Threshold model would describe a large proportion of the driver's behaviour. As the driver becomes more experienced, it might then be expected that fewer situations appear hazardous and their behaviour may be better described using the Zero Risk model. Since both of these models depend on an individual driver's perception of risk, this transition is complicated by the driver's innate motivation to seek or avoid risk and the extent to which growing driving experience may modify the driver's innate motives.

In an attempt to summarise the key factors in both of these models, Summala developed the Multi-sieve model, as shown in Figure 2.5.3 [96]. Although the rows and columns in Figure 2.5.3 suggest various combinations of discrete factors, the Multi-sieve model says nothing about the detail of their interactions. It is perhaps more useful to recognise that Figure 2.5.3 contains three perpendicular axes, each representing a fundamental aspect of driver behaviour.
2.5.4.3 The Threat Avoidance Model

In the Threat Avoidance model, it is assumed that drivers' priorities are to reach their destination and to avoid hazards. The continual conflict between these priorities creates threat or risk. However, in contrast to the previous models, here risk is subsidiary to the driver's motives, rather than a primary influence on them. The Threat Avoidance model proposes that driving involves repeated stimulus - response activity, where a stimulus is the driver's perception that they need to take action, for example steering to negotiate a bend or avoid a pedestrian. The driver determines their response to a stimulus based on their appraisal of reward (continuing their journey) or punishment (being delayed, breaking the law, or having an accident).

This model has some commonality with the agent-based approach used in ST-SIM, in that both are essentially 'Event Driven'. However, a major difference is that the ST-SIM driver model also uses a number of low level driving rules and driver preferences. These represent a behaviour model at the control level in Figure 2.5.2 that enables various manoeuvring actions, such as vehicle following and overtaking, to emerge without their explicit programming. As noted in [89], this is
not possible in the Threat Avoidance model.

2.5.4.4 The Task Capability Interface Model

The Task Capability Interface model is a further refinement of the previous Threat Avoidance model, representing driver behaviour as a dynamic balance between their capability to control their vehicle and the demand-for/difficulty-of vehicle control. According to this model, if the current demand is low in comparison to capability, the driving task is easy. When demand and capability are equally matched, the driving task is very difficult and when demand exceeds capability, there is a loss of control. This model has a number of interesting implications:

- The model is concerned with task demand, rather than some other factor such as complexity, in relation to a driver’s capability. Hence, a complex task can be perceived easy if capability far exceeds demand. Conversely, a simple task can be highly demanding if its demand exceeds capability.

- Task difficulty is inversely proportional to the difference between task demand and driver capability.

- Given a static level of driver capability, any event that increases task demand will reduce this critical difference, increasing task difficulty and potentially challenging safety, for example using a mobile phone, lighting a cigarette, changing radio station, etc, all increase task demand.

- A significant element of task demand involves not hitting pedestrians, other vehicles, and various inanimate objects. The actions of pedestrians and other road users can significantly and rapidly increase or decrease task demand but the overall effect of these on task difficulty depends on driver capability.

- When task demand begins to exceed capability, loss of control may sudden due to increased sensitivity to a minor error, for example the driver is simply unable to maintain the desired trajectory, avoid an obstacle or stop in time, or gradual due to prioritisation and neglect of less important tasks, such as lane discipline or decreasing frequency of mirror use.
2.5.4.5 The Theory of Planned Behaviour

Unlike the previous models, which all offer interpretations of different aspects of the driving task, adopting the Theory of Planned Behaviour from the wider area of social psychology enables driving to be analysed as an example of wider human activity. As shown in Figure 2.5.4, the particular focus of this theory is that human behaviour results from the intention to perform the behaviour, which in turn is influenced by a range of personal factors and beliefs.

The Theory of Planned Behaviour provides an important bridge between the specialisation of human activity needed to achieve driving and the more fundamental factors that influence the human state, intentions, and behaviour. All human aspects of driving are a consequence of each driver’s life experience, which is achieved through interaction of individual neuro-chemical processes and physical interaction with their world. In turn, driving experience contributes or adds to their continuing life experience, influencing future behaviour. From a modelling perspective, the major difference between the Theory of Planned Behaviour and the preceding models is that it provides a framework that can accommodate the influence of many factors.

Figure 2.5.4 Theory of Planned Behaviour
As shown in Figure 2.5.4, the theory relates the intention to behave in some particular way to four primary factors:

**Actual Control:** This represents the extent to which a person has the opportunity, resources (including skills) and motivation to perform the intended action.

**Perceived Behavioural Control:** This is the person's perception of the ease or difficulty of the intended behaviour and their confidence in performing it. Perceived Behavioural Control encompasses the influence of previous experience, anticipation, perceived opportunity and resources (including skills) by integrating a number of previous, more restricted, theories concerning Internal Locus of Control (belief that outcomes are determined by own behaviour), Perceived Self-Efficacy (self-judgement of competence) and the Theory of Achievement Motivation (perceived probability of success).

**Subjective Norm:** This is the perceived social pressure to perform or not perform the behaviour.

**Personal Attitude:** This indicates the person's positive or negative evaluation of the intended behaviour.

In addition to these primary factors, the Theory of Planned Behaviour also involves an underpinning system of beliefs from which the perceptions and, finally, intention develop. As shown in Figure 2.5.4, beliefs that are salient to an intention can be categorized according to each of the subjective primary factors. Typically, each of the subjective primary factors is a function of the total effect, or summation, of individual beliefs, such that

\[
B_c = \sum_{i=1}^{N_c} p_i c_i \quad (2-16)
\]

where

\(N_c = \text{number of salient control beliefs}\)

\(c_i = \text{subjective evaluation of the } i^{\text{th}} \text{ control belief}\)

\(p_i = \text{perceived power of the } i^{\text{th}} \text{ control belief to facilitate or inhibit}\)

\[
B_n = \sum_{i=1}^{N_n} p_i n_i \quad (2-17)
\]
where

\[ N_n = \text{number of salient normative beliefs} \]
\[ n_i = \text{subjective evaluation of the } i^{\text{th}} \text{ normative belief} \]
\[ p_i = \text{motivation to comply with the } i^{\text{th}} \text{ normative belief} \]

Behavioural Beliefs \[ B_b = \sum_{i=1}^{N_b} p_i b_i \] (2-18)

where

\[ N_b = \text{number of salient behavioural beliefs} \]
\[ b_i = \text{subjective evaluation of the } i^{\text{th}} \text{ behavioural belief} \]
\[ p_i = \text{strength of the } i^{\text{th}} \text{ behavioural belief} \]

As catalogued in [90] the Theory of Planned Behaviour has been used to explore several aspects of driving behaviour, including drinking and driving, dangerous overtaking, close following, lane discipline and speeding. A further investigation can also be added to this list, concerning prediction of fundamental influences on pedestrian behaviour [91]. All of these applications have typically addressed particular issues investigated via other models reviewed here, demonstrating that the Theory of Planned Behaviour provides a realistic explanation in the wider context of social psychology.

A second notable type of application has been use of the theory as a framework for developing measures to influence driver behaviour, assuming that the Theory of Planned Behaviour is not only an adequate model of intention, but also of receptivity to new influence. Particular examples of this are the FOOLSPEED campaign [92] and injury prevention measures [93].

In all of these applications, salient beliefs were developed via participants’ self-reporting. However, as noted by Ajzen [100], the Theory of Planned Behaviour is open to interpretation. For example, Sutton [101] discusses how salient beliefs reported by subjects depend on how they are obtained. In particular, questions prompting affective responses, such as ‘like’, ‘dislike’, etc, elicit different responses to questions that look for instrumental outcomes concerning perceived advantages and disadvantages. In addition, it has been noted in [102] that the subjective nature of factors within perceived behavioural control may overlap with personal attitude, leading to significant bias in the prediction of intention. In an effort to address such issues, Persson [90] reports an experiment investigating drivers’ tendency to speed, in which self-reported behaviour
was compared with data recorded from their vehicles over several weeks of routine driving. Despite a number of procedural and technical difficulties, the experiment demonstrated that the Theory of Planned Behaviour could be used with salient beliefs derived from both subjective and objective data. Together with a number of previous points, this is an important indicator that the Theory of Planned Behaviour may provide a conceptual framework that may be developed in several directions. In particular

- Its use in FOOLSPEED and other influencing measures suggests algorithmic implementations that may guide development of the theory as software tool to mimic aspects of driver intention and behaviour within larger traffic models.

- The development of salient beliefs from combined self-reporting and real-world experiments can provide important insight into drivers' self-perception as well as supporting the theory's use as a software model of driver psychology.

- As a conceptual framework, the Theory of Planned Behaviour identifies that a number of factors influence intention, but does not elaborate on how this influence is achieved, or how the relative importance of the factors and their influence may change due to feedback from previously executed behaviour or other influencing measures. As suggested below, insight into these issues may be found in areas such as cognitive psychology and neuroscience, offering the possibility the Theory of Planned Behaviour may be a convenient starting point for developing a comprehensive model of driver behaviour.

### 2.5.5 Road Networks

In developing ST-SIM, provision has been made for its future use with road network modelling tools by defining an appropriate interface. However, in the work discussed here, effort has concentrated on making sure that the internal ST-SIM road definition works with the current driver and vehicle models. The road network model in ST-SIM must achieve the following:

- Provide a mathematically adequate surface for realistic vehicle movement;
- Be detectable by the driver vision model
- Be geometrically accurate for accident reconstruction and simulation of traffic in other circumstances.

These requirements are met in ST-SIM using Computer Aided Design techniques for the definition of overall road and junction geometry, along with modelling techniques borrowed from the mesh generation part of the Finite Element method for mathematical and geometric accuracy of road
surfaces. This section reviews the background to these techniques.

### 2.5.5.1 Finite Element method

The Finite Element (FE) method is a computational technique that is used to solve physics based problems that often involve complicated geometries [21]. In simple terms, a complicated geometry is divided into a mesh containing a finite number of simple shapes, called ‘elements’. Elements are connected via ‘nodes’ at which the desired physical quantities are calculated. The FE calculation procedure is possible because elements and their defining nodes have specified mathematical properties. Although elements can be of any dimensionality, only 2-dimensional quadrilateral elements are considered here because they are particularly relevant to the road network model. Figure 2.5.5 shows examples of two such elements, each having different mathematical properties. Although each element may have a complicated shape in x, y coordinates, each is defined as a square in its own local coordinates, simplifying the mathematics underlying the FE method. In general terms, for an element using R nodes, the x, y and local coordinates are related through

\[
x = \sum_{i=1}^{R} N_i(x, \eta) x_i \quad (2-19)
\]

\[
y = \sum_{i=1}^{R} N_i(x, \eta) y_i \quad (2-20)
\]

\[
\phi = \sum_{i=1}^{R} N_i(x, \eta) \phi_i \quad (2-21)
\]

where \( N_i \) is the shape function for the \( i \)th node [21], and \( \phi \) is the quantity calculated by the FE method.
2.5.5.2 Road Network Modelling

In ST-SIM, road network modelling involves two branches of transportation research - Highway geometry and Traffic control. The following sections provide an introduction to basic concepts in each area.

- **Highway geometry**
  
The highway system consists of road segments connected by various junctions. In designing a road segment, essential factors are its geometrical plan and cross section profile that influencing capacity, speed limitation, horizontal alignment, and vertical alignment design. Geometrical plan and cross section design are influenced by a number of issues including traffic volume and composition, construction cost and available funds, social- and environment concerns, etc. In definition, horizontal alignment refers to the series of intersecting tangents and circular curves (with or without transition curves) that constitute the road plane plan. The vertical alignment specifies the vertical profile of the road using combinations of tangents and curves.

For road junctions, in Britain, there are three general types of junction [105]:

![Diagram of a bi-linear element](image1)

(a) A bi-linear element in (x,y) and local (ε, η) coordinates

![Diagram of a bi-quadratic element](image2)

(b) A bi-quadratic element in (x,y) and local (ε, η) coordinates

Figure 2.5.5 Examples of two-dimensional elements.
(1) Grade separated intersection (see Figure 2.5.6); (2) Roundabout (see Figure 2.5.7, Figure 2.5.8), and (3) Interchanges (see Figure 2.5.9). Grade separation design is based on the peak hourly flow which varies according to road type and according to whether the road is motorway or all-purpose. For roundabout, three main types are commonly planned (i.e. Normal, Mini and Double) in UK and other forms of roundabouts which are variants of these basic types. The interchange is a grade separation in which vehicles moving in one direction of flow may transfer direction by the use of connecting roadways (see Figure 2.5.9).

Figure 2.5.6 A Sample Grade Separated Junction to Absolute Minimum TD 22/92 Standards [105]

Figure 2.5.7 Normal roundabout[105]
Figure 2.5.8 Mini-roundabout [105]

Figure 2.5.9 The sample 3 Level Roundabout connections between Three Legs with Free Flow Interchange Links [105]

- Traffic control system

To coordinate traffic flow in the road network, a traffic control system is required. The two main forms of control are signals and signs/road markings. The signal control systems now in use
include fixed-time signals where the green periods and cycle times have predetermined fixed durations and vehicle-actuated systems that respond to traffic demand estimated using nearby detectors. Traffic signs and road markings can advise, warn, and control drivers' behaviour, to providing directions and driver location information. Two basic types of signs and marking are: (a) warning signs that alert the driver of an impending hazard, whether actual or potential, or permanent or temporary, for which they would not otherwise be prepared; and (b) the regulatory signs and markings that are either mandatory or prohibited, used to govern the speed and direction of vehicles and to specify lawful road use. Visibility and legibility are the key factors in the design of traffic signs and road markings. Detailed considerations concern size, shape, colour and location in the environment relating to road curvature, hedges, trees and urban buildings.

2.5.6 Vehicle Dynamics Modelling

"Vehicle dynamics is concerned with the movements of vehicles. The movements of interest are acceleration and braking, ride, and turning. Dynamic behaviour is determined by the forces imposed on the vehicle from the tires, gravity, and aerodynamic [114]". This section reviews background knowledge for vehicle dynamic modelling in ST-SIM. For clarity, the Society of Automotive Engineers (SAE) convention coordinate systems for Vehicle Dynamic Modelling is first introduced, followed by brief descriptions of the basic component models of a vehicle and their related dynamic theories.

2.5.6.1 Vehicle Fixed Coordinate System

Figure 2.5.10 shows the SAE Vehicle Axis System used in ST-SIM. The vehicle motions are defined with reference to a right-hand orthogonal coordinate system (the vehicle fixed coordinate system), which originates at the CG (Centre of Gravity) and travels with the vehicle. By SAE convention [114] principal axes and motions are:

- x – Forward and on the longitudinal plane of symmetry
- y – Lateral out the right side of the vehicle
- z – Downward with respect to the vehicle
- p – Roll velocity about the x-axis
- q – Pitch velocity about the y-axis
2.5.6.2 Earth Fixed Coordinate System

Vehicle attitude and trajectory through the course of a manoeuvre are defined with respect to a right-hand orthogonal axis system fixed on the earth. This is normally selected to coincide with the vehicle fixed coordinate system at the point where manoeuvre is started, as shown in Figure 2.5.11:

- **X** - Forward travel
- **Y** - Travel to the right
- **Z** - Vertical travel (positive downward)
- \(\Psi\) - Heading angle (angle between x and X in the ground plane)
- \(v\) - Course angle (angle between the vehicle’s velocity vector and X-axis)
- \(\beta\) - Sideslip angle (angle between x-axis and the vehicle velocity vector)
2.5.6.3 Basic Vehicle Component Models and Dynamic Theories

Before the development of adequate computers, understanding of vehicle dynamics was greatly constrained by the need for mathematical idealisations. Since a vehicle is a mechanical system consisting of many components, the nonlinearity of these components' dynamic performance and their interactions made it impossible to make a comprehensive model of the vehicle. In recent years, the principal method of simulating vehicle dynamics has been Multi-body System (MBS) analysis [108]. The models of individual vehicle components are assembled into a dynamic system matrix, which can be solved using various numerical analysis techniques. The vehicle model implemented in ST-SIM consists of the following component models:

- Vehicle body
- Suspension
- Tyre
- Steering

The primary aim of developing these models is to provide an approximate representation of overall vehicle behaviour, but also to do this in a way that enables easy future development of additional and more detailed component models. The theory underlying each of these core component models is discussed in the following sections.

