EVALUATION OF THE GHR CAR FOLLOWING MODEL FOR TRAFFIC SAFETY STUDIES

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ABSTRACT

Traffic safety studies mandate more than what existing micro-simulation models can offer as they postulate that every driver exhibits a safe behaviour. All the microscopic traffic simulation models are consisting of a car-following model and the Gazis–Herman–Rothery (GHR) car-following model is a widely used model. This paper highlights the limitations of the GHR car-following model capability to model longitudinal driving behaviour for safety study purposes. This study reviews and compares different version of the GHR model. To empower the GHR model on precise metrics reproduction a new set of car-following model parameters is offered to simulate unsafe vehicle conflicts.

NGSIM vehicle trajectory data is used to evaluate the new model and short following headways and Time to Collision are employed to assess critical safety events within traffic flow. Risky events are extracted from available NGSIM data to evaluate the modified model against the generic versions of the GHR model. The results from simulation tests illustrate that the proposed model does predict the safety metrics better than the generic GHR model. Additionally it can potentially facilitate assessing and predicting traffic facilities' safety using microscopic simulation. The new model can predict Near-miss rear-end crashes.

INTRODUCTION

During the past 60 years, varieties of car following (CF) models are proposed namely, GHR, linear model, Collision avoidance models and psychophysical models.CF is a major sub-model for every microscopic simulation model. Gazis–Herman–Rothery (GHR) (Gazis et al. 1959, Herman et al. 1959, Rothery 1997) and linear models (Pipes 1967) were the mainstream models in the beginning of the traffic simulation history. Later safety distance or collision avoidance models set up a safety distance in their model. The Gipps CF model (1981), the most successful collision avoidance model, was able to switch between free flow and following states. Psychophysical CF models simulate driver performance as sequential control reacting to a few thresholds.

CF entails the interaction of nearby vehicles in the same lane, and so has a major role in traffic safety studies. CF model has been also used in new technologies, such as Advance Vehicle Control Systems, to mimic driver actions (Brackstone & McDonald 1999).The potential of micro-simulation to evaluate safety related factors has been recognized by different studies (Bonsall et al. 2005, Hamdar & Mahmassani 2008, Bevrani & Chung 2011). Though there has been small advancement in applying these models to analyse traffic safety. Some safety studies using microscopic simulation have been undertaken particularly at intersections (Archer 2005).

If we look at the motorways' safety condition, one of the most common types of motorways crashes are rear-ends crashes. Mehmood et al. (2003) discussed that the study of driver CF behaviour is necessary in development of Advanced Vehicle Control and Safety System (AVCSS). One of the reasons that this model is studied in this paper is that the GHR CF model is the most used model for the in-vehicle crash avoidance systems. Therefore Mehmood et al.

(2003) stated that to date the most significant contribution to the CF models development was made by the General Motors (GM), particularity by (Chandler et al. 1958, Gazis et al. 1959, Gazis et al. 1961, Herman et al. 1959).

'Safety Indicators' in the current paper has been used for the safety evaluations. In real traffic situations, frequent near crash events called 'safety indicators' which can be used instead of real crashes. Rear-end crashes are this paper focus, and consequently CF will be examined. Out of different types of safety indicators, Time to Collision (TTC) and Short following headways are preferred, which directly show the potential rear-end crash risk metrics.

The following section explains the GHR model structure. The next section discusses the used real data and calibration process of the simulation models. The third Section demonstrates the current GHR model performance and specifically analyses Headway and TTC reproduction in it. In fourth part, based on the observation of the GHR CF model simulation results, modifications are proposed which lead to the proposing new parameters sets for the GHR model. Afterward the modified model performance is compared with the generic GHR model. Later the improvements of the safety indicators reproduction using the calibrated model are illustrated. Last section of this paper presents the summaries and achieved conclusions.

