ABSTRACT
Testing and assessing of vehicle control systems require realistic environment, which requires enormous workload; to some extend it is impractical to set up the realistic environment. A comprehensive traffic environment simulation model has been designed and implemented for supporting vehicle control system development. The model consists of tow sub models: the motorway traffic flow model and driver behaviour model. The traffic flow model provides realistic simulation according with empirical data collected from a typical section of motorway. Following this, the principle of microscopic simulation and the representation of road users are discussed. Driver models for both car following and lane changing are then developed. The microscopic parameters in the driver models are then optimized to fit the simulation results with existing empirical data. The integrated simulation software provides support for vehicle control system development such as adaptive cruise control system.

KEY WORDS: traffic environment simulation model, traffic flow model, driver behaviour model, vehicle control systems, simulation software

1 INTRODUCTION
At present more and more vehicle control systems are being replaced or integrated with embedded microprocessor systems for more comfortable and safer driving environment. Vehicle equipped with microprocessor-controlled systems could reduce driver fatigue and the rate of auto accidents, whilst increasing fuel efficiency. Development of the embedded vehicle control systems could be carried out in house; nevertheless testing and assessing the system normally require a realistic traffic environment. It demands enormous effort to set up the realistic environment; to some extend it is impractical to carry out. It would expose the public to danger if the under construction system was tested on the motorway. This paper presents the design and implementation of a traffic environment simulation model, which can greatly reduce the risk and workload of setting up realistic testing and assessment traffic environment.

The work concentrated on a typical section of the motorway in UK, which is very prevalent in traffic connections between cities. There are approximately 100 motorways totalling over 3500Km in UK, with the amount of lanes varying between two up to eight. The work is concerned with the simulation of a straight, three-lane section of road with no junctions and a maximum gradient of 7% (4 degrees) which is...
currently the design maximum allowed by legislation\textsuperscript{[1]}. Each lane has typical width of 4m, as the structure of the motorway is shown in Figure 1.

<table>
<thead>
<tr>
<th>Hard Shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 m</td>
</tr>
<tr>
<td>Lane 1</td>
</tr>
<tr>
<td>4 m</td>
</tr>
<tr>
<td>Lane 2</td>
</tr>
<tr>
<td>4 m</td>
</tr>
<tr>
<td>Lane 3</td>
</tr>
<tr>
<td>Central Reservation</td>
</tr>
</tbody>
</table>

Figure 1 Motorway structure

Driving convention considered within this work is by the UK traffic legislation that motorists should drive on the left, and when driving on the motorway they should keep to the KLEWO (Keep Left Except When Overtaking) system. Additionally, the speed limit on many sections of the motorways is restricted to 70Mph for passenger vehicles and 60Mph for Heavy Goods Vehicles (HGV’s) and Lorries\textsuperscript{[2]}. The paper is organized as follows: section 1 presents the overall simulation principle, section 2 describes the driver behaviour model, section 3 presents the lane changing with traffic flow modeling, section 4 gives the simulation result.

2 ROAD TRAFFIC MODEL

The simulation involves a microscopic representation of road users. They are represented over a two-kilometre section of road, at the centre of which will lay the host vehicle, which is to be controlled by the vehicle embedded control system. The dynamics of each road user will be evaluated with respect to the host vehicle. That is the difference in velocity between the host and each other vehicle will dictate their position in the simulation. There is an initialization procedure, where each simulated vehicle is assigned a desired speed and given a random position in the simulation plane. Each vehicle obtains the correct following distance to its leader and simulation then start automatically.

As the simulation evolves, faster vehicles will exit the simulation section reference to the host vehicle’s front, while slower vehicles will exit to the rear. When this occurs, new vehicle will be added with randomly generated speed to the simulation section. If the desired speed is greater than that of the host vehicle the newly added vehicle will enter the rear of the simulation and vice versa. The simulation principle is shown in Figure 2.
The methodology used to generate random samples with a normal distribution is based on a pseudo-random number generator, such as a computer’s random algorithm, possesses a uniform distribution. Given two normalized random numbers $x$ and $y$, both with a uniform distribution and value between 0 and 1, the normal form of the Box-Muller transformation may be used to produce two random numbers $Z_0$ and $Z_1$ both having a normal distribution centred about 0 with a standard deviation of 1.