- Vehicle Body

In a simulation, the vehicle body model should provide following information:

a. vehicle dimensions
b. vehicle body location in the global coordinated system
c. the driver/passenger’s location within the vehicle
d. kinematics parameters including:
   - moving speed
   - moving direction
   - yaw angle/speed
   - roll angle/speed
   - pitch angle/speed...
e. for dynamic analysis, the body should include:
   - An interface to a suspension model representing the dynamics mechanisms in vehicle body's motion translated via the chassis.
• The aerodynamic impacts on the vehicle body, which involve the topics like drag force on the vehicle, driving stability, and fuel economy

Table 2.5.2 shows the aerodynamic forces working on the principal axes, of the vehicle. The design of vehicle body has significant influence on the aerodynamic performance; one of the common requirements is the need of low drag effect, which in consequence leads to the optimization of vehicle front design [109], body shape [110], and rear end design, etc [117].

<table>
<thead>
<tr>
<th>Direction</th>
<th>Force</th>
<th>Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal (x-axis, positive rearward)</td>
<td>Drag</td>
<td>Rolling Moment</td>
</tr>
<tr>
<td>Lateral (y-axis, positive to the right)</td>
<td>Side-force</td>
<td>Pitching moment</td>
</tr>
<tr>
<td>Vertical (z-axis, positive upward)</td>
<td>Lift</td>
<td>Yawing moment</td>
</tr>
</tbody>
</table>

Table 2.5.2 Aerodynamic forces working on the vehicle principal axes [117]

In ST-SIM, the modelling of vehicle body presents the calculation and output of items (a-d) above. For (e), interfaces have been developed for further model development.

• Suspension and Roll Centre Analysis

Vehicle suspension systems are intended to isolate the vehicle body from wheel movement and support the loads generated by vehicle manoeuvres. Its basic functionality includes [113]:

■ Reduction of vertical wheel load variations
■ Isolation of road input from the body
■ Control of transmission of handling loads to body
■ Control of wheel plane geometry due to compliant effects
■ Control of wheel plane geometry due to kinematics effects
■ Comprehension of component load environment

Modern suspension systems operate independently and are commonly specialised for their location, i.e. front/rear, driven/undriven, and steered/unsteered wheels [113]. In addition, suspension research covers several areas, such as kinematics analysis, roll centre analysis, force analysis, and anti-squat/anti-dive design [113]. Suspension roll centre is the point in the transverse vertical plane through the wheel centres at which lateral forces may be applied to the sprung mass without producing suspension roll [116]. Gillespie [115] further explained the roll centre as the virtual roll axis of suspension interaction points with the vertical planes through the centres of two wheels, Figure 2.5.12.
• **Steering System and Steady-State Cornering**

Steady state cornering is interpreted as the normal cornering status of a vehicle while it is well controlled by the driver. Steering systems generally consisting of the steering wheel shaft connected by a universal joint and vibration isolators to the steering gearbox that translates the rotation of steering wheel to the appropriate motion of the front wheels. In steady state cornering, the low speed steering angle is defined as the Ackerman Angle [116] (see Figure 2.5.13). In the high-speed situation, the Ackerman angle is usually much smaller than the turn radius, hence, the outside and inside front wheel steer angles are assumed equal. This simplified vehicle turning geometry is applied with the Newton’s Second Law for the cornering equations introduced by Gillespie [117]. The details of this turning model are presented in section 3.2.2 for the vehicle dynamic model design implemented in ST-SIM.

\[ \delta_e = \frac{L}{R + \frac{t}{2}} \]
\[ \delta_s \approx \frac{L}{(R - \frac{L}{2})} \quad (2-23) \]

Ackerman Angle: \( \delta = \frac{L}{R} \) (Assuming small angles) \( (2-24) \)

In ST-SIM, for the simulation of steady-status cornering manoeuvre, the suspension model is constructed with the attribute of front/rear stiffness and the roll centre model for the vehicle lateral acceleration and body roll angle calculation.

- **Tyres and Friction Circle**

Tyres are the interface between motor vehicle and road surface. With the exception of aerodynamic forces, the contact patches of tyres and road surfaces are the locations for all the primary control force, and disturbance forces experienced by a highway vehicle. The basic functions of tyres can then be summarized as:

1) Support the static and dynamic loads imposed on the vehicle due to its contact with the road surface.

2) Generate longitudinal and lateral forces for vehicle control.

The second function demands two key dynamic properties of tyres, i.e. their ability to transmit longitudinal traction force and lateral cornering force. In acceleration and braking, friction force is developed and sustained by the deformation of the rubber elements in the tyre tread as they deflect in contact with the road surface. This causes slip – the difference between the tyre rolling speed and vehicle travel speed in the contact patch that consequently producing the acceleration and braking force. Slip can be defined non-dimensionally as a percentage of the forward speed [118], according to:

\[ \text{Slip} \% = \left( 1 - \frac{r \omega}{V} \right) \times 100 \quad (2-25) \]

Where:
- \( r \) = tyre effective rolling radius
- \( \omega \) = Wheel angular velocity
- \( V \) = Forward velocity

The friction force is also related to the vertical load of vehicle, inflation pressure, road surface friction parameters, and speed as described in [118]. During vehicle cornering, the lateral force has two main contributors i.e. tyre slip angle and camber thrust. The slip angle is the difference
between the directions of tyre heading and travel as shown in Figure 2.5.14 [119]. The second contributor involves the camber angle emerging as the inclination of the tyre rolling at a non-vertical orientation. This produces a lateral camber thrust, as shown in Figure 2.5.15 [120].
2.6 Road Traffic Accident Investigation

2.6.1 Road Traffic Accident Data Collection

Collection of accident data involves the gathering and statistical analysis of both physical and semantic description of accident related information. Many organizations have been working in this area, including police forces and research institutes. Detailed investigation of methodologies used in data collection is beyond the scope of this project, the following points briefly summarize the various types of collected data that is needed to support accident reconstruction analyses.

Commonly in the traffic accident report, the collected data includes three catalogues:

1. **Accident Event Related Data** includes information specific to the accident event itself such as the accident date, time, and location, etc.

2. **Accident Attendants Data**, the attendants here refer to the objects involved in an accident:
   a. Human attendants' data including details of the road users (e.g. driver, pedestrian, cyclist, or motorcyclist) involved in the accident. The record typically captures the attendant's name, age, gender, injury information and his/her personal...
semantic statement relating to the accident.

b. Vehicle data including vehicle manufacturer, type, manufacture year, damage details (e.g. body collision marks, screen breakage, airbag activation, etc.) The more detailed data collection methods of research projects such as OTS [22] also includes related dynamic parameters like skid marks, steering wheel position and information from dashboard.

3. **Traffic Circumstance data** includes:
   a. Road information including the road type, road geometry, or junction type (if investigation area covers road junctions), etc
   b. Traffic controls such as road marking, traffic light, speed limitation, or speed ramp, etc.
   c. Other circumstance data including whether, roadside buildings, and road side plants, etc.

### 2.6.2 Physical Laws for Accident Reconstruction

Accident reconstruction aims to reveal the causation of accidents and the major events that took place. Two main aspects of current reconstruction work are reviewed here. One is the engineering centred aspect based on the analysis of vehicle dynamic/kinematics analysis. The main objective of this is to re-produce the vehicle’s motion and phases (i.e. status in every time step) during the accident. The second concerns injury analysis, which focuses on the accident attendants’ movement or reactions during the collision. This involves anatomy, biomechanics, and injury analysis. This section reviews the current basic physical laws of engineering aspects that used in accident research as following:

- **Constant Linear Acceleration Equations** [121]

Driving under linear constant acceleration, the following basic kinematics equations are used to relate vehicle speed, acceleration, and position [122]:

\[
v_f = v_i + at \quad (2-26)
\]

\[
v_f^2 = v_i^2 + 2a(s_f - s_i) \quad (2-27)
\]

\[
s_f = s_i + vt + \frac{1}{2}at^2 \quad (2-28)
\]

\[
s_f = s_i + \frac{1}{2}(v_i + v_f)t \quad (2-29)
\]
Where:

\[ s_i = \text{initial position (measured as the distance along the trip)} \quad \text{(m)} \]

\[ s_f = \text{final position} \quad \text{(m)} \]

\[ v_i = \text{initial velocity} \quad \text{(m/s)} \]

\[ v_f = \text{final velocity} \quad \text{(m/s)} \]

\[ a = \text{acceleration due to gravity} = 9.81 \quad \text{(m/s}^2) \]

\[ t = \text{duration in seconds} \quad \text{(s)} \]

- **The Impulse Momentum theory (IMT)[123]**

Momentum is the product of mass and velocity. If no external forces act on a system involving one or more objects, the system momentum does not change. So, in the collision of two vehicles, assuming that the friction force between tyre and road surface is small compared with the vehicles' collision force, we have following conservative equation.

\[ m_1v_{i1} + m_2v_{i2} = m_1v_{f1} + m_2v_{f2} \quad (2-30) \]

Here:

\[ v_{i1} - \text{initial velocity of vehicle 1 before collision} \quad \text{(m/s)} \]

\[ v_{f1} - \text{final velocity of vehicle 1 after collision} \quad \text{(m/s)} \]

\[ v_{i2} - \text{initial velocity of vehicle 2 before collision} \quad \text{(m/s)} \]

\[ v_{f2} - \text{final velocity of vehicle 2 after collision} \quad \text{(m/s)} \]

\[ m_1 - \text{mass of vehicle 1} \quad \text{kg} \]

\[ m_2 - \text{mass of vehicle 2} \quad \text{kg} \]

Obeying the impulse and momentum relation rule, the change of a system's momentum equals to the impulse, \( P \), acting on the system, where the impulse is defined as the product of external force acting on the system and the duration of the force. So, vehicle momentum change can be presented with following equations (2-31):

\[ m_1v_{i1} - m_1v_{f1} = m_2v_{i2} - m_2v_{f2} = P \quad (2-31) \]

From (2-31), we have

\[ v_{f1} = v_{i1} - \frac{P}{m_1} \quad (2-32) \]
\[ v_{2f} = v_{2i} - \frac{P}{m_2} \]  \hspace{1cm} (2-33)

Here:
P-impulse worked on each vehicle during the collision \(\text{N} \cdot \text{s}\)

- **Coefficient of restitution**

This coefficient relates the final vehicle velocity to its initial velocity as following:

\[ e = \frac{v_{2f} - v_{1f}}{v_{1i} - v_{2i}} \]  \hspace{1cm} (2-34)

Physically, the value of \(e\) presenting the type of impact as following:

If \(e = 1\), the impact is an Elastic Collision in which the total kinetic energy of the colliding bodies after collision is equal to their total kinetic energy before collision.

If \(e = 0 - 1\), the impact is an Elastoplastic Collision which has energy loss due to body break down or rotation, etc.

If \(e = 0\), the impact is a Plastic Collision where the colliding objects remain together after initial contact.

One of the common pre-conditions of applying IMT and the restitution coefficient in collision analysis is the external force (normally referred to the tyre-road surface friction force) is negligible compare to the impact force.

In practical research, the analysis of collisions strongly relates to the calculation of crash impulse and initial speed estimation. For example, in [122], using the kinematics equations (2-26)-(2-29), the following non-linear models in equation (2-35) is developed to predict the vehicle’s location in the road during a rear-end collision.

\[
x_k(t) = \begin{cases} 
v_k t_i, & t \leq t_{0k} \\
v_k t - 0.5a_k (t - t_{0k})^2, & t_{0k} < t \leq t_{0k} + \frac{v_k}{a_k} \\
v_k t_{0k} + \frac{v_k^2}{2a_k}, & t > t_{0k} + \frac{v_k}{a_k} 
\end{cases}
\]  \hspace{1cm} (2-35)

Where \(t_{0k}\) is the time at which driver \(k\) began braking. The initial speed vehicle was assumed to be
travelling at a constant speed $v_k$. After coming to a stop at time $t_0+k\frac{v_k}{a_k}$ the vehicle's location remained unchanged, and $a_k$ is the braking deceleration. In order to evaluate the influence of these parameters, reference to the driver's headway and reaction time to the collision, the Markov Chain Monte Carlo (MCMC) program WinBUGS is used to compute Bayes estimates of them equation (2-35). The comparison of outputs generated by the different initialization driver parameters with real data revealed that other drivers in the traffic flow prior to the collision vehicle might also have contributed to the accident.

As shown above, the engineering approach provide good foundation in reveal what happened in the accident, however, to understand what caused an accident, the human factors like driver psychology and behaviour research is beyond the coverage of physical principles introduced above. By integrating driver decision and vision models with the models from engineering aspects (i.e. vehicle dynamics and road network models), ST-SIM makes the accident reconstruction work start 'earlier' before the collision time, which means the reconstruction of human decision process and the influence factors before the accident.

### 2.6.3 Driver involvement

Road Traffic Accidents (RTAs) can be described as those situations where normal traffic fails caused by either driver or physical (i.e. vehicle and road situation) factor. Common approaches in driver behaviour research usually rely on the questionnaire and statistic results to identify these factors. As in [124], aberrant driver behaviour's relationship to the crash involvement was investigated using Driver Behaviour Questionnaire (DBQ), 28 items in four catalogues (error, lapse, violation and aggressive violation) and their correlation with crash involvement are measured. The results are showing that in crash prediction, errors and lapse factors are significant predictors of crashes. Furthermore, the errors factor is predictive of both active and passive crash involvement. In Germany, Barbara [125] applies the Hypermasculinity Inventory (HMI) [126] as a measure of macho personality, and DBQ to measure the aggressive driving. The measured results are used to evaluate the role of macho personality, age, and power of car as predictors of aggressive driving behaviour. Barbara's work reveals aggressive driving is significantly more common among younger drivers, drivers endorsing a macho personality pattern, and drivers owning high-performance cars. Compare with these questionnaire based research work. ST-SIM concentrates on the driver's decision process right before the accident to reveal the key factors that influencing driver's action. Instead of relying on the questionnaire-based methodology, the integrated models can provide the virtual collision avoidance scenario to investigate the different behaviour patterns among the drivers with different driving experience [19]. This provides a flexible platform to investigate the factors influencing driver decision and behaviour. Hence, ST-
SIM's application in accident reconstruction work can provide a powerful tool helping the experts' investigation work.