GAZIS–HERMAN–ROTHERY (GHR) MODEL

The GHR model is the most well-known car following model. It was developed by Chandler et al. (1958). Chandler et al. were quite optimistic that the traffic dynamic system can be synthesized. In this model acceleration of the follower is a function of the follower's speed, relative speed, spacing and driver reaction time delay. To support their mathematical model and hypothesis Chandler et al. conducted an experiment with an instrumented car at General Motors research laboratories in Detroit. They discovered that spacing is not significantly correlated to acceleration, while speed differences are highly correlated to the acceleration which drivers choose. The general formula of GHR type models is shown Equation 1 where in Chandler et al. (1958) $l = m = 0,\ \ c = 0.17 - 0.74,\ and\ \ T = 1.0 - 2.2$ are recommended.

$$a_n(\mathrm{t}) = \mathrm{c}\ \mathrm{v}_\mathrm{n}^\mathrm{m}(\mathrm{t}) \frac{\Delta\mathrm{v}(\mathrm{t}-\mathrm{T})}{\Delta\mathrm{x}^\mathrm{l}(\mathrm{t}-\mathrm{T})} \quad (1)$$

where

a_n	=	acceleration of vehicle n implemented at time t
V	=	speed of the follower vehicle
$\Delta\mathrm{x}(\mathrm{t}-\mathrm{T})$ and $\Delta\mathrm{v}(\mathrm{t}-\mathrm{T})$	=	relative spacing and speeds, respectively between the follower and leader vehicle at an previous time $(t - T)$, and T is the driver reaction time
$m, l\ and\ c$	=	constants to be determined.

While coefficient m shows the extent of the speed of n^{th} vehicle, it can affect the implemented acceleration of vehicle n at time t by driver. While l shows how much Δx relative spacing contribute to the following relationship. c is sensitivity constant or scaling constant relates to T (reaction time).

Chandler et al. interestingly mentioned that traffic accidents can occur firstly because of human error which they believe cannot be analytically modelled and secondly they believed that driver cannot avoid crash if s/he follows their immediate leader closely. And a possible crash can be caused by a sudden perturbation much further downstream by another car, which is amplified upstream.

According to the linear stability of a long line of following vehicles Chandler et al. (1958) developed their model. They stated that the margin between stable and unstable traffic flow operation is pretty narrow. In a dynamic system like traffic flow, the equilibrium start point is assumed to be stable. They argued that their model is stable only in high density traffic conditions where vehicles have to follow each other very closely. Interestingly Chandler et al. identified that driver anticipation helps to have a more stable flow, which is however ignored in their model. They made another assumption that sensitivity to stimuli in both acceleration and deceleration is identical, which they regard that as a true assumption in low speed traffic flow.

Another interesting phenomenon that Chandler et al. discovered is that the traffic dynamic can become easily unstable in a situation where vehicles are in very small spacing distance independent of its speed as it occurs in rush hour in high speed traffic. Any fluctuation in this situation can amplify and cause an accident if the line of vehicles is long enough. However in long line of vehicles an existence of a driver which is more conservative and keeps a longer distance can highly help to damp out any fluctuation. The time lag also was under investigation by Chandler et al., where they observed that by increasing the time lag, the traffic system dynamic becomes more unstable. An emergency control also is planned by them. Once the follower car becomes closer than a critical distance to the vehicle in front, driver breaks with the maximum feasible rate.

To date different figures have been suggested for Equation 1. =A lot of work has been done to calibrate and validate this model, for example (Ozaki 1993). Ozaki stated that his parameters supports both free flow traffic with temporary disturbances and also steady congested traffic flow. Therefore because of significant conflicting results with the real traffic data, in the literature, the best GHR model shape is still uncertain.

Two reasons for the weakness of this model has been identified by Brackstone and McDonald (1999). Firstly, because of the nature of following behaviour which changes in accordance with different traffic situations in real traffic where the GHR model cannot adapt. Secondly most of the empirical tests took place at low speeds and in stop-start situations. Therefore, variety of 'l' and 'm' have been suggested by different studies to calibrate and validate this model. Brackstone and McDonald (1999) in a comprehensive review on the literature of GHR CF type models summarized the parameters combinations in Table 1. These parameters combinations provide less contradictory results compared with the rest of studies. For sensitivity constant 'c' Chandler et al. (1958) proposed 0.37 sec^{-1} and also for the time lag they recommend 1.5 sec. While Ozaki (1993) suggested c=1.1 sec and different 'm' and 'l' for acceleration and deceleration as it is shown in Table 1. Once two vehicles become nearer than a critical distance which may depend on the follower car's speed, an emergency break is applied to prevent any collision (Chandler et al. 1958). The emergency break is the most severe feasible break. Though Chandler et al. had their own formula for emergency break, in our study for uncomplicated analysis we use the other reported emergency brake in the literature which is -7.5 m/s^2 (Touran et al. 1999), while ABS brakes also reported to be -8.5 m/s^2.