The transformation is given mathematically as (1).

\[
Z_0 = \cos(2\pi x) \cdot \sqrt{\frac{2 \ln(y)}{y}}
\]

\[
Z_1 = \sin(2\pi x) \cdot \sqrt{\frac{2 \ln(y)}{y}}
\]  

(1)

The more common polar form of the transformation is not utilized in this simulation because, although it requires fewer calls to math functions and is statistically more efficient, approximately 21% of samples are discarded based on simple testing criteria. This makes it unsuitable for the purposes of real time simulation because, however small the probability, it cannot be guaranteed that in a given time period two random samples will be generated that both satisfy the criteria.

### 3.1 Representation of Road User

In order to represent road users, a simplified dynamic model is employed. The car-following model generates the acceleration signal $\alpha$, which acts as the main input to the model. The dynamics are represented by (2).

\[
x_t = V_h - V_2
\]

\[
V_2 = \min(\alpha, \alpha_{\text{max}})
\]  

(2)

$x_t$ is the vehicle position within the simulation section, $V_2$ is the vehicle velocity, $V_h$ is the host vehicle velocity. For the purpose of realistic simulation, the
acceleration signal is saturated at a maximum level $\alpha_{\text{max}}$ for both acceleration and braking. There are many factors that could affect the performance of acceleration and braking. Previous research has indicated that a simple speed-dependent maximum is sufficient to provide a realistic model. Within this simulation a linear dependence is assumed. For passenger vehicles, relationships for level ground acceleration and braking are represented by (3)\(^{[3]}\).

$$\begin{align*}
\alpha_{\text{acc, l max}} &= 4 - 0.07x_2 m/s^2 \\
\alpha_{\text{brake, l max}} &= 4.5 - 0.023x_2 m/s^2
\end{align*} \tag{3}$$

**Passenger Vehicle Performance**

![Figure 3 Car acceleration/speed relationships](image)

Similarly the HGV’s relationships\(^{[3]}\) for level ground acceleration and braking are given by (4).

$$\begin{align*}
\alpha_{\text{acc, l max}} &= 2 - 0.05x_2 m/s^2 \\
\alpha_{\text{brake, l max}} &= 3 - 0.017x_2 m/s^2
\end{align*} \tag{4}$$

**HGV Performance**

![Figure 4 HGV acceleration/speed relationship](image)
To incorporate the effect of road gradient, a simple formula is used to modify the level ground acceleration $a_l$ and the final maximum acceleration $a_{\text{max}}$ together with the effects of weather conditions are given by (5)\(^3\).

$$a_{l,\text{max}} = a_{l,\text{max}} - \frac{G_g}{100} m/s^2$$

$$a_{\text{max}} = \mu a_{l,\text{max}} m/s^2$$

Table 1 shows the typical values of $\mu$ for a given set of weather conditions.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>1</td>
</tr>
<tr>
<td>Wet</td>
<td>0.8</td>
</tr>
<tr>
<td>Snow</td>
<td>0.3</td>
</tr>
<tr>
<td>Ice</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 1. Friction Characteristics

3 DRIVER BEHAVIOUR MODEL

Microscopic driver modeling deals with the creation of an ‘intelligent driver’ for each of the simulation vehicles. This intelligent driver controls both the longitudinal and lateral vehicle motion, depending on the current road situation. Longitudinal motion is concerned with generating an acceleration signal for the vehicle, and lateral motion with deciding when to change lanes in response to certain stimuli.

In this simulation three different types of longitudinal motion are modelled:

1. Free Driving — intelligent driver endeavours to achieve and maintain the desired speed.
2. Following — the intelligent driver attempts to safely approach an oncoming vehicle in the same lane and maintain a safe distance to it.
3. Emergency Braking — the intelligent driver slows the vehicle severely in order to attempt to achieve the desired separation due to an unexpected event e.g. a cut-in.