2.7 Chapter Summary

This chapter has reviewed a broad range of knowledge underpinning the development of ST-SIM. It covered the knowledge literature of traffic flow theories in Microscopic/Macroscopic view, driver behaviour research, road network model with reference to FE method, and basic vehicle dynamics theories. In addition, the accident reconstruction topics are introduced in the final section.

In macroscopic, scientists simulate the traffic flow based on the fluid dynamic theories from macroscopic point of view; in microscopic, scientists proposed the traffic model theories of Car Follow ing, Cellular Automation, and Three-Phase Hypothesis. Based on the microscopic work, the agent-based modelling methodology is applied to the simulation work. In road network modelling, the high accuracy geometrical description of road network is required in our project to incorporate with the vision model developed by previous researchers. The FE method is introduced for the road geometrical shape and surface description and the selected basic concepts of road network design in transportation research are reviewed. In vehicle modelling, this chapter introduces the basic components of vehicle structure (i.e. vehicle body, suspension, tyre, and steering system) and related dynamic concepts. In the driver psychology and behaviour research, this chapter introduced the three main branches existing now, i.e. risk-related, task-capability and theory of planned behaviour. In the accident investigation, this chapter reviews the data collection, basic physical principles, and driver involvement research. Based on above knowledge, it reveals the opportunity to construct an integrated traffic simulation framework-ST-SIM.

Compare with the traditional traffic flow simulation, the sub-models in ST-SIM can construct a virtual traffic environment. The simulation framework separates the driver and vehicle in the traffic flow and adopts the Perceive – Decide – Act loop in driver model (see section 2.5.2). This step greatly expands the research scope of in traffic modelling. Because it enabled the investigation of driver's different behaviour and decisions due to the different perception capability and human characteristics.

In the accident research, the previous work has focused almost entirely on identifying significant factors predicting accident rates. In addition, commonly used performance limits on information-processing tasks as predictors, it implicitly assumes that pre-crash behaviour represents the limiting capabilities of drivers. The questionable validity of this assumption and the restricted
focus on the range of behaviour that may precipitate crashes are likely reasons for the lack of success of efforts to identify predictors of safe driving. ST-SIM virtual environment may reconstruct the accident involved traffic scenario based on the basic models from driver, vehicle, and road design area. It provides the opportunity to investigate different influencing factors in driver decision process.
3 Synthetic Traffic SIMulation (ST-SIM)

Framework Analysis and Design

3.1 Introduction

The overall structure of ST-SIM is divided into three core modules: Driver, Vehicle, and Road Network. Each module corresponds to a distinct area of traffic related research/practice, and as shown in Figure 3.1.1, consists of different models and interfaces between modules.

Figure 3.1.1 shows the overall structure of ST-SIM, identifying the key component models in each module. To maintain clarity in the system design and to ensure objective development of each component and the framework, each model only contains a decided level of fundamental functionality. Figure 3.1.1 also summarizes the external interfaces between the agents, highlighting the type of information that is exchanged.

This chapter is concerned with the design of this framework starting from the broad knowledge
base outlined in Chapter 2 and the previous research work [2][9]. The following part is divided into three sections, section 3.2 for the framework components analysis and design, section 3.3 introduces the interfaces of the simulation framework, and section 3.4 summarises this chapter.

3.2 Framework Components Analysis and Design

This section reviews the engineering and semantic theory built into the ST-SIM component models. In the driver agent, this includes a discussion of previous work on the vision model and the decision making model along with their further development in this project. This section also covers assembly of component theory in the vehicle model and the methods for shape and geometry definition for road segments.

3.2.1 Driver Module

As shown in Figure 3.1.1, the driver module currently consists of vision, decision, and action models, it includes the basic components for the driver's perceive-decision-action behaviour loop shown in Figure 2.5.1. This apparently simple loop can be put into a broader context of driver behaviour as shown in Figure 3.2.1. Based on this context, ST-SIM implemented the key elements including image capture, pixel map analysis, the simplified rule based decision and vehicle control.
In the behaviour loop, vision model captures the objects including road, and other vehicles information. The human factors of driving experience, physical and mental wellbeing, etc, are introduced and may influencing the information extraction such as distance and relative speed estimation, etc, for decision-make. In application, ST-SIM implemented the driving experience variable in the simulation loop as in [19]. The decision process is based on the developed Computational Model of Psychology Driven Decision-Making (PsyDS). Previewed driver behaviour models are referenced in the decision process design. For the vehicle control action, basic orders (i.e. slow down/speed up and steering) are sent to vehicle module for the vehicle movement control. The human control models is now simplified as the control instructions directly send to the vehicle model triggering the update of vehicle dynamics and kinematics status in implementation.

### 3.2.1.1 Vision Modelling

A previous project [20] introduced a vision model as a precursor to driver decision making. In contrast to 'perfect vision' where drivers share accurate information about other vehicles and the road network, the vision model enables drivers 'see' by estimating the position and orientation of other objects. In doing this, driver agents become less certain (more realistic) in their perception of...
their environment. The underlying assumption is the driver's visual interaction with traffic environment can be abstracted to the key process of object detection (i.e. an image capturing process), followed by simple visual information extract to estimate object position and speed. Comparing with the traditional statistics based driver psychology/behaviour models introduced in section 2.5.4. The adoption of a vision model in ST-SIM is the first step to investigate how drivers interact with their environment and interpret the captured information (i.e. visual image) for decision-making.

3.2.1.1.1 The image capturing process

In the original eye design shown in Figure 3.2.2, the visual capability of each driver agent is based on simple vector analysis and ray tracing. The vision model consists of two 'artificial eyes' each represented as a two dimensional matrix of cells consisting of n rows and m columns. Rays are projected from a retinal point, behind the matrix, through each cell and into the environment. Using equation (3-1) for each ray, the corresponding is assigned a binary value of '1', if the ray intercepts an object. Otherwise, it is assigned a binary '0'. When carried out through succeeding time steps, this produces different 2D binary patterns because of object movements and changes in orientation.

Figure 3.2.2 Relationships between eyes, rays, and planes []

The ray and object surface interaction was calculated with following function:

\[
\begin{align*}
t & = \frac{D - n \cdot a}{n \cdot b} \\
& \text{Here, } D = n \cdot P_i \text{ is the plane data describing an object surface.} \\
& n \text{ The surface outward normal vector with components } (n_1, n_2, n_3) ; \\
& P_i \text{ A point along each ray with coordinates } (x_i, y_i, z_i), \text{ measured from the "retina" of each eye;}
\end{align*}
\]
Chapter 4 Software Development for ST-SIM

\[ t \] the intersection parameter of each ray on the object surface;
\[ a, b \] Position and direction vectors of each ray.

3.2.1.1.2 Visual information Extraction

The original process of estimating apparent speed, distance, and direction of motion is achieved using a 16-plane visual memory scheme to store consecutive images, see Figure 3.2.3. Each memory plane is associated with a tag used to extract encoded information from the planes so that specific visual functions can be performed. Various cognitive processes (e.g. focus of attention, anticipation, or learning) associated with driving can also be achieved based on comparing image patterns between consecutive memory planes.

![Eye Structure](image)

\[ r_1, \ldots, r_n = \text{Right eye rays} \]
\[ r_l, \ldots, r_n = \text{Left eye rays} \]
\[ R, R' = \text{Focal point or 'retina' for left and right eye respectively} \]
\[ a_l, a_r = \text{Position vectors of left and right eye} \]
\[ H = \text{Centre of the head about which it can rotate} \]

Figure 3.2.3 Eye Structure

This overall approach to above vision modelling has two limitations. Firstly, it uses the actual interaction points' position for object distance estimation, which is similar to the 'perfect vision' in sharing object position information between drivers. Secondly, the disparity based distance estimation [127] algorithm proposed was not implemented due to the computing power bottleneck that develops with the need for increasing accuracy. Hence, as discussed in the next section, a pixel map based distance and relative speed estimation method has been implemented, along with a new stereo matching method.

3.2.1.1.3 Pixel Map Based Analysis

The basic pixel based vision model discussed in the previous section has been enhanced to include the following

- Distance estimation
Relative speed estimation

Steering angle estimation

Stereo match and Collision detection

Colour perception and Traffic sign information retrieval

Distance estimation

For distances less than around 100 feet, distance can be estimated by comparing the minor difference of objects' positions in images captured by the right and left eye (i.e. disparity) [127]. The realization of this methodology requires accurate image generation with high resolutions to present the difference. For distances beyond 100 feet, the disparity is almost invisible [127]. In this scope, distance estimation is based on monocular cues such as familiar size (i.e. compare the object size in memory with its size in distance), occlusion (i.e. the nearer object may cover the object behind it in image), size perspective (i.e. similar objects nearer to the eye appear bigger in size), etc [127]. ST-SIM uses these cues to set up the pixel based distance estimation. As shown in the following Figure 3.2.4.

![Figure 3.2.4 Pixel map based distance estimation](image)

Figure 3.2.4 shows the driver's view on a straight road segment following one vehicle in the same lane, the estimated distance is based on the number of pixel rows starting from the bottom of front vehicle to the image bottom. Similarly, the driver preferred forward distance range is also defined by some number of rows. Comparison of these estimates with preferred forward distance range is used to trigger various driver actions.

Relative speed estimation

The relative speed (i.e. the speed difference of observed objects and the subject vehicle) is also estimated by X and Y pixel differences of objects in successive images divided by the time difference between the images, as shown in Figure 3.2.5.
Steering angle estimation

As shown in Figure 3.2.6, the vision based steering angle estimation algorithm in ST-SIM uses pixel counting and maintenance of the PL/PR ratio.

Assuming a driver starts from position O in cross section 1, to maintain the pixel ratio in the foreseen cross section 2, the driver needs to steer the vehicle follow the direction OC. The direction difference of vector OC and current speed direction is the driver's anticipated yaw angle and is used to estimate the steering angle input.
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- Stereo matching and Collision detection
A further extension of the original vision model is that ST-SIM implemented the eye facets/cells to store object IDs and the ray interception point with the object surface. This simplifies stereo matching to the comparison of captured object IDs in each eye. Also, object collision estimates are obtained by simple distance calculation using the captured interaction points. The nearest captured points will eliminate other record points in the same ray that is actually blocked by it in the scene (e.g. the road surface under the vehicle).

- Colour perception and Traffic control information retrieval
The objects' colours in ST-SIM are perceived by identifying the colour IDs embedded into the media, such as traffic signs or light signal. Traffic control information like speed limitation, stop light, or road number were also coded into IDs. Similar to the stereo match, the vision model capture the object IDs of them and extract the information IDs for drivers decision make. In this context, ST-SIM implemented the stop sign and traffic light status in simulation loop. More comprehensive colour based information extraction is left as further work.

3.2.1.2 A Computational Model of Psychology Driven Decision-Making (PsyDS)

The way in which selected aspects of driver behaviour are modelled in ST-SIM was initially proposed to follow the Finite State Machine approach in PsyDS (See APPENDIX A Decision Making Data-Flow Diagram) [refs], using six state transition rules as follows:

- Slow down
- Speed up
- Maintain minimum headway
- Maintain minimum rear distance
- Maintain position within lane
- Change to preferred lane

These rules receive information from driver vision at each time step in the simulation, using this to determine the driver's next action on changing speed and direction. The six rules are common to all drivers; however, each rule has a weight (importance) which can be set independently for each driver. Each driver also has two sets of driving parameters; one is 'current', i.e. defining the current state of the driver on the road. The other is 'preferred', which defines the driver's desired state on the road. Both sets of parameters are combined with vision data to calculate the relevance of each rule as it occurs in that drivers’ specific situation. The rules
are then ordered into descending importance of relevance. A ‘rule usage’ value is calculated for each rule, as the product of relevance, weighting, and a random factor. The rule with the highest usage determines the driver’s action, with the random factor allowing for some degree of uncertainty in decision-making. The rules and parameters together provide a pragmatic but robust method of prescribing driver behaviour at the level of their interactions with immediate neighbouring vehicles. By selecting different weights (levels of importance) for each rule, it is possible to specify a wide range of driver attitude and behaviour.

Rather than simply transferring this decision making model from PsyDS into ST-SIM, it has been re-designed to be a summary of various factors and issues discussed in the previous chapter. This re-design has provided a software structure for the driver model that can easily be expanded to introduce a wide range of psychological factors, as discussed in the next section.

**3.2.1.3 ST-SIM Driver Model Analysis and Design**

The broader context for the driver decision-making model implemented in ST-SIM is shown in Figure 3.2.7. In addition to allowing continued use of the original rules in PsyDS, this context enables a wide range of driver models, based on the driver psychology and behaviour reported in the previous chapter, to be developed in the future. This section provides an overview of the designed context of how new aspects of driver behaviour can be introduced.
Figure 3.2.7 ST-SIM Driver Decision-Behaviour Context

Figure 3.2.7 is the context encapsulating the structure of driver decision-behaviour process in ST-SIM with the current ST-SIM implementation mainly covered the shaded frame. The whole context provides many feedback paths that enable driver behaviour to be influenced by internal (personal) and external (traffic situation) factors.

Considering the personal factors, the approach proposed by the rule based PsyDS model is an opportunity to look into the driver’s decision process and reveal the potential factors may influence his behaviour. In PsyDS, the rule relevance is determined by using the driver’s current state and the current states of the other vehicles in the simulation. The rule weight is specified prior to commencing the simulation allowing each driver to be prescribed a rudimentary ‘personality’ or driving style [9]. In designing ST-SIM driver agents, there has been an opportunity to explored how rule weight and relevance may represent or summarize a wide range of factors that influence how basic vehicle control actions (i.e. deceleration/acceleration and steering) arise as a consequence of perception and decision making. The driver decision model should be influenced by personal factors such as age, gender, social background, etc, perhaps implemented through some form of rule-based definitions. Accounting for this at the design stage has allowed the implementation of a driver-modelling framework in ST-SIM that allows many influences to act on the detail of the Perceive – Decision – Action loop within the driver.
In designing the Driver Preference and Driver Action sections of Figure 3.2.7, another challenge has been to translate between qualitative driver decision making and quantitative control of the vehicle. In order to link the influencing factors with the vehicle control action, the concepts of vehicle handling error tolerance (VHT) and vehicle feedback tolerance (VFT) are defined to provide the investigation scenario for human/non-human factors influencing driver/vehicle interaction (see Figure 3.2.8 and Table 3.2.1). In the context of vehicle handling and driver preference loop, ST-SIM implemented the shaded elements. The blank elements are simplified in current implementation. For example, the brake pad/throttle levels are abstract as the experiment based deceleration/acceleration values directly send to vehicle models.
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Figure 3.2.8 ST-SIM driving preference and vehicle handling loop context
<table>
<thead>
<tr>
<th>Elements Name</th>
<th>Description</th>
<th>Possible Related Human Factors</th>
<th>Possible Related Non-Human factors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle Handling</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Error Tolerance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direction</td>
<td>The angle between vehicle travelling direction and anticipated direction</td>
<td>Age, gender, driving experience, driving intention</td>
<td>Current vehicle speed, Road situation (e.g. lane width, boundary painting...)</td>
</tr>
<tr>
<td>Relative speed</td>
<td>speed-the vehicle travelling speed relative to driver selected reference object (e.g. front vehicle)</td>
<td>Age, gender, driving experience, driving intention</td>
<td>Weather, current vehicle speed, road situation</td>
</tr>
<tr>
<td>Distance</td>
<td>distance to the selected object (e.g. lane boundary) in the traffic circumstance</td>
<td>Age, gender, driving experience, driving intention</td>
<td>Weather, current vehicle speed, road situation</td>
</tr>
<tr>
<td><strong>Vehicle Feedback</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tolerance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yaw Angle</td>
<td>Angle of vehicle body yaw due to the driver steering action</td>
<td>Age, driving experience, gender, mental wellbeing, physical condition, driving intention</td>
<td>Vehicle condition, road situation</td>
</tr>
<tr>
<td>Yaw Velocity</td>
<td>Change ratio of vehicle body yaw angle in sample time step</td>
<td>Age, driving experience, gender, mental wellbeing, physical condition, driving intention</td>
<td>Vehicle condition, road situation</td>
</tr>
<tr>
<td>Roll Angle</td>
<td>Roll Angle of vehicle body due to vehicle turning manoeuvre as the response of driver steering action.</td>
<td>Age, driving experience, gender, mental wellbeing, physical condition, driving intention</td>
<td>Vehicle condition, road situation</td>
</tr>
<tr>
<td>Roll Velocity</td>
<td>Change ratio of vehicle body roll angle in sample time step.</td>
<td>Age, driving experience, gender, mental wellbeing, physical condition, driving intention</td>
<td>Vehicle condition, road situation</td>
</tr>
<tr>
<td>Acceleration Force</td>
<td>Force work on driver body due to vehicle acceleration</td>
<td>Age, driving experience, gender, driving intention</td>
<td>Vehicle condition, road situation</td>
</tr>
<tr>
<td>Deceleration Force</td>
<td>Force work on driver body due to vehicle deceleration</td>
<td>Age, driving experience, gender, driving intention</td>
<td>Vehicle condition, road situation</td>
</tr>
<tr>
<td>Speed Meter</td>
<td>Speed value read from the speed meter.</td>
<td>Age, driving experience, gender, driving intention</td>
<td>Vehicle condition, road situation</td>
</tr>
</tbody>
</table>