Table 1: Most reliable estimation of GHR model's parameters

Source	m	l
Chandler et al. (1958)	0	0
Herman and Potts (1959)	0	1
Hoefs (1972) dcn no brk/dcn brk/acn	1.5/0.2/0.6	0.9/0.9/3.2
Treiterer and Myers (1974) dcn/acn	0.7/0.2	2.5/1.6
Ozaki (1993) dcn/acn	0.9/-0.2	1/0.2

* (dcn/acn): deceleration/acceleration; brk/no brk: deceleration with and without the use of brakes.
Source: Adapted from Brackstone and McDonald (1999).

REAL DATA AND CALIBRATION

The NGSIM program collected comprehensive vehicle trajectory information on southbound US 101, Hollywood Motorway, in Los Angeles, CA, on June 15th, 2005. The area covered was roughly 640 metres in length and included five mainline lanes. In this paper 15 minutes of data are used: from 7:50 to 8:05 a.m. including around 3000 vehicles. The major focus of this research is CF behaviour therefore among the available trajectories, those vehicles that either themselves or their leader experience lane changes were omitted. 251 trajectories remain and the rest of study is applied to these trajectories. All these 251 vehicles experience at least one TTC below 3 seconds and vehicles should have headways less than 1.50 seconds.

For calibration of the different GHR versions, the sum of UTheil's Inequality Coefficient of speed and space as an objective function is then minimized. A Genetic Algorithm (GA) is implemented to search for global solutions for minimizing the objective variables for each trajectory. In this way the GHR model parameters are calibrated. At first instance the location of the follower and leader is reset to the real position and then by taking the leader trajectory and applying the GHR CF model, simulation is conducted.

In this study, the main safety indicators are headway= $\frac{\Delta x}{v}$ and TTC= $\frac{\Delta x}{\Delta v}$. It is important to understand the relationship between the two. Short headways occur more frequently than short TTCs. However short headway does not necessarily results in a crash, because it has to simultaneously occurs with instability in the traffic where driver cannot react on time. On the other hand TTC includes both a short headway and an instability. In other words a short headway eventually needs to end to a short TTC to cause any serious risk. Therefore short headways can indicate a potential risk of a crash in case of any instability in future, while TTC shows a present risk of crash that has occurred. Any model that can present both of these indicators with a higher level of accuracy it is expected to be a better model for safety analysis studies.

ANALYSIS

Individual level study

The GHR CF model is tested at an individual level. Two following vehicle trajectories are chosen from the NGSIM data. The following vehicle is simulated with GHR CF model with both Chandler and Ozaki parameters and the leader vehicle is created as it is observed in the real data. Figure 1 and Figure 2 demonstrate the simulated vs. Observed speed profile, headway and TTC in GHR CF model with Chandler and Ozaki Parameter sets. Figure 1 and Figure 2 illustrate that the Ozaki parameters posses a better agreement with real trajectories.

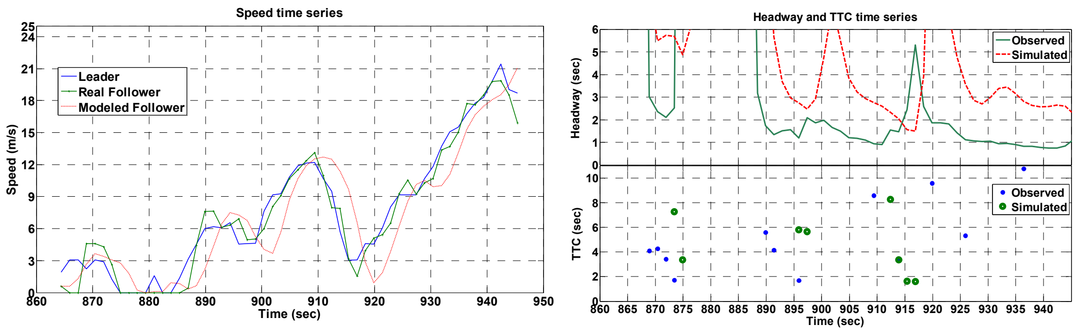


Figure 1: Simulated vs. Real speed and headway profile and reproduced TTC and in GHR CF model with Chandler Parameters sets