Two different models, with appropriate switching in between can represent these types of driving. The free driving model used in this simulation is a basic proportional controller that acts on the error between the desired and actual velocities, as shown in Figure 5.

![Figure 5 Free driving model](image-url)
As the vehicle approaches its desired speed the error and hence the acceleration signal $a_{fd}$ will fall to zero.

The car following model\textsuperscript{[4]} to be used in this simulation has a slightly more complex nature, and is based on a modified version of a modified version of a proportional-derivative controller\textsuperscript{[3]}. As with most controller of this nature, a constant time headway separation is preferred to a constant distance headway separation. The concept of time headway is defined by (6).

\[ t_h = \frac{v}{d_i} \quad (6) \]

$v$ is the vehicle velocity and $d_i$ is the distance to the lead vehicle. The desired following headway time for each driver model is generated with a normal distribution centred at 1.2 seconds, with a standard deviation of 0.15 seconds\textsuperscript{[4]} to achieve realistic behaviour. The car following model is shown in Figure 6.

$K_v$ is the velocity feedback gain, $K_p$ is the forward gain, $\alpha_{cf}$ is the acceleration of the following vehicle. To provide a realistic model, experiments have been carried out on real data and a half-normal distribution of proportional gain was found with mean value of 0.02, and standard deviation of 0.055. The relationship between $K_v$ and $K_p$ are found by experiments thus represented by (7).

\[ K_v = 0.1839 + 2.5719K_p - 5.5182K_p^2 \quad (7) \]

Examination of the operation of the free driving and car following models yields a simple switching method between the two, which is given in (8).

\[ \alpha = \min(\alpha_{cf}, \alpha_{fd}) \quad (8) \]

$\alpha$ is the actual applied acceleration signal, $\alpha_{cf}$ is the acceleration resulting from the car following/emergency braking model, $\alpha_{fd}$ is the acceleration signal resulting from the free driving model if they are both evaluated at each sample interval. The switching method basically decides the minimum of the two acceleration signals ensuring that the car decelerates to the correct following distance should a lead vehicle be encountered. If the lead vehicle starts to accelerate, it will followed at a safe distance without being ‘chased’ above the driver’s desired speed. When a slow lead vehicle is encountered, the driver also has the option of overtaking if a faster lane is free.
3.1 Lane Changing Model

Lane changing model is a notoriously difficult and complex behavioural process to model\cite{4}. It is best considered in terms of a number of perception thresholds, which consider the risk involved in accepting a gap in neighbouring lanes, compared to a benefit factor of some kind when performing the manoeuvre. This simulation is concerned with discretionary lane change. A discretionary lane change is performed when the driver is not satisfied with the driving conditions in the current lane, and can be split into three different manoeuvres each with their own motivation. There are three types of lane changing categories\cite{5,6}.

1. Driver’s side lane change (Overtaking) – this is performed when a driver perceives a certain speed benefit in moving to a faster lane.

2. Passenger side change (Yield) – this is performed when the driver is currently occupying either the middle or faster lanes, and perceives a faster car approaching from the rear.

3. Passenger side change (KLEWO) – this manoeuvre is again performed when the driver is occupying either the middle or fast lanes, and moves over to the left after overtaking. The presence of a faster car approaching from the rear is not necessary.