Table 3.2.1 VHT and VFT Elements Definition
3.2.2 Vehicle Steady State Handling Dynamics

The current simulation of vehicle manoeuvres in ST-SIM covers common driving behaviour, including lane following, slow down/speed up, and steady state turning. The steady state vehicle handlings investigate includes two main situations: 1) low-speed turning and 2) high-speed cornering. The former has been introduced in section 2.5.6.3 with the concept of Ackerman turning geometry. This section introduces the High-speed cornering manoeuvre in ST-SIM. The cornering equation is defined as:

\[ \delta = 57.3 \frac{L}{R} + \left( \frac{W_f}{C_{of}} - \frac{W_r}{C_{or}} \right) \frac{V^2}{gR} \]  

(3-2)

where:
- \( \delta \) = Steer angle at the front wheels (deg)
- \( L \) = Wheelbase (m)
- \( R \) = Radius of turn (m)
- \( V \) = Forward speed (m/sec)
- \( g \) = Gravitational acceleration constant = 32.2 m/sec²
- \( W_f \) = Load on the front axle (lb)
- \( W_r \) = Load on the rear axle (lb)
- \( C_{of} \) = Cornering stiffness of the front tyres (lb/deg)
- \( C_{or} \) = Cornering stiffness of the rear tyres (lb/deg)

The tyre cornering stiffness \( C_a \) for each tyre is load dependent and defined as:

\[ C_a(w) = c_1 \left( 1 - e^{-c_2 w} \right) \]  

(3-3)

Where
- \( c_1, c_2 \)-cornering stiffness parameters \((6.88 \times 10^4, 7.17 \times 10^4)\)

In simplified form (3-2) can be written as:

\[ \delta = 57.3 \frac{L}{R} + K a_y \]  

(3-4)

where:
- \( K \) = Understeer gradient (deg/g)
$a_y = \text{Lateral acceleration (g)}$

The *understeer gradient* represents the variation of steering angle to negotiate with the turning curve in relation to the turning speed or lateral acceleration. Three situations exist:

- **Neutral Steer**, when the understeer gradient $K=0$ (i.e. $\frac{W_f}{C_{af}} = \frac{W_r}{C_{ar}} \rightarrow \alpha_f = \alpha_r$). Here, $\alpha_f$ and $\alpha_r$ correspond to the front and rear wheel slip angles. Physically, this means the steering angle input on the front wheel is independent of the vehicle turning speed due to the identical variation of slip angles on both front and rear wheels generated by the lateral acceleration acting on the centre of gravity.

- **Understeer**, when the understeer gradient $K>0$ (i.e. $\frac{W_f}{C_{af}} > \frac{W_r}{C_{ar}} \rightarrow \alpha_f > \alpha_r$). In this case, when the vehicle accelerates in a constant radius turn, the driver must increase the steer angle input, or the turning radius will increase if steering angle is fixed. The lateral acceleration causes a bigger slip angle at the front wheels than at the rear wheels, which consequently requires larger lateral forces (i.e. steer angle) at the front wheel to maintain the turning radius.

- **Oversteer**, when the understeer gradient $K<0$ (i.e. $\frac{W_f}{C_{af}} < \frac{W_r}{C_{ar}} \rightarrow \alpha_f < \alpha_r$). In contrary to the understeer case, oversteer is caused by a larger slip angle on the rear wheels than the front wheels due to the lateral acceleration force on the centre of gravity. The driver has to reduce the front steer angle input to diminish the rear outward drift and maintain the constant turning radius; otherwise, upon the same steer angle and the forward speed, the turning radius will be smaller than the neutral steer.

With the Steady-State Handling model, the Yaw Velocity, Lateral Acceleration, and Vehicle Body Roll Angle are calculated as follows:

- **Yaw Velocity Gain**

  The yaw velocity $r$ of a steady-state turning vehicle is decided by the ratio of its forward speed $V$ to the turning radius $R$, and the yaw velocity gain $G_{yaw}$ is counted as the ratio of the steady-state yaw velocity to the input steer angle at the front wheels as following:
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\[ G_{\text{yaw}} = \frac{r}{\delta} = \frac{V}{L + KV^2 / g} \]  

**Lateral Acceleration Gain**

The lateral acceleration is the main purpose for steering a vehicle, its ratio to the steer angle is defined as the Lateral Acceleration Gain, and it is given as:

\[ G_{\text{acc}} = \frac{V^2 / gR}{\delta_f} = \frac{a_y / g}{\delta_f} = \frac{V^2}{gL + KV^2} \]  

**Vehicle Body Roll Angle**

The vehicle roll centre during a turning manoeuvre was introduced in section 2.5.6.3 (see Figure 2.5.12). The virtually defined roll axis connects front and rear roll centres to obtain the roll moment distribution of the vehicle, induced from the moment equation. The roll angle \( \phi \) is given as:

\[ \phi = \frac{Wh_i V^2 / (Rg)}{K_{\phi} + K_{\phi} - Wh_i} \]  

where

- \( W \) = Vehicle Load
- \( h_i \) = height of vehicle roll centre
- \( K_{\phi} \) = front suspension roll stiffness
- \( K_{\phi} \) = rear suspension roll stiffness

The roll rate \( R_{\phi} \) may be obtained by differentiating equation (3-7) with respect to the lateral acceleration, giving equation (3-8).

\[ R_{\phi} = \frac{d\phi}{da_y} = \frac{Wh_i}{[K_{\phi} + K_{\phi} - Wh_i]} \]  

The fundamental dynamic/kinematics models described above are incorporated into ST-SIM, interacting with the Driver and Road Network models.
3.2.3 Road Network Modelling

This section introduces details of the road network system in ST-SIM, including the geometry and traffic control objects modelling. Due to the needs of the vehicle and driver models in ST-SIM, the road network model has to provide much detail and accuracy. ST-SIM relies on available computing performance to achieve exactly the data required at the time.

3.2.3.1 Road Boundary Curve Interpolation Algorithms

The commonly applied Spline interpolation algorithm for curve description in engineering is used for road boundary description. This section introduces the Spline interpolation methods [128] used for the road boundary generation.

- **Spline Description of Road Boundary**

Spline methods in Engineering describe curves using interpolation functions that pass through points on the curve. The points through which the curve passes are known as *nodes* or *control points*.

*Hermitian Spline* functions are used to interpolate smoothly between nodes. They enable a curve to be drawn when nodes, as well as their derivatives, are specified (see Figure 3.2.9). This characteristic enables *Hermitian Splines* to maintain C1 continuity (i.e. the continuity of derivatives at neighboured node).

![Sample Hermitian Spline](image)

Figure 3.2.9 Sample Hermitian Spline

Assuming the function of this curve is:

$$H(s) = as^3 + bs^2 + cs + d \quad (3-9)$$

Where $s$ is the parameter range from 0 to 1 and presenting the portion of desired points $P_s$ on the
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curve from P1 to P2 in Figure 3.2.9. The first order derivative is:

\[ H_f(s) = 3as^2 + 2bs + c \]  \hspace{1cm} (3-10)

Using the boundary conditions:

\[ H(1) = a + b + c + d \]  \hspace{1cm} (3-11)
\[ H(0) = d \]  \hspace{1cm} (3-12)
\[ H(I) = 3a + 2b + c \]  \hspace{1cm} (3-13)
\[ H(0) = c \]  \hspace{1cm} (3-14)

Solving the above function for a, b, c, d, and we can have 4 Hermite Basis functions.

\[ H_{10}^1(s) = 2s^3 - 3s^2 + 1 \]
\[ H_{02}^1(s) = -2s^3 + 3s^2 \]
\[ H_{11}^1(s) = s^3 - 2s^2 + s \]
\[ H_{12}^1(s) = s^3 - s^2 \]  \hspace{1cm} (3-15)

In \( H_m^i(s) \), m is the order of the derivative, i designates either start or end node of the Spline segment, and n represents the nth-order Hermite polynomial which is a polynomial of order 2n+1.

The algorithm can be expressed with vector and matrix algebra as following:

\[ S = \begin{bmatrix} s^3 \\ s^2 \\ s^1 \\ 1 \end{bmatrix}, \quad C = \begin{bmatrix} P_1 \\ P_2 \\ T_1 \\ T_2 \end{bmatrix}, \quad H = \begin{bmatrix} 2 & -2 & 1 & 1 \\ -3 & 3 & -2 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \]  \hspace{1cm} (3-16)

Where:

- Vector S: The interpolation-point and its powers up to 3:
- Vector C: The parameters of Hermite curve:
- Matrix H: The matrix form of the 4 Hermite polynomials:

To calculate a point on the curve we build the Vector S and multiply it with the matrix H and Vector C.
Furthermore, the Catmull-Rom Spline functions are implemented in ST-SIM to remove the need of tangent values, saving real measurement work.

In a Catmull-Rom Spline, the tangent $T_i$ at knot $i$ is defined as:

$$T_i = 0.5(P_{i+1} - P_{i-1})$$

(3-18)

Hence, given the control points $P_0, P_1, P_2,$ and $P_3$ (see Figure 3.2.10) and the value $t$, signifying the portion of the distance between the two nearest control points, the location of a point, $P$, can be calculated as (assuming uniform spacing of control points):

$$P = 0.5 \ast S \ast H \ast C_p$$

(3-19)

where

$$C_p = \begin{bmatrix}
    P_1 \\
    P_2 \\
    P_3 \\
    P_4 
\end{bmatrix}$$

(3-20)

Figure 3.2.10 Catmull-Rom Spline

Because a segment requires control points to the outside of the segment endpoints, the segments at the extreme ends of the Spline cannot be calculated. Thus, to define $S$ segments, $S+3$ control points are required. This algorithm enables us to draw the road bound shapes without the tangent values of the control points.

- **Coordinate Transformation System**

Coordinate transformation can be achieved by the rotation of local coordinate system $x$-$y$ with angle $\theta$ and then translation of the origin to the point $(x_0, y_0)$, see Figure 3.2.11.
Hence, the following matrix algebra can be used to represent the transformation:

\[
\begin{bmatrix}
  x \\
  y
\end{bmatrix} =
\begin{bmatrix}
  \cos(\theta) & -\sin(\theta) \\
  \sin(\theta) & \cos(\theta)
\end{bmatrix}
\begin{bmatrix}
  x' \\
  y'
\end{bmatrix} +
\begin{bmatrix}
  x_0 \\
  y_0
\end{bmatrix}
\]  

(3-21)

or simplify as:

\[ P_n = TP_n' + P_0 \]  

(3-22)

By Substituting (3-22) into (3-19), in the horizontal map of road geometry, any boundary curve can be defined as follows:

\[ P = 0.5 \times S \times H \times C_{\text{TP}} \]  

(3-23)

where

\[
C_{\text{TP}} =
\begin{bmatrix}
  P_1 \\
  P_2 \\
  P_3 \\
  P_4
\end{bmatrix} =
\begin{bmatrix}
  TP_1' + P_0 \\
  TP_2' + P_0 \\
  TP_3' + P_0 \\
  TP_4' + P_0
\end{bmatrix} =
\begin{bmatrix}
  T & 0 & 0 & 0 & P_0 \\
  T & 0 & 0 & 0 & P_0 \\
  T & 0 & 0 & 0 & P_0 \\
  T & 0 & 0 & 0 & P_0
\end{bmatrix}
\]

\[ P' = M_T P_T \]  

(3-24)

here \( o \) stands for the column vector of zero that has same dimensions as \( P_n \) (i.e. Spline nodes) and \( M_T \) is independent of the Spline nodes \( P_T \).
3.2.3.2 Road Network Structure

The general structure of the ST-SIM road network is shown in Figure 3.2.12. The network is a hierarchy consisting of segments, divided into surfaces to enable mesh generation.

A three-step methodology is designed in ST-SIM for road network construction.

1. **Load OTS map** of the investigated road segments for raw geometry data collection. The basic points (i.e. nodes) coordinates for road geometry interpolation will be picked out from the OTS map loaded into ST-SIM.

2. **Road Segment Division.** Based on the map of the investigated road segment, the road segment are divided into surfaces with unique Surface IDs, the lanes within each surface are
also initialized with Lane IDs to help define a driver's route (see Figure 3.2.13). As required in common driving behaviour, driver's route choices are accomplished by the selection of road (e.g. A512) and then the required lane (e.g. middle lane). In ST-SIM, the route following is based on the match of aimed lane ID in the right surface (i.e. planned surface IDs).

Figure 3.2.13 Sample T-Junction Division

3. Road Surface Mesh Generation
As shown in Figure 3.2.14, a hierarchical approach is used to create the road surface mesh, where element size and density can be changed considering the complexity of the road geometry. For example, in segment B, the mesh is achieved by the division of mesh A. The balance between computing time and geometrical accuracy level is the main consideration for mesh density selection.
3.2.3.3 Traffic Control Objects

In the current design, generally, all TCOs in ST-SIM have three basic attributes:

1) **Position**-globally defined in a three-dimension coordinate system as part of the road network geometric plan.

2) **Information**-the information such as speed limitation or ‘Give-way’ carried by the TCO is obtained by the driver once they have seen the TCO ID through their vision model.