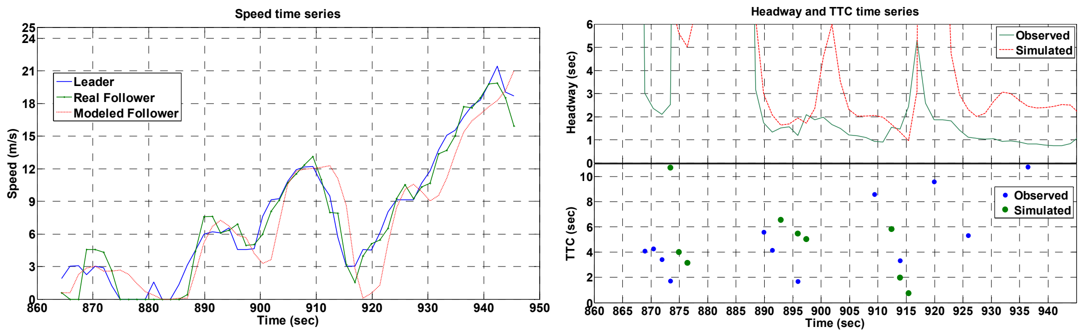


Figure 2: Simulated vs. Real speed and headway profile and reproduced TTC and in GHR CF model with Ozaki Parameters sets

Aggregate level study

To increase the reliability of the previous test and to not just rely on a couple of vehicles trajectories at previous section, it is necessary to compare the GHR model with Candler and Ozaki parameter sets using a lager sample data. Therefore the GHR model parameters of Chandler et al. and Ozaki are tested on the entire NGSIM data (251 trajectories). The level of robustness of the GHR model with the two scenarios, Chandler et al. (1958) and Ozaki (1993) parameters sets are investigated and result shown in Figure 3, Figure 4 and Table 2. It is shown that the Ozaki parameter sets can reproduce a closer frequency of critical TTCs compared with Chandler parameter set. In Table 2, all of the RMSE values of the Ozaki parameter sets are less than the Chandler et al. parameter sets. The last row of the Table 2 relates to the next section of this paper and it explains the proposed modified model performance which will be discussed later on. However headway distributions in both cases are quite far from real headways distribution and both of them seem to be unable to regenerate short headways distribution as in the observed headway distribution. This shows that the GHR type models are not robust for reproduction of headways.

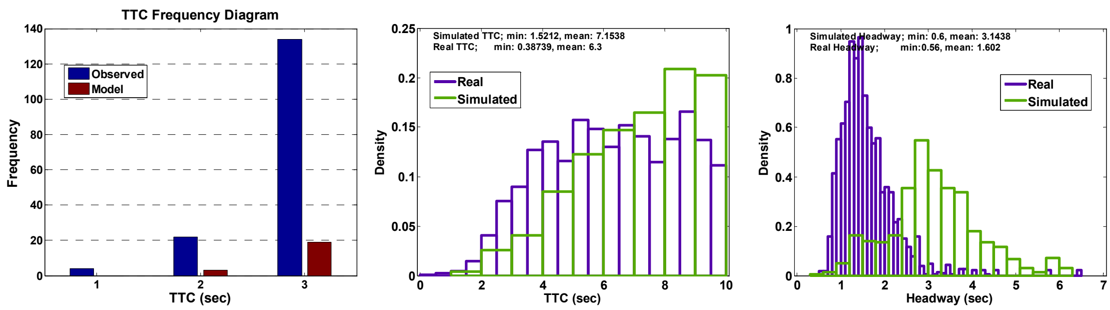


Figure 3: The level of robustness of GHR model with Chandler et al. (1958) parameter sets