The lane change model developed for this simulation consists of a driver side change model that implements rule 1, and a passenger side change model that follows rules 2 and 3. The models developed for this simulation consist of a simple ‘gap acceptance’ principle\cite{3}. The gap, in both cases, is defined as the time headway to nearest vehicle in the destination lane both to the front and rear of the considered vehicle. This is illustrated in Figure 7.

\[
T_{\text{lead}} = \frac{V}{D_{\text{lead}}}, \quad T_{\text{lag}} = \frac{V_{\text{lag}}}{D_{\text{lag}}} \quad (9)
\]

For naturalistic, there is an absolute minimum clearance distance that must be exceeded for the movement to be initiated. There minimum lead and lag clearances are modelled by (10)\cite{5}.

\[
D_{\text{lead}} = \min(\max(\ell, (V - V_{\text{lead}}) + 0.5V) \delta.1) \quad (10)
\]

\[
D_{\text{lag}} = \min(\max(\ell, (V_{\text{lag}} - V) + 0.8V_{\text{lag}}) \delta.1) \quad (10)
\]

\[
t_{\ell} \text{ is the time for the lane change to take place. A minimum clearance separation from the lead vehicle in the same lane must be exceeded for a change to take place, which is given by (11).}
\]

\[
D_{\text{front}} = 2.2 \cdot (V - V_{\text{front}}) + I \quad (11)
\]
3.2 Driver Side Lane Changes

The motivation for making a lane change on the drivers’ side is primarily due to speed inconvenience caused by a slower lead vehicle. In order to implement rule 1, $U_{overtake}$ is defined as a measure of the urgency of the lane change.

$$V_e = \frac{(V_d - V)}{\xi}$$

$$U_{overtake} = K_{o1} \left(1 - e^{-5(V_d - V)} \right), \quad l = 1,2$$

(12)

$V_d$ is the driver’s desired velocity and the parameter $\xi$ is a sensitivity factor that may be adjusted to suit different driver types. The parameter $K_{o1}$ is introduced to provide a scaling gain dependent on the drivers’ current lane, as motivation for overtaking may be stronger if travelling in a slower lane. The urgency is related to the actual required gap for manoeuvres by (13).

$$t_{lead} = 3.86 \cdot U_{overtake}$$

$$t_{lag} = 3.44 \cdot U_{overtake}$$

(13)

A simulation result for the speed inconvenience in respect to the required gap is shown in Figure 8. It is derived that smaller speed inconvenience will required a larger gap (and vice versa).

![Figure 8 Driver side overtaking](image)

3.3 Passenger Side Lane Changes

The motivation for making a lane change on the drivers’ side is primarily dependent on rule 2 and rule 3. In order to implement rule 2, $U_{yield}$ is defined as the measure of the urgency of the lane change.

$$V_i = \frac{(V_d - V_{fd})}{\xi}$$

$$U_{yield} = K_{y1} \left(1 - e^{-5(V_d - V)} \right), \quad l = 2,3$$

(14)

$V_d$ is the driver’s desired velocity, $V_{fd}$ is the following driver’s desired velocity, $V_i$ is an indicator of the inconvenience factor of the following driver, $\xi$ is the sensitivity factor that can be adjusted to suit different driver types, $K_{y1}$ provides a scaling gain dependent on the driver’s current lane. The urgency is related to the actual required gap for manoeuvre by (15).
\[ t_{\text{lead}} = 3.86 \cdot U_{\text{lead}} \]
\[ t_{\text{lag}} = 3.44 \cdot U_{\text{yield}} \]  

The simulation is shown in Figure 9. It indicates that the stronger the speed inconvenience requires smaller gap.

![Graph showing Lane Gap Acceptance (Yielding)](image1)

Figure 9 Passenger side lane changing

### 3.4 KLEWO Model

In order to implement rule 3, a KLEWO model has been developed. It has been discovered that adherence to the KELWO principle decreases as overall traffic flow increases; this is incorporated as a gap acceptance model where the lead gap increases in direct proportion to the traffic flow. This simulation is mainly concerned with traffic flows less than 6000 vehicles/hour. The developed model is defined by (16).

\[ t_{\text{lead}} = \max \left( \frac{F}{6000} \cdot t_{K_{\text{max}}} \cdot 1.93 \right) \]  

(16)

\( F \) represents the traffic flow, \( t_{K_{\text{max}}} \) is effectively the gap size that must be present for the lane change to be worthwhile. A simulation result is shown in Figure 10 indicating that the gap acceptance increases in direct proportion to the traffic flow.