3) **Corresponding Road**- since drivers in ST-SIM detect all the TCOs in their visual field, it requires the ability to separate the TCOs that apply to a current lane or route in a trip plan from other objects. In ST-SIM, this information is embedded in TCOs and can be extracted by the driver model.
3.3 ST-SIM Interfaces Analysis

Three interfaces layers (see Figure 3.3.1) are embedded in ST-SIM serving different communicating actors:

a) **External Layer**, provides communication channels for simulation framework with external entities including databases (currently using plain data file), traffic investigators, and other software developers.

b) **Middle Layer**, bridges the different modules in ST-SIM. The exchange of data necessarily held in different formats within models requires proper filtering and re-formatting during communication.

c) **Inner Layer**, which is the communication layer for ST-SIM agents to ensure their synchronisation during the simulation.

Following sub-sections will introduce the design of these interface layers.

![Figure 3.3.1 Layer Structure of ST-SIM Interfaces](image-url)
3.3.1 External Interfaces

The external interfaces (outer layer in Figure 3.3.1) mediates ST-SIM's communication with external entities, it takes the responsibilities of transfer user input, raw data process for simulation scenario setup, and post-modelling results output. The system API for software developers is also placed in this layer. These tasks are accomplished by four sub-interfaces:

a) Graphic User Interface (GUI)
In ST-SIM development, the GUI design is based on the requirements of traffic scenario reconstruction and results display as shown in Table 3.3.1. The GUI design serves for the accident investigation.

b) Input Database connection
As shown in Table 3.3.1, constructing a traffic scenario involves a significant amount of data defining vehicles, drivers, and road networks, it is appropriate for ST-SIM to access a database and to provide appropriate automation of various initialisation tasks. Since detailed database development is not part of this project's objectives, a simple plain data file based approach has been used to help identify the following basic database functionality:

- Retrieve accident scene terrain for road network reconstruction
- Process geography data for road geometry reconstruction and traffic controls specification.
- Access driver and vehicle files and distil required data for traffic scenario initialization

c) Post simulation translation
Since the efficient storage and processing of ST-SIM simulation results is demanding in terms of the volume of data and data dependencies, various qualitative and quantitative techniques have been developed for their investigation. This has required the design task to include an interface that packages simulation results in different ways. As with the input database, in current stage, this has been implemented using plain files, corresponding to the investigated objects’ outputs as shown in Table 3.3.2. In general, the basic future tasks for post simulation involve:

- Generation of graphs and diagrams showing kinematics and/or dynamic vehicle performance
- Interpretation of driver behaviour in the simulation in terms of various aspects of human factors’, including the influence of changes in driver model parameters on their behaviour
- Adequate presentation of the road network geometry, especially for accident reconstruction
<table>
<thead>
<tr>
<th>Requirements</th>
<th>Objectives</th>
<th>Interface Users</th>
<th>Realized In Program</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstruct road geometry.</td>
<td>• Define driving routes</td>
<td>• Traffic Investigator • Road network module • Driver module</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>• Provide geometry spaces for objects position and tracking</td>
<td>• Traffic Investigator • Road network module • Driver module • Vehicle module</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>• Provide direction reference for drivers</td>
<td>• Traffic Investigator • Driver module</td>
<td></td>
</tr>
<tr>
<td>Setup traffic controls (i.e. road marks, traffic lights)</td>
<td>• Control traffic flow</td>
<td>• Traffic Investigator • Road network module • Driver module • Vehicle module</td>
<td>Stop light and Giveaway Sign</td>
</tr>
<tr>
<td></td>
<td>• Provide speed/direction control reference for drivers</td>
<td>• Traffic Investigator • Driver module</td>
<td>Yes</td>
</tr>
<tr>
<td>Initialize Vehicles</td>
<td>• Initialize vehicle position/speed</td>
<td>• Traffic Investigator • Vehicle module</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>• Select/Setup vehicle dynamics parameters</td>
<td>• Traffic Investigator • Vehicle module</td>
<td></td>
</tr>
<tr>
<td>Initialize Drivers</td>
<td>• Input driver personal information (i.e. name, gender, age, and occupation)</td>
<td>• Traffic Investigator • Driver module</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>• Select/Setup rule-based driver characters</td>
<td>• Traffic Investigator • Driver module</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>• Initialize Vision model (i.e. eye pixel resolution)</td>
<td>• Traffic Investigator • Driver module</td>
<td>Yes</td>
</tr>
<tr>
<td>Simulation Results Display</td>
<td>• Post Simulation Analysis</td>
<td>• Traffic Investigator</td>
<td>Plain output data file provide for diagram drawing and 3D Scene construction</td>
</tr>
<tr>
<td>3D Scene Display</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.3.1 ST-SIM GUI requirements analysis
### Initialization Parameters

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Initiative Parameters</th>
<th>Simulation Outputs (in each simulation time step)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Vehicle ID</td>
<td>• Speed</td>
</tr>
<tr>
<td></td>
<td>• Speed</td>
<td>• Position</td>
</tr>
<tr>
<td></td>
<td>• Position</td>
<td>• Longitudinal/Lateral acceleration</td>
</tr>
<tr>
<td></td>
<td>• Shape (Width, Height, Length, Frontal Area)</td>
<td>• Yaw angle/speed</td>
</tr>
<tr>
<td></td>
<td>• Dynamic Parameters (e.g. Engine Power, total weight at front/rear axle, height of mass centre above ground, etc.)</td>
<td>• Roll angle</td>
</tr>
<tr>
<td>Driver</td>
<td>• Driver ID</td>
<td>• Preferred speed</td>
</tr>
<tr>
<td></td>
<td>• Driving rule set (preferred parameters for driving rules)</td>
<td>• Preferred driving direction</td>
</tr>
<tr>
<td></td>
<td>• Vision system parameters (e.g. eye pixel resolution, horizontal/vertical visual angle, and looking direction, etc.)</td>
<td>• Vision pixel map</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Driving rule preference (i.e. rules’ weights)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Steering Angle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Steering Speed</td>
</tr>
<tr>
<td>Road Network</td>
<td>• Raw road geometry data (i.e. basic points (nodes) coordinates of road/lane boundaries)</td>
<td>• Road geometry reconstruction results (i.e. road surface patches vertexes coordinates, lane boundary points coordinates, and slope angle)</td>
</tr>
<tr>
<td></td>
<td>• Road map</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• TCO data (i.e. position, information content)</td>
<td></td>
</tr>
<tr>
<td>ST-SIM Environment</td>
<td>• Frequency (i.e. time step used during simulation)</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>• Time length (i.e. the duration simulated in real world)</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.3.2 ST-SIM initialization parameters and outputs
d) ST-SIM API

In order to provide an open platform of traffic research, it is very important to maintain a well-defined API for further system development and to enable ST-SIM to interact with other software. Using an Object-Oriented and model based design approach has enabled interfaces dividing the internal modelling algorithms from their interaction with other framework components. Hence, adding new models or updating existing models will only require localised revisions.

3.3.2 Middle-Layer Interfaces

In ST-SIM, the different Modules interact via the Middle-Layer Interfaces (inter-circle in Figure 3.3.1), which has three sub-items for Driver-Vehicle, Driver-Road network, and Road network-Vehicle interaction. Each of these is discussed below.

3.3.2.1 Driver and Vehicle Interaction

One of the main advantages in ST-SIM is the separation of human from vehicle so that vehicle control is generated by the Driver Module as a consequence of traffic circumstance and human intentions. Feedback from the vehicle reports the vehicle’s status to the driver is part of the driver’s perception and will affect their intention. In controlling their vehicle, a driver’s intentions and actions are essentially qualitative but result in measurable changes to steering wheel and speed change. Similarly, the driver’s perception of vehicle status/behaviour is qualitative, and results from the variation of measurable vehicle parameters. As shown in Figure 3.3.2, the interface between the driver and vehicle has been designed to reflect these transformations between quantitative and qualitative processes.
Interpret Human Controls

The driver's control to vehicle is divided into direction control (i.e. steering) and speed control (i.e. acceleration/brake):

- **Steering** command is given when vehicle's moving direction is different with driver anticipated direction. Drivers made qualitative decisions (i.e. steer left/right) instead of selecting accurate steering angles for vehicle control. To model the steering behaviour, steering angle (STA), steering velocity (STV), and steering force (STF) are key factors in consideration [129] [130]. One of the common investigation approaches for solving this action level problem is using statistics based models to identify the key factors influencing human behaviour for human control estimation [131]. In ST-SIM, the Driver-Vehicle interface solves this problem by using the result of the driver vision based steering angle calculation to interpret human steering requirements (see Figure 3.3.3). The result of the pixel based angle calculation (see Section 3.3.2.2) is compared with the driver direction error tolerance (see Figure 3.2.8) to obtain the required steering angle and steering velocity.
Vision Model: unspecified

Driver Profile: unspecified

Driver-Vehicle Interface (Driver Order Interpretation Part)

Get Pixel Based Steering Angle

Compare With Direction Error Tolerance

Within the tolerance

Beyond the tolerance

Get Behaviour Rule Set

New Driver

 Experienced Driver

Load Steering Angle/Velocity

Maintain Current Direction

Figure 3.3.3 Interpreting Driver steering order to Steering Angle/Velocity for new/experienced Driver

- **Acceleration or brake** happens when vehicle speed is different to driver's current preferred speed. An ST-SIM driver accelerates/brakes the vehicle within a range of values bounded by experiment based data [19]. Similar to the steering process, the acceleration/brake commands are given when the difference between pixel map based distance and speed estimation (see section 3.2.1.1) exceeds the driver's preferences and tolerances. In general
terms, these tolerances are influenced by a range of psychological factors (see section 3.2.1.3). It should also be noted that acceleration is also constrained by engine power in the vehicle model.

• **Vehicle Feedback**

Vehicle motion parameters are calculated using the theory in section 3.2.2 and fed from the vehicle to the driver-vehicle interface as numerical values. Within the interface, they are converted into a range of qualitative indicators, such as steering too much/little, brake too hard/gentle and accelerating too slow/fast. To demonstrate the conversion process, Figure 3.3.4 shows interpretation of vehicle roll angle.

![Figure 3.3.4 Vehicle Body Roll Angle Feedback Interpretation](image-url)
3.3.2.2 Driver-Road Network Interaction

In controlling their vehicle, ST-SIM drivers capture their local traffic situation through their vision model and make decisions based on information extracted from pixel images. As shown in Figure 3.3.5, this requires detection of road geometry, traffic controls, and other objects, e.g. vehicles and pedestrians, on the road around them.

![Figure 3.3.5 Driver Road Network Interaction](image)

- **Road geometry recognition and steering angle estimation**

  Road geometry recognition provides the data required for lane following in ST-SIM. The mechanism is based on the ID marking set used for the road network introduced in section 3.2.3. The vision model presents the captured image as a pixel map, as shown in Figure 3.3.6 and Figure 3.3.8. Lane IDs are used to 'patch' the road surface in the image. An ideal situation would be the detection of road/lane boundaries to determine vehicle position based on the distance to the lane boundary. However, the capture of boundary lines with a facet based vision model requires high pixel density that is not practical for current computing resources. The alternative approach applied in ST-SIM is to use the whole lane surface width for the pixel analysis (See Figure 3.3.6), so that the numbers of pixels in PL and PR are used to determine the driver's distance to the lane boundary. The vision based steering angle estimation algorithm in ST-SIM uses pixel counting and ratio maintenance of PL/PR (see Figure 3.3.6). To maintain the pixel ratio, the driver will drive the vehicle to the point C. Two assumptions here are (1) the vehicle track is a straight line in the given short time steps in the simulation; (2) the driver's looking direction is the same as current speed direction V when
estimating the steering angle. Figure 3.3.7 and followed equations showing the algorithm used for steering angle calculation.

Figure 3.3.6 Pixel Counting for Driver Self-Positioning and Steering Angle Estimation

Figure 3.3.7 Vision Based Steering Angle Estimation
Vehicle yaw angle during each time step \( t \): 
\[
Y = \alpha \times \frac{CD}{AE}
\]  
(3-25)

According to equation (3-5), the steering angle on the front wheel \( \delta \) will be:

\[
\delta = \frac{Y}{G_{\text{yaw}}} = \frac{Y \times \left( L + KV^2 / g \right)}{V \times t} = \frac{\alpha \times CD \times \left( L + KV^2 / g \right)}{V \times t \times AE}
\]  
(3-26)

where

\( \alpha \) = driver horizontal vision angle

\( V \) = current speed direction

\( V' \) = speed direction at point \( C \)

\( CD \) and \( AE \) are presented by pixel numbers counted within the reference row (see Figure 3.3.7) in the vision map.

The steering angle estimation process provides an opportunity to look at some aspects of the linkage between driver behaviour and personal factors. For example, considering foreseen distance (i.e. the selection of next vehicle position for reference in Figure 3.3.7), the reference point \( C' \) will lead to a bigger steering angle than point \( C \), in another words, the driver will take the short cut by bigger steering angle at point \( O \) that leads to a sharper turn. Factors including driver’s experience and vehicle performance may lead to different foreseen distance choices.

- **Detection of other vehicles and pedestrians**

Figure 3.3.8 shows how a typical ST-SIM traffic scene looks using VRML for rendering and a driver’s raw pixel map, along with an expansion of the central portion of the pixel map to show how object IDs are used to aid the vision process.

![Figure 3.3.8 Visual Image in (Left) VRML and (Right) Pixel Map consisting of object IDs](image)
• Traffic control information extraction

In the vision model, TCOs are recognised using their IDs. Having done this, ST-SIM currently uses a process similar to perfect vision in which the TCO information is simply shared with the driver. In the same way that the vision model introduces visual uncertainty, the driver / TCO interface can be developed further to accommodate information retrieval through different driver actions, such as attention and glancing. To establish the designed TCO / driver interface, Give Way road markings and a simple stop/go light have currently been implemented.

3.3.2.3 Vehicle and Road Network

The direct interaction between vehicle and road network works on the tyres' friction and adaptation to different road surfaces (see Figure 3.3.9).

![Figure 3.3.9 Vehicle-Road Network Interaction](image)

In ST-SIM, vehicle position in vertical-Z coordinate is calculated based on the road surface geometry and travelling velocity by looking for the correspondent height of road surface with respect to the horizontal position (XY position). This provides input data for vertical speed/acceleration calculation.
3.4 Chapter Summary

This chapter presents the system analysis and design of the ST-SIM framework. The overview of the framework summarized the analysis and design tasks into two catalogues, i.e. the components models and framework interfaces development. The achievements include:

1. The adoption of ID based object recognition mechanism in vision model. This mechanism implemented in pixel based distance, speed estimation and object information retrieve.

2. Expanding decision model's application context (see Figure 3.2.7 and Figure 3.2.8) based on the literature review of driver decision knowledge.

3. Design of vehicle steady state handling model for ST-SIM.

4. Construction of road network model with reference to the FE method. The Spline interpolation algorithms are used for road geometry description and different IDs is assigned to the road and traffic control objects for identification.

5. Interfaces analysis and design in three levels:
   a. external level for framework application data process,
   b. middle level for the model communication,
   c. and internal level for agents' synchronization.

The work in this chapter applies the broad knowledge reviewed in Chapter 2. The model-based framework provides the opportunity to create the virtual traffic scenario with basic elements of road, vehicle, and driver investigation. The computing based implementation of this framework will be presented in next chapter.
4 Software Development for ST-SIM

4.1 Introduction

The ST-SIM software aimed to provide a platform for traffic problems investigation; it is developed based on the design context in Chapter 3. This chapter will present the ST-SIM software development procedure including the concepts of Object-Oriented Design (OOD) [132], the software design in Rational Rose [133], and implementation with Visual C++ [135] in Visual Studio.NET platform [136]. Serving for accident reconstruction work, the Graphic User Interface is developed with Microsoft Fundamental Classes (MFC) [137] and GDI+ [138] and the 3D scene is constructed with VRML [139].