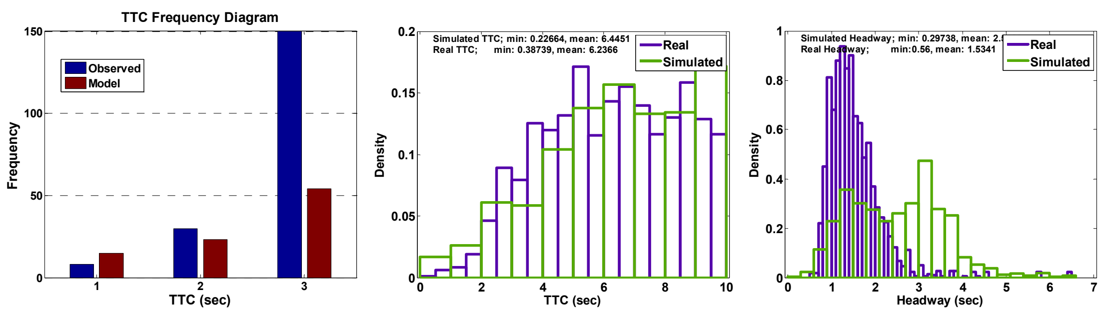


Figure 4: The level of robustness of GHR model with Ozaki (1993) parameters set

Table 2: The aggregate errors for NGSIM data for GHR car following models with different scenarios

Measure / Scenario	$\frac{Simulated}{observed}$		RMSE				
	TTC < 3 sec frequency	**hdwy<1 sec frequency**	$X\ (m)$	$v\ (m/s)$	$a\ (m/s^2)$	$TTC(s)$	$Hdwy(s$
GHR (Chandler et al.)	0.14	0.02	24.00	1.62	1.51	1.96	1.38
GHR (Ozaki)	0.18	0.02	18.63	1.35	1.47	1.52	1.06
GHR (Modified)	1.10	0.15	19.04	1.77	1.79	1.78	1.08

Sensitivity tests

GHR model parameters and the Safety Metrics

Since it has been validated that the Ozaki version of the GHR CF model functions better than the Chandler et al version, the Ozaki version of the GHR model which uses different parameters for acceleration and deceleration, is used as the basis in the rest of this study.

It is discussed that the GHR model is among the CF models which predicts acceleration. Some other CF model such as the Gipps CF model (1981) predicts speed of the following vehicle. To investigate how any changes in the predicted acceleration by the GHR model, can change the reproduced TTC, a sensitivity test has been conducted. As it is already mentioned:

$$\mathrm{TTC} = \Delta\mathrm{x}/\Delta\mathrm{v}$$

Therefore any changes in l or m or c and as a result in the acceleration $\delta\mathrm{a}$, will cause changes in TTC as below:

$$\boldsymbol{TTC} = (\Delta\boldsymbol{x} + \boldsymbol{\delta a} * \boldsymbol{T}^2)/(\Delta\boldsymbol{v} + \boldsymbol{\delta a} * \boldsymbol{T}) \quad (2)$$

If we assume that a leader vehicle has constant speed and the follower vehicle decelerate with a lower rate (negative $\delta\mathrm{a}$), as a result $\Delta\mathrm{x}$ will be lower and $\Delta\mathrm{v}$ will be higher which means a shorter TTC and a more dangerous event in the simulation model. Therefore any change in the acceleration has two effects on TTC values. Now the question is how these changes in the acceleration rate can be observed on the reproduced TTC values?
A sensitivity test is implemented to see these effects. A base case is assumed to have:

$$\Delta\mathrm{x} = 9\ (\mathrm{m})\ \&\ \Delta\mathrm{v} = 3\ (\frac{\mathrm{m}}{\mathrm{s}}) \qquad \text{As a result} \longrightarrow \quad \mathrm{TTC} = 3 \text{ sec}$$

The acceleration rate changes $(\delta\mathrm{a})$ ranges from 0 to 2 for different simulation steps are tested. Figure 5 illustrates the outcome of the test. Two interesting conclusions from the TTC graph in Figure 5 can be derived. First, as $\Delta\mathrm{x}$ and $\Delta\mathrm{v}$ are inter-correlated and any changes in the acceleration rate results in nonlinear