![Graph showing KLEWO Adherence](image2)

Figure 10 KLEWO model simulation
3.5 Lane Change Trajectory

A sinusoidal trajectory has been implemented for this simulation. It satisfies the criteria for an acceptable trajectory profile due to its continuous nature and accommodation of changing velocity. The lane change trajectory is shown in Figure 11.

\[ y(t) = y_s + \frac{y_d}{2} \sin \left( -\pi + 2\pi \frac{t-t_0}{t_1} \right) \]  \hspace{1cm} (17)

\( y_d \) is the desired \( y \) position after the lane change and \( t_1 \) is the required time to complete the desired manoeuvre.

4 SYSTEM INTEGRATION

An integrated simulation software package has been developed, which provides traffic environment simulation support for embedded vehicle control system development. The embedded system is to be used to control the throttle and brakes of a simulated vehicle travelling down a motorway. A host PC is to implement all the required equations of motion, and full motorway simulation, in real-time. The host PC will generate sensor signals for, and read in actuator signals from, the embedded control system. In order to be able to assess the efficiency of the embedded system design, the host PC must both be able to log data at arbitrary time intervals regarding the state of the simulation, and control the simulation scenario. Figure 15 shows an overall schematic of the test facility.
In order to ensure that the test facility is realistic, a complex non-linear model is used to represent the host vehicle as it travels down the motorway. This model includes concepts such as wheel slip, thus requiring the embedded system to implement ABS and traction control algorithms in addition to the main system, an Adaptive Cruise Control system (ACC). This host vehicle will be integrated with an intelligent driver, who will enable/disable the ACC system and decide when to change lanes etc. The simulation will be controlled by a scenario file, which may be loaded or created before the simulation starts. Figure 16 shows a text based simulation process.

5  SIMULATION RESULTS

The research concentrates on the M1 motorway section in UK, which has been operated for a long time therefore, can be considered as a typical representation of the motorway systems. In order to create an effective and realistic simulation, it is necessary to obtain data regarding traffic flows, traffic composition and average speeds for this motorway. According to latest figures published by the UK department for transport, the average traffic flow in 2002\(^1\) was approximate equal to 4167 vehicles/hour. The speed limit for passenger vehicle, and hence the mean for generation of desired speeds is 70 Mph with a standard deviation of 7.5Mph. The lane change rate is found to vary quite wildly, even for identical flow values, with an approximate mean located around 1100 events/Km/h. This value remained quite steady over the whole flow regime, with fluctuations of up to 50% occurring at some flows. The empirical data is presented as lane occupancy graphically in Figure 12. Although the exact figure varies between countries and different areas within the same country, a basic flow/occupancy relationship exists that has the general basic shape as shown in the Figure 12.
The simulation\cite{8} result from the developed model is shown in Figure 13 and Figure 14. The lane occupancy and change rate for approximate flow regimes from 500 to 4600 vehicles/hour. It can be found that the lane occupancy figure (Figure 13) has the basic relationship represented in Figure 12, and the desired occupancy crossover points are similar to those found in the empirical data set. Figure 14 shows the lane change rate. It can be seen that flows greater than 2000, the approximate mean lane change rate is 1250 events/Km/h. This is approximate 150 greater than the empirical data, but as the empirical data set has large fluctuations in value for identical flows and overall the simulation results fit into the data range.
6 CONCLUSIONS
We have described the development of a simulation model for motorway traffic flows. The simulation principle was described, and suitable driver models were then developed. Empirical data for a suitable section of motorway was then described, and the simulation parameters then optimized based on key points of interest in the empirical data. The simulation results show a good correlation to this empirical data. We have presented the development of comprehensive computer based traffic environment simulation software package. With the integrated simulation software, embedded vehicle control system engineers could test and assess an under-developing vehicle control system without setting up a realistic testing/assessing environment, which sometimes would be expensive or even impractical to be constructed.

7 ACKNOWLEDGEMENT
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