4.2 Object-Oriented Design and Iterative Development

Structured programming was the commonly used method in early ages of software engineering; the developers wrote the functional code block like print function and used it in the system wherever needed. Along with the increasing complexity and size of software, its main drawback came out when the code block changed in one place; the developer had to locate all the applying points of it and make the correspondent amendment in the whole system. In OOD, the system is constructed by the clarified definition of objects and encapsulating the object’s characteristics (i.e. attributes) and behaviours (i.e. functions) within the objects implementations. This enabled the ‘assembling’ of different objects pre-defined to construct the software system and the change only need to be made inside the objects that applied or creating the unique objects of this system. With OOD, ST-SIM required flexibility and extension can be achieved by updating the sub-models and the add-in of new modelling components. It also have benefits came from its inheritance and polymorphism characteristics [140]. Inheritance is the concept of creating new objects from the old ones by inheriting the qualities and made the required change or amendment. For example, in ST-SIM, most of the objects are inheriting from the CObject class of MFC [141] that can be dynamically generated and destroy during the simulation process. Polymorphism in OOD is the
concept presenting same behaviour (i.e. function) with different means and results for different objects, in ST-SIM, for example, same drawing function has different means in road segment and vehicle body due to the different shape. When updating the software, polymorphism concept makes the change only need to happen at the object with the required functionality, hence, to apply a new drawing method for road segment only need to change the correspondent drawing function in road segment instead of change the drawing method of the whole ST-SIM system.

The second issue in the software development for ST-SIM is the development procedure. The Waterfall (see Figure 4.2.1) and Iterative (see Figure 4.2.2) procedures are commonly applied in software engineering. The Waterfall procedure requires the thoroughly analysis of system at the project outset to guarantee the minimum misalignment between the system design and user requirements. Nevertheless, the designation of ST-SIM aimed to provide a research platform. The new requirements are bound to appear in different research scenario. Consequently, the Iterative process commonly applied in OOD is used in this project.

Figure 4.2.1 Waterfall Process

Figure 4.2.2 Iterative Process
4.3 System Development with Visual Modelling in Rational Rose

Rational Rose is a visual modelling tool for software analysis and design. It is developed in IBM Rational Software Corporation [133]. The Visual Modelling process is the process used to capture the system information and presents it with a standard set of graphical notations. Rational Rose adopts the notation set of Unified Modelling Language (UML) [134] used by the majority of the industry as well as the standards governing boards such as America National Standard Institute (ANSI) [142] and the Object Management Group (OMG) [143]. This section, in correspondent to the ST-SIM design context presented in Chapter 3, the UML based software design is implemented in Rational Rose. To be precise, we will use the modelling processes of Car-Following and Lane-Change scenarios to describe ST-SIM software analysis, design, and development process.

4.3.1 Modelling the Car-Following Scenario

ST-SIM provided the platform to simulate the car following scenario in micro level. The driver can going through the scenarios of car-following, overtake, or lane change. The car-following scenario is in a straight segment where one vehicle following the aiming vehicle and keep estimating and adjusting the front distance based on the driver’s personal preference. We describe the scenario with the Activity diagram in UML (see Figure 4.3.1) as following.
Figure 4.3.1 ST-SIM Car-Following Activity Diagram

This activity diagram is used to reveal the function flow of ST-SIM in the car-following scenario,
the basic vehicle handle actions are *brake* and *accelerate*, the decision related actions are *see*, *speed/relative speed estimation*, and *distance estimation*. The *overtake possibility check* and *overtake manoeuvre* will need separate diagrams to explain. To be precise, they will be put in Rose analysis file. Following the activity diagram, the detailed analysis for the system function flow corresponding to the objects is presented with sequence diagram in Figure 4.3.2.

![Figure 4.3.2 Sequential Diagram for Car Following](image)

### 4.3.2 Modelling the Route Following Scenario

In the common driving situation, driver follows the certain lane to accomplish the driving task. The route choice is the plan for travelling on certain road network. In ST-SIM, the driving route is ‘remembered’ by the driver (i.e. setup in the driver’s profile) and consists of the lanes to follow. In micro level, during the route following, ST-SIM enabled the modelling of maintain in lane position and lane change behaviour. This section presents the basic route following scenario in ST-
SIM where the short period lane change allowed when going through the aimed lanes in route plan. Figure 4.3.3 and Figure 4.3.4 showing the lane following behaviour and sequence diagrams in ST-SIM.

Figure 4.3.3 ST-SIM route following activity diagram
Compare with the car-following scenario, the new driver action *steering* is identified for vehicle control. New decision related actions are identified as *check road surface ID*, *check lane ID* and *ID matching*.

### 4.3.3 ST-SIM Objects Description with Rational Rose

In correspondent to the framework design in Chapter 3, the analysis with Rose leads to four main packages for the system, the *vehicle*, *driver*, *road network* and *algorithms* packages. The algorithms packages provided the basic mathematic support for the system operation including the interpolation functions and matrix conversion methods. Its independent design in the system allowed the choice of different algorithms for the optimization and accuracy level requirements.

The diagram analysis for the system activities in last section identifies the objects in the ST-SIM and their attributes/behaviour (i.e. functions). In this section, the class diagram is used to present the objects in ST-SIM software system, Figure 4.3.5 showing the class diagram of the driver package. Figure 4.3.6 is the detailed object design of *FacetRay* Class in the ST-SIM.
Figure 4.3.5 Class diagram for Driver
Chapter 4 Software Development for ST-SIM

Figure 4.3.6 FacetRay class details in the Driver package of ST-SIM

The class diagram based analysis is the key step in ST-SIM objects analysis and design, as shown above in driver's package (see Figure 4.3.5); the objects including driver, head, eye and eye facet, etc are presented. The arrowed lines are used to presents the relationship among the objects [144]. In the implementation, objects are inheriting from the CObject of MFC to enable the dynamic generation and destruction during the simulation process. Next section will give a brief introduction of software development for ST-SIM with VS.Net based on the Rational Rose design.

4.4 ST-SIM Development with MFC in Visual Studio.Net

The C++ programming language is an Object-Oriented computing language that has been commonly applied in different areas, benefit from the OOD concept, the C++ developers were able to create reusable libraries of classes that may be adopted by different applications to raise the develop efficiency together with software reliability and performance. Previous researchers of this project had developed the driver model in C programming language. The ST-SIM restructured the previous developed models based on the OOD concept and assembled the newly developed vehicle and road network packages to construct the simulation framework. Its software development requires the reformation of application and data structure to unify the models implementation and provide the interfaces for the framework operation. ST-SIM used the Microsoft Fundamental Classes (MFC) [137] in the Visual Studio.Net [136] platform (see Figure.
4.4.1. MFC is reusable C++ libraries provided by Microsoft for software development. ST-SIM software is a Windows based application adopting MFC application architecture. By Inheriting the MFC objects, ST-SIM objects can reuse their build-in features (e.g. dynamic memory allocation) for more efficient software development. The ST-SIM software development adopts the MFC document-view structure [146] and Graphic Device Interface (GDI+) [138].

Figure 4.4.1 Screen shot of Visual Studio.Net platform

Besides the objects analysis and design, the Graphics User Interface (GUI) is required for the ST-SIM implementation. Different requirements may raise for variant research problems, in current stage, the GUI development is aimed to help the accident reconstruction of OTS team. Its GUI is developed for accident reconstruction procedure, the basic steps include:

1. **Load accident scene map**, the OTS accident scene map from ordinary survey is loaded as the background for the canvas (see Figure 4.4.2). The user may draw directly on the map and pick the required road network information for reconstruction.
(2) **Construct road network referencing to the loaded road map.** Based on the road network design in section 3.2.3, road segment reconstruction is realized by the direct picking up of geometrical information from the map. For example, in lane construction, the required lane boundary points for interpolation are retrieved by mouse left clicking on the map, when finished (by mouse right clicking), the boundary curve will be interpolated based on the picked points and stored for the current lane. ST-SIM software implemented the straight and curved road segment reconstruction in 2D map, the 3D reconstruction API is provided in the software for further development. The APIs for future work also includes the road features of roundabout and priority junctions' reconstruction. For TCOs, the traffic light and give-way sign are implemented with APIs for more TCOs implementation.
(3) **Add vehicles into the scene.** The vehicles are initialized with the basic parameters showing in Figure 4.4.4.

![Figure 4.4.3 ST-SIM sample road construction view](image)

![Figure 4.4.4 ST-SIM vehicle setup dialog](image)
Figure 4.4.5 ST-SIM sample view with added vehicle

(4) Add drivers to the vehicle. The driver setup dialog is developed as shown in Figure 4.4.6 based on the driver model introduced in section 3.2.1. The driving route can be initialized by directly picking from the map (by clicking the road segments will be gone through in the driver route plan).

Figure 4.4.6 ST-SIM driver setup dialog
(5) **Run Simulation and Simulation results output.** After the setup of simulation scenario, the user can set up the simulation time and step length (i.e. sample frequency) before start the simulation (see Figure 4.4.7). The simulation results are current stored in plain *dat* file as shown in Figure 4.4.8.

![Figure 4.4.7 Simulation Time and Step setup dialog](image)

![Figure 4.4.8 Sample simulation output in *dat* file](image)
4.5 3D Scene Generation with Virtual Reality Modelling Language (VRML)

The VRML was originally developed to provide a 3D exploration environment on the World Wide Web. It is a hierarchical scene description language defining the geometry and behaviour of a 3D scene or "world" [147]. In ST-SIM, based on the simulation output, it is applied to the 3D scene generation for the road accident reconstruction. Figure 4.5.1 showing a sample accident scene in two different time points that before and after the crash in VRML. VRML enabled the user to navigate with different or dynamic view points in the scene, in the mean time during an accident reconstruction, the ST-SIM provided the driver's head position in every time step. The driver's view before the crash point in 3D scene maybe regenerated based on the accident case description in correspondent to the pixel maps manipulated by the vision model, following Figure 4.5.2 presented the blue lorry's driver view point before the accident.
4.6 Chapter Summary

This Chapter introduces the software design and development of ST-SIM. The software design methodology and relating development tools are showing in

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Software Design and Analysis</td>
<td>Rational Rose</td>
</tr>
<tr>
<td>Object-Oriented Design</td>
<td>UML</td>
</tr>
<tr>
<td>Software Development</td>
<td>Visual C++</td>
</tr>
<tr>
<td>Object-Oriented Programming</td>
<td>MFC</td>
</tr>
<tr>
<td>3D Scene Construction</td>
<td>VRML Programming</td>
</tr>
<tr>
<td>VRML</td>
<td>Visual Studio.NET</td>
</tr>
</tbody>
</table>

The Object-Oriented concept is applied and Visual Modelling technique in UML is adopted with Ration Rose for the software system analysis and design. The applying of OOD and UML analysis requires the fully understand of the specified system. While ST-SIM aims to provide a research platform for traffic investigation, the new problems and requirements are bound to appear in the software development; consequently, the commonly applied iterative development process is applied. The system design in Rational Rose is further realized with C++ programming language adopting the MFC support in Visual Studio.NET platform. The MFC data structure and application style (i.e. view-document) are adopted for the development of ST-SIM software and GUI. The plain dat file is used for the presence of ST-SIM simulation result and VRML is used for the 3D traffic scenes generation. VRML provides the animated scene construction and enables the multiple viewpoints allocation for the users based on the simulation output. In next Chapter, we will present TRL driving simulator based driver behaviour analysis and the investigation procedure of accident reconstruction with ST-SiM.
5 ST-SIM Applications

5.1 Introduction

Traffic Research covers broad areas including Road Network, Vehicle Dynamics, and Driver Psychology/Behaviour research. ST-SIM framework constructs virtual traffic scenarios with modelling techniques from these three areas to provide a research platform. This chapter presents the applying of ST-SIM for the basic traffic simulation and accident reconstruction. The general modelling process is introduced and three samples are included:

1) A virtual roundabout case is used for simulation scenario setup introduction

2) The collaboration work with TRL [19] is for driving manoeuvres including car-following, lane-following, and lane changing investigation.

3) The accident reconstruction for OTS case 50123 with the GUI support

5.2 ST-SIM Modelling Process

In ST-SIM, the modelling process can be summarized into three main steps:

A) Traffic scenario setup. This step initializes the simulation process by the construction of required actors (i.e. road network, vehicles, and drivers) in the traffic scene. In general traffic simulation, to be efficient, the data is input by reading initialize data from the plain documents of the Driver, Road Segment, and Vehicle. The GUI is provided for accident reconstruction work.

B) Simulation procedure setup. This step setup the Modelling time length and frequency. The simulation frequency is decided by the time step length for every simulation loop. High frequency (i.e. short time step) can increase the simulation accuracy because it is more close to real continuous traffic scenario. However, the required computing time will be increased. The balance between computing time and achieved simulation accuracy level is the main consideration for the user's reference.

C) Output data organization and formatting. ST-SIM outputs may be organized into four
catalogues as shown in following Table 5.2.1:

<table>
<thead>
<tr>
<th>Output Catalogue</th>
<th>Content (outputs in every time step)</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>Position, Speed, Longitudinal/Lateral acceleration, Yaw/Roll angle</td>
<td>Plane data with description in individual file for each output</td>
</tr>
<tr>
<td>Driver</td>
<td>Steering Angle, Looking Direction, Pixel Map of Vision Model, Manoeuvre Decision</td>
<td>Plane data with description in individual file for each output; see Appendix C for the pixel map details.</td>
</tr>
<tr>
<td>Road Network</td>
<td>3D Map of Road Geometry in Points coordinates</td>
<td>Plane data in three dimensional coordinates format</td>
</tr>
<tr>
<td>VRML</td>
<td>3D description required data including vehicle track, driver head position, road geometry data</td>
<td>Plane data with respect to 3D scene generation</td>
</tr>
</tbody>
</table>

Table 5.2.1 ST-SIM output format for plain document

5.3 Cross the Roundabout-Simulation of Basic Driving Manoeuvres

In section 4.3, we have used the Visual Modelling process for the Car-Following and Route Following scenarios to demonstrate the software analysis and design of ST-SIM. In this section, a virtual cross roundabout scenario is simulated assembling the basic driving manoeuvres to explain the working procedure of current simulation platform.

5.3.1 Geometrical Description of the Roundabout

The ST-SIM road network is constructed based on the geometry description methods and FE method referenced in section 3.2.3. The road network structuralized description that shown in Figure 3.2.12 is applied to the roundabout in Figure 5.3.1. The virtual roundabout is divided into 32 surfaces with two lanes in each surface, the four digital number (e.g. 1101, 1102...) is used to mark the surface ID. The key points' coordinates are collected and presented in formatted road network input file showing in Figure 5.3.2.In the case study, three basic shape elements are picked to compose the road map-Straight Line, Circle, and Curve, correspondent to the shape description, the required measurement is shown in following Table 5.3.1.
Figure 5.3.1 Virtual Roundabout Map

Figure 5.3.2 Sample text description of road geometry
Chapter 5 ST-SIM Applications

<table>
<thead>
<tr>
<th>Shape Element</th>
<th>Geometry Data Collection Requirements</th>
<th>Description Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight Line</td>
<td>Start point, length, direction angle</td>
<td>Straight line function</td>
</tr>
<tr>
<td>Circle</td>
<td>Circle centre, radius, start angle and finish angle of the circle curve</td>
<td>Cardinal circle function</td>
</tr>
<tr>
<td>Curve</td>
<td>Start point, end point, and at least other three points evenly distributed</td>
<td>Spline interpolation function Polynomial equation description</td>
</tr>
</tbody>
</table>

Table 5.3.1 Basic road geometry element in ST-SIM

5.3.2 Vehicle Initialization

ST-SIM vehicle initialization includes the dynamics and the physical parameters (i.e. size, location, and travelling direction, etc.). In the virtual round about case, the vehicles are initialized with default dynamics parameters with reference to section 3.2.2 and positioned in the map as shown in Figure 5.3.3. Six vehicles involved in the scenario cross the roundabout in different directions.

Figure 5.3.3 Virtual Roundabout scene
5.3.3 Driver Initialization

In this virtual roundabout case, the drivers are setup with default profiles for the simulation. The driver's profile including the definition of travelling route is presented in Figure 5.3.4. The travelling route is defined based on the road surfaces that the driver going through instead of using fixed track that presented by vehicles position in every time step. In Micro-level, this allows the drivers to lane change or overtake in the simulation based on their own decision (i.e. rule based decision model output).

```
driverID 5
VehicleID 5
speed 0
drivingDir 0
preFD 0
preBD 0
preSpeed 15
lane 0
profile 3
anglePercept 0
currentSurfaceID 0
driverTrack(surfaces_number_surfaceID_laneID_DriverPreferredSpeed_laneNumber_headRotationAngle)
8
1102 1 60 2 0
1104 1 30 1 0
1200 1 30 1 0
1207 1 30 1 0
1208 1 30 1 0
1604 1 60 2 0
1602 1 60 2 0
0 0 0 0
```

Figure 5.3.4 Sample Driver Profile in ST-SIM

In Figure 5.3.4, the driver initialization-vision system setup is using the definition inherited from vision model [20] of human eye. The pixel resolution (i.e. number of rows and columns for facets in the human eye) are 50x50. In the travelling route part, first line tells the number of surfaces will be travelling through during the trip, in each surface; five numbers are used to describe Surface ID, Preferred Lane ID, Preferred Speed in current surface, Total Lane Number in current surface and Lane Intersection Angle at the surfaces change point. The bottom line with ‘0’s presents the end of the trip.

5.3.4 Simulation Procedure Setup and Result

In this virtual roundabout case, simulation time length was set to 3 seconds, time step in 0.05 second (20Hz). The simulation output including vehicle, driver, and road network description files.

- Road network output
The road network was constructed based on the geometry input file as presented in section 5.3.1. In plain data format, two output files were generated after the simulation for the road network that both consist of the basic elements in 3D point coordinates. One is the patch-based description of road surfaces recording the patch vertexes coordinates and second records the point series, which are the interpolation results for lane boundary curves. These results are used in 3D scene construction in VRML.

- Vehicle output

The vehicle dynamics outputs include Vehicle Track, Speed, Longitudinal Acceleration, Lateral acceleration, Vehicle Yaw Angle, and the Vehicle Body Roll angle in each time step. Figure 5.3.5 showing the sample dynamics diagrams of the vehicle's speed output in virtual round about case.

![Figure 5.3.5 Vehicle dynamics output sample diagram](image)

- Driver output

In the driver output file (see Figure 5.3.6), the driver vision pixel map is recorded along with the driver head position, driver track information, objects in driver stereo view, driver steering angle and driver preferred speed in each time step.
5.3.5 3D Scene Reconstruction with VRML

VRML is a description language for 3D scene construction; the object nodes can be designed based on the output data from ST-SIM. The vehicle track and yaw angle output provided the 3D animation design for vehicles in the virtual roundabout. The patches and road geometry outputs were used for the 3D road segment generation. See Figure 5.3.7.

One advantage of VRML is it provided the different animated viewpoint's features that may be used to simulate the driver's visual perception in the simulation process correspondent to the pixel map generated by the vision model as shown in Figure 5.3.8.
5.4 Validation with Traffic Research Lab (TRL) Driving Simulator for Collision Avoidance

5.4.1 Lane Change for Collision Avoidance

The Driving Simulator at TRL consists of a medium sized saloon car surrounded by projection screens onto which are projected the graphic images to create the virtual environment. The vehicle is mounted on hydraulic rams to supply motion, simulating the heave, pitch, and roll experienced under normal braking, accelerating and cornering. Realistic engine, road, and traffic sounds complete the virtual setting. Scenario specification for the behaviour of all autonomous traffic vehicles included in simulated scenarios is determined by applying specific programming commands via SCANeR (Champion et al, 1999). Beyond simple lane- and distance-keeping rules, the simulated vehicles have no in-built intelligence. The addition of software to provide artificially intelligent vehicles would greatly enhance the realism with which simulator trials could be created since the autonomous vehicles would be capable of responding in a realistic manner both to the behavioural responses of the participant and to any pre-programmed autonomous vehicle behaviour (e.g. a vehicle programmed to disobey a red traffic light). This would improve participants' immersion into simulator scenarios increasing the likelihood that they will drive in a more realistic and representative manner with the consequence that greater confidence can be placed in resulting analyses. The current project is to validate some aspects of the current ST-SIM framework. For the simulator study, 60 participants between the ages of 18 and 68 were recruited.
from TRL's participant database of over 1200 members of the public. Participants were grouped by both age and experience see tables Figure 5.4.1 and Figure 5.4.2.

<table>
<thead>
<tr>
<th>Experience grouping</th>
<th>N</th>
<th>Years Since licence acquisition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Age Mean</td>
</tr>
<tr>
<td>Novice (0-5 years)</td>
<td>9</td>
<td>20.89</td>
</tr>
<tr>
<td>Experienced (6-25 years)</td>
<td>24</td>
<td>34.75</td>
</tr>
<tr>
<td>Veteran (&gt;25 years)</td>
<td>27</td>
<td>56.00</td>
</tr>
<tr>
<td>Total</td>
<td>60</td>
<td>42.23</td>
</tr>
</tbody>
</table>

Figure 5.4.1 Demographics of participants, grouped by driving experience

<table>
<thead>
<tr>
<th>Age grouping</th>
<th>N</th>
<th>Years Since licence acquisition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Age Mean</td>
</tr>
<tr>
<td>Younger (18-42)</td>
<td>31</td>
<td>29.94</td>
</tr>
<tr>
<td>Older (43-68)</td>
<td>29</td>
<td>55.38</td>
</tr>
<tr>
<td>Total</td>
<td>60</td>
<td>42.23</td>
</tr>
</tbody>
</table>

Figure 5.4.2 Demographics of participants, grouped by age

In the task, participants were instructed to drive along the motorway as they normally would in the light ambient traffic conditions. At 20.580km into the trial, there was an obstruction vehicle parked in the fend-in position in lane 1 of the motorway. At a distance of approximately 1 mile before the obstruction vehicle, the ambient traffic was removed from the driving environment so that participants were not impeded when making the avoidance manoeuvre. Participants had to move from lane 1 into lane 2 of the motorway to avoid the obstruction vehicle.

Data was recorded at 20Hz over the course of the trial. Parameters recorded were time, current lane, distance through the trial, lateral distance, steering wheel angle, accelerator and brake pedal depression, and the speed of the driven vehicle.

5.4.2 Lane Change for Collision Avoidance in ST-SIM

In ST-SIM, the scenario is set up in a straight three-lane motorway segment based on the TRL simulator data; two vehicles with default profiles are initialized. The driver’s changing lane manoeuvre is simulated in the experiment to prevent the collision with a obstruct vehicle parking
in his/her driving lane (see Figure 5.4.3).

Figure 5.4.3 Collision Avoidance scenario in ST-SIM

Based on TRL driver profiles, 25 sample data sets are selected from the 60 drivers and organized into groups of Novice (9 samples), Experienced (5 Male and 5 Female samples), and Veteran (3 Male and 3 Female samples). The related ST-SIM setup parameters are shown as following:

- **TS**: Simulation Time Step (0.06s)
- **TL**: Simulation Time Length (4.5s)
- **STS**: Sample Time Steps from experiment data (selected based on the experiment data)
- **X**: Initial Abscissa (0m for driven vehicle, 80m for obstruct vehicle)
- **Y**: Initial Lateral Distance to road centre (m)
- **Spd Dir**: Initial Speed Direction (deg)
- **SPL**: Speed Error Limitation under which driver take no action, defined as the percentage of current prefer speed (deg)
- **APL**: Angle Percept Limitation below which driver will not take any manoeuvre, defined as the percentage of current horizontal vision angle (deg).
- **FR**: Foreseen Range (i.e. the foreseen distance for driver's steering angle decision)
- **HL**: Headway Limit, the driver's safe distance to the front driver, defined by the percentage of pixels occupied by the front vehicle in the pixel map
- **SYL**: Safe Yaw Limitation, the yaw velocity below which driver will feel safety (deg/s)
- **PreSpeed**: Preferred Speed (mph)

The applied rules are showing in Table 5.4.2. SEL, APL, FR, and HL are setup based on the driver's decision rule weights in decision model in following Table 5.4.1:

<table>
<thead>
<tr>
<th>Driver Group</th>
<th>Rule1</th>
<th>Rule2</th>
<th>Rule3</th>
<th>Rule4</th>
<th>Rule5</th>
<th>SEL</th>
<th>APL</th>
<th>FR</th>
<th>HL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Novice</td>
<td>0.3</td>
<td>0.8</td>
<td>0.8</td>
<td>0.3</td>
<td>0.6</td>
<td>5</td>
<td>0.1</td>
<td>0.8</td>
<td>0.02</td>
</tr>
<tr>
<td>Experienced</td>
<td>0.6</td>
<td>0.7</td>
<td>0.5</td>
<td>0.5</td>
<td>0.7</td>
<td>2</td>
<td>0.05</td>
<td>0.85</td>
<td>0.01</td>
</tr>
<tr>
<td>Veteran</td>
<td>0.7</td>
<td>0.6</td>
<td>0.3</td>
<td>0.6</td>
<td>0.8</td>
<td>0.5</td>
<td>0.01</td>
<td>0.9</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 5.4.1 Driver Rule Setup for Collision Avoidance
### Table 5.4.2 Driver Rule Set

<table>
<thead>
<tr>
<th>Rule no.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Slow down</td>
</tr>
<tr>
<td>2</td>
<td>Speed up</td>
</tr>
<tr>
<td>3</td>
<td>Maintain Preferred speed</td>
</tr>
<tr>
<td>4</td>
<td>Maintain Preferred lane</td>
</tr>
<tr>
<td>5</td>
<td>Maintain Preferred forward distance</td>
</tr>
<tr>
<td>6</td>
<td>Maintain Preferred rear distance</td>
</tr>
</tbody>
</table>

### 5.4.3 Results and Analysis

Figure 5.4.4 presents selected examples drawn from ST-SIM simulation runs and TRL simulator results. The results compare the behaviour of real drivers and simulated drivers for the three categories of driving experience – novice, experienced and veteran. As a simple demonstration, we provide the results for two novices, two experienced, and two veterans. The driving profiles show the lateral positions of the drivers as they travelled in the northbound direction of the motorway. Both the real and simulated drivers were able to make an avoidance manoeuvre by moving from lane one, lane two and lane three to avoid the obstruction vehicle. The actual and simulated veteran drivers agreement is good, with slightly greater variation between simulated and actual driving for one of the experienced drivers. However, there is a noticeable difference in simulated and actual behaviour of the novice drivers. This is contributed to by three factors: The actual novice driving is relatively erratic; Fine tuning of driver character in ST-SIM is currently a demanding task; The current vehicle model in ST-SIM lacks some of the detailed inertial and frictional effects found in the steering and suspension of real vehicles so, creating a driver character in ST-SIM to match real vehicle behaviour implicitly involves some compensation for this. However, it is important to note that ST-SIM provides a framework in which the realism of the component models can be developed in the future.
Figure 5.4.4 Comparison of driving profiles for real and simulated drivers

Figure 5.4.5 (a) provides qualitative visualisation of one instant in the scenario, as seen from the driver’s viewpoint, when the real driver’s car has moved to lane two to avoid the parked car on the left (lane one). Figure 5.4.5 (b) shows the pixel map generated in the driver vision model within ST-SIM at the same instant.

5.5 OTS Accident Reconstruction with ST-SIM

The 'On-The-Spot' (OTS) accident research (OTS) project began in 2000. Its aims are to help ensure that our roads become safer for everyone and also contribute to the Government’s Road
Safety Strategy of 40% road casualty reduction target for 2010. The project enables expert investigators to attend the scene of an accident within 15 minutes of the incident occurring. There are teams at VSRC in the Midlands of England and TRL in the South. Objectives include establishing an in-depth database, and better understanding the causes of crashes and injuries that can be used to develop effective strategies for reducing road accidents and injuries to road users.

5.5.1 OTS CASE 50123 Scenario

In this section, we reconstruct the OTS case 50123 to demonstrate the applying of ST-SIM GUI for traffic accident scene reconstruction. The case scenarios are introduced in Figure 5.5.1 and Table 5.5.1.

![Figure 5.5.1 OTS Case 50123 Accident Scene Plan](image)

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Scenario Description</th>
<th>Road Segment Type</th>
<th>Driver/Passenger Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>50123</td>
<td>Astra van south bound A46 overtaking other vehicle was in collision FO/S LGV travelling north bound, Astra van then rotated and hit Clio causing it to rotate and loose control.</td>
<td>Straight segment with hill climb.</td>
<td>Astra Van: Driver only (M). LGV: Driver only (M) Renault Clio: Driver Only (M)</td>
</tr>
</tbody>
</table>

Table 5.5.1 OTS Case 50123 Description
5.5.2 OTS Accident Scene reconstruction with ST-SIM

ST-SIM GUI is provided to for accident reconstruction that including four main steps:

1. Load the accident scene map. ST-SIM draws the map based on the scale and map size (see Figure 5.5.2). The mouse cursor position is correspondent to the map covered physical area in the accident scene for the convenience of direct point coordination record.

![Figure 5.5.2 Set up the map covered area in ST-SIM.](image)

2. Road network reconstruction based on the accident scene map (see Figure 5.5.3-Figure 5.5.5), the 'road-segment-lane' hierarchy (see section 3.2.3) is followed. The lane boundary points for the curve interpolation are collected by direct clicking on the map.
Figure 5.5.3 Add road A46 to the network

Figure 5.5.4 Add Segment for road A46
3. The vehicles are added in after the road network construction (see Figure 5.5.6), the user may set up the vehicle's initial position by direct clicking on the map.
Figure 5.5.6 Screen shot for vehicle add in

4. The driver setup screen shot is shown in Figure 5.5.7, the driver are initialized with basic human factors as shown in Figure 5.5.7, his/her travel route may be selected on the map and shown in driver property dialog.

Figure 5.5.7 Driver setup screen shot
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The ST-SIM screen shot of VRML 3D scene constructed based on the simulation output is shown in Figure 5.5.8-Figure 5.5.10.

Figure 5.5.8 Screen shot of OTS 50123 case scene (Top view)

Figure 5.5.9 Menu for different viewpoint selection
5.5.3 Driver Decision Output and Discussion

The key functionality of ST-SIM framework is the modelling of driver decision process (see Table 5.5.2) with rule-based decision model (see section 3.2.1.2). In case 50123, Astra overtaking period (i.e. time needed to finish the overtake manoeuvre) and the overtaking peak speed are selected for evaluation, the driver behaviour reconstruction concentrates on the white Astra van driver's overtake decision process. In the scenario, the Volvo (see Figure 5.5.9) is assumed travelling at the driver's preferred speed when the Astra is catching up in the same lane. Two human factors are investigated: the Volvo driver's preferred speed and the Astra drivers' preferred forward distance (PFD). Assuming Astra driver can finish the overtake manoeuvre, these two factors' qualitative effects on overtaking period and overtaking peak speed are evaluated.

As shown in Figure 5.5.11, the overtaking period increases (+1.55 second) with the Volvo driver's preferred speed. The overtaking period is the time scope in which driver's overtake decision is '1' as shown in Table 5.5.2. In the mean time, the Astra driver's acceleration time also increases (+1.50 second) to finish the overtaking manoeuvre (see Figure 5.5.12).
Current Time (s) | Steer Right | Steer Left | Brake | Accelerate | Overtake |
---|---|---|---|---|---|
4.65 | 0 | 0 | 0 | 0 | 0 |
4.7 | 0 | 1 | 0 | 0 | 0 |
4.75 | 0 | 0 | 0 | 0 | 0 |
4.8 | 0 | 1 | 0 | 0 | 0 |
4.85 | 0 | 1 | 0 | 0 | 0 |
4.9 | 1 | 0 | 0 | 0 | 0 |
4.95 | 1 | 0 | 0 | 0 | 0 |
5 | 0 | 0 | 0 | 0 | 0 |
5.05 | 0 | 0 | 0 | 0 | 0 |
5.1 | 0 | 0 | 1 | 0 | 0 |
5.15 | 0 | 0 | 0 | 1 | 1 |
5.2 | 1 | 0 | 0 | 1 | 1 |
5.25 | 1 | 0 | 0 | 1 | 1 |
5.3 | 1 | 0 | 0 | 1 | 1 |
5.35 | 1 | 0 | 0 | 1 | 1 |
5.4 | 1 | 0 | 0 | 1 | 1 |
5.45 | 1 | 0 | 0 | 1 | 1 |
5.5 | 1 | 0 | 0 | 1 | 1 |

Table 5.5.2 Sample Astra Driver Decision Output

- Different Volvo Driver Speed Preferences Simulation Output

Two set of initialize speeds in Table 5.5.3 are used for this evaluation.

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Vehicle</th>
<th>Initial Speed (m/s)</th>
<th>Driver Preferred Speed (m/s)</th>
<th>Driver Preferred Forward Distance (Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astra Van</td>
<td>20</td>
<td>27.4</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Volvo S40</td>
<td>13.7</td>
<td>13.7</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario 2</th>
<th>Vehicle</th>
<th>Initial Speed (m/s)</th>
<th>Driver Preferred Speed (m/s)</th>
<th>Driver Preferred Forward Distance (Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astra Van</td>
<td>20</td>
<td>27.4</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Volvo S40</td>
<td>13.7</td>
<td>27.4</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.5.3 Different Volvo S40 driver preferred speeds initialization data
Chapter 5 ST-SIM Applications

Overtaking period when Volvo driver preferred speed is 13.7/s

Overtaking period when Volvo driver preferred speed is 27.4m/s

Figure 5.5.11 Astra driver overtaking period for Volvo driver with different speed preferences (The Astra driver's overtake time is increased (+1.55 second) with the Volvo driver's speed preference.)

Overtake acceleration period when Volvo driver preferred speed is 13.7/s

Overtake acceleration period when Volvo driver preferred speed is 27.4m/s

Figure 5.5.12 Astra driver acceleration period for overtaking Volvo with different speed preferences (The Astra driver's acceleration time is increased (+1.50 second) with the Volvo
driver's speed preference.)

- Different Astra Driver Preferred Forward Distance Simulation Output

In the implementation, the driver preferred forward distance are defined based on the vehicle travelling speed (i.e. Forward distance/Speed), “two-second rule” [145] is used as the default preference of ST-SIM driver. In this evaluation, the Astra van driver is given different speed preferences as shown in Table 5.5.4.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Vehicle</th>
<th>Initial Speed (m/s)</th>
<th>Driver Preferred Speed (m/s)</th>
<th>Driver Preferred Forward Distance (s)</th>
<th>Overtake start time (s)</th>
<th>Overtaking period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Astra</td>
<td>20</td>
<td>27.4</td>
<td>2.0</td>
<td>5.45</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>Volvo</td>
<td>13.7</td>
<td>13.7</td>
<td>2.0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>Astra</td>
<td>20</td>
<td>27.4</td>
<td>3.0</td>
<td>3.80</td>
<td>3.75</td>
</tr>
<tr>
<td></td>
<td>Volvo</td>
<td>13.7</td>
<td>13.7</td>
<td>2.0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>Astra</td>
<td>20</td>
<td>27.4</td>
<td>1.0</td>
<td>6.70</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Volvo</td>
<td>13.7</td>
<td>13.7</td>
<td>2.0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 5.5.4 Overtake scenarios with different Preferred Forward Distance (Astra Driver)

As shown in Table 5.5.4 and Figure 5.5.13, the longer preferred forward distance triggers the overtaking behaviour to happen earlier. However, the overtaking period also increases, which leads to the longer acceleration period and results in the higher peak speed for overtaking (see Figure 5.5.14).
Figure 5.5.13 Overtake period with different Preferred Forward Distance

Overtaking peak speed with 3 seconds PFD

Overtaking peak speed with 2 seconds PFD

Overtaking peak speed with 1 second PFD

Figure 5.5.14 Astra overtaking speed diagram with different PFD

- Conclusion and Discussion for Driver Output

Based on the ST-SIM output for the Astra driver’s overtake decision process in Case 50123. The Volvo driver’s preferred speed and Astra driver’s preferred forward distance (PFD) are evaluated relating to the overtaking time and overtaking peak speed in a qualitative level. The results showing that, in ST-SIM, the increasing of Volvo driver’s preferred speed will increase the time (i.e. overtaking period) needed for the overtake manoeuvre. Longer Astra driver’s PFD may cause the driver start the manoeuvre earlier but results in a longer overtaking period and higher overtaking peak speed. This is due to the longer acceleration period required in overtaking.

In the driver point of view, based on the ST-SIM driver modelling context introduced in section 3.2.1.3, these evaluations provide the space for further investigation on human factors’ (including age, gender, and driving experience) in a traffic accident. Because the human factors are influencing the driver’s preferences that leads to different manoeuvre style. For example, the research work on driver’s preferred forward distance’s relationship with his or her driving experience. In ST-SIM’s preliminary development stage, quantitative analysis (e.g. delay time for human reaction and vehicle mechanical transition) is not available in the simulation. It requires the
further reinforcement of driver model in ST-SIM to validate with results from experiments.

5.6 Chapter Summary

This chapter applies the ST-SIM for the validation work in TRL driving simulator and OTS accident case reconstruction work. The general working procedure of ST-SIM is introduced with a virtual roundabout scenario covering the key modules including road segment reconstruction, driver/vehicle initialization, and simulation procedure setup. The input and output structure are organized in plain files. The validation work is based on the experiment data from TRL driving simulator-recorded data for novice, experienced, and veteran drivers' behaviour in a motorway collision avoidance scenario. The validation well achieved in a quality level matching the driver's behaviour pattern as discussed in section 5.4.3. For accident reconstruction, ST-SIM Graphic User Interface (GUI) is provided and presents in section 5.5.2, the OTS case 50123 is reconstructed based on the accident scenario. The driver decision process is reconstructed in the overtaking scenario and the outputs are evaluated on a qualitative level. The results reveal driver preferences' effects on the overtaking manoeuvre are discussed in section 5.5.3.

The basic models in driver, vehicle, and road network modelling areas enable ST-SIM to reconstruct the accident involved traffic scenario to evaluate the factors may influence the driver decision process. In preliminary stage, the comprehensive accident scenario reconstruction still need more model elements for the virtual environments to achieve the quantitative simulation results, for example, the driver reaction and vehicle mechanic transition time need to be considered to measure the real driver manoeuvre time with ST-SIM driver manoeuvre time. However, the ST-SIM has provided a multi-model based framework to qualitatively evaluate the factors influencing driver decision in traffic scenario as shown in section 5.5.3. Corporate with the traditional questionnaire and statistic based drive behaviour research; it is an efficient platform to reconstruct traffic scenarios for computing based validation. In addition, its open framework and components based design provide opportunities for further development to meet the requirements of traffic research.
6 Conclusions and Further Work

6.1 Introduction

The primary contribution of this project is the design, development, and application of ST-SIM framework for traffic research. This chapter presents the conclusions drawn from this project and the contributions made from the research work. Section 6.2 summarizes the newly constructed ST-SIM framework and presents the functionalities available for the traffic related research. Section 6.3 summarizes the research conclusions from the project, and section 6.4 discusses the further work of this project.

6.2 ST-SIM Framework

ST-SIM is a computer based traffic simulation framework, it is designed aim to bridge the knowledge gaps in the traffic research by integrating basic models from different research areas including road network, vehicle dynamic/kinematics, and driver modelling (see Figure 6.2.1). This project constructs the simulation framework and applies this platform to investigate the basic traffic problems including TRL vehicle collision avoidance and accident reconstruction cases for OTS. Corresponding to each research area covered in the simulation; we summarize the platform components and functionalities as following:
Road network module reconstructs the road segment and traffic control objects with the hierarchical road description method (see section 3.2.3). The output of road network reconstruction including the three-dimension coordinates for the description of road geometry and the road surface patches for the interaction with the vision model. The traffic control objects are created with basic information including position, control information, and corresponding road (see section 3.2.3.3).

Vehicle module is based on the fundamental vehicle models presented in section 2.5.6 including vehicle body, tyre, and steering model. The module output includes basic kinematics parameters such as speed, lateral acceleration, longitudinal acceleration and so on.

Abs [2] Driver vision model is amended to achieve basic vision tasks including:
- Dynamic visual image (i.e. pixel map) generation
- Pixel based distance and relative speed estimation
- ID based stereo match
- ID based colour recognition and traffic control information retrieve

The driver behaviour and decision model is extended into a broader context to accomplish the perception-decision-action loop (see Section 3.2.1.3).
Chapter 6 Conclusions and Further Work

- Generate the 3D scene reconstruction data for VRML description file.

6.3 Research Conclusions

This project proves the feasibility to integrate the knowledge from different areas of traffic investigation. The current platform that constructed in ST-SIM successfully links the Road Network, Vehicle, and Driver modelling systems for the reconstruction and evaluation of real world scenarios. The research achievements include:

- This project allowed the reconstruction of real world traffic scenarios with the basic traffic components (i.e. road network, vehicle, and driver). It provided the opportunity to investigate the traffic problems with an intermediate view by adjusting and the evaluation of the involved actors.

- The ST-SIM is validated with the TRL real driving simulator of collision avoidance scenario [19]. The driving scenario data are collected from both the driving simulator and the ST-SIM reconstructed environment. The satisfied matching of vehicle track and driver steering behaviour are achieved in a qualitative level with correspondence to the drivers group of different driving experiences.

- The ST-SIM is applied to the OTS accident case reconstruction (see section 5.5). By modelling the basic components of the crash scenario, it provided the chance for multi-point views of the accident causation and enabled the evaluation of the accident involving factors (e.g. driver preferences).

- A well-grounded knowledge base has been constructed in the literature review (see Chapter 2) for this project. Its coverage in traffic simulation, driver psychology, and behaviour modelling area leads to a broad research context for ST-SIM (see section 3.2.1.3).

- This project provides opportunities to apply the Computing techniques in research platform-ST-SIM as shown in Chapter 4. The computing based virtual world is a feasible and efficient approach for traffic research.
6.4 Further Works Recommendations

To improve the functionalities and realism for ST-SIM, the further works for the research platform are recommended for both the enforcement of framework modules and the add-in of new modelling components.

6.4.1 Advanced Driver Decision Model

The current applied rules-based driver decision model encapsulated the top-level driver behaviour orders instructing for the basic manoeuvres. In a broader context as presented in section 3.2.1.3, the human factors such as age, gender, or social background worth a deeper investigation to reveal their relationships with driving preferences. In the vehicle handling aspect, the fuzzy of human perception and manoeuvres raised the gap between driver decision and behaviour modules, a further development for the more detailed human behaviours modelling is recommended for realistic quantitative inputs and output analysis from the drivers. For example, the add-in of human brain model applying fuzzy-neural knowledge to realistically simulate the driver’s reaction time and speed in relation with the tiredness and driving experience. However, the attention must be laid to prevent the losing of inside view into the actual driver decision process while using the neural network techniques for the driver decision reproduces.

6.4.2 Driver Perception Layer Enhancement

The current vision modelling system in ST-SIM commenced the driver perception layer design and development in this project. It highly abstracted the human eye into planes consists of pixel with rays for objects detection (see section 3.2.1.1), however, the relative high pixel resolution required for the object speed and distance estimation in human eye leads to the exhausting of computing powers. In addition, it still needs more realistic experiment validation like the representation of visual effects including ambiguity vision due to the light level, whether effect, etc. In another aspect, the real driver perception layer required the detection of noise, vibration factors. Development of this perception channels can fulfil the driver perception layer. The deeper understand of human perception layer can expose the broader knowledge foundation for the driver
6.4.3 Advanced Vehicle Modelling

Currently applied fundamental vehicle modelling system for common driving scenario simulation has ignored the many mechanical details. For example, the evaluation of suspension system may require the independently definition of Trailing Axis. Further development also requires putting attention on the crash dynamic modelling system. For example, the top brake performance in a sudden stop in the accident involved scenario.

6.4.4 Enhance of Road Network Modelling Package

The road network reconstruction module in this project is design and developed reference to The Finite Element concept. The basic traffic control objects (i.e. stop light and give way sign) are considered in the development. For the evaluation of road network design, the variant objects in the traffic scenario such as buildings, trees, and roadside barriers etc. need to be considered in the further development of road network modules.

6.5 Future Application Areas of ST-SIM

The ST-SIM platform covers knowledge areas of research scopes including driver behaviour/decision, visual system, vehicle dynamics, and road network design. It has broad future application areas as following.

- **Multi-Model based accident reconstruction system.** ST-SIM provided key actors modelling package in a vehicle accident. The reconstruction of an accident is initialized from the basic elements of the scenario. It can be used to simulate the driver decision process in the accident involved traffic scenario to identify and evaluation the key factors influencing drive psychology and behaviour.

- **Vehicle dynamics investigation.** The future development of driver's perception layer (e.g. visual, sound, and vibration feedback) will enable the research platform to link the vehicle’s dynamic feedback to the driver’s action. A broad research context of ergonomic can be
established based on the *perception-decision-action* loop introduced in section 3.2.1.3.

- **Road network evaluation.** The road network modelling system in ST-SIM enables the evaluation of road network system from different viewpoints in further work. For example, in Macro-level, the geometrical plan analysis with large amount of traffic flow, or in Micro-level, the detailed design of roundabout and traffic control signals allocation.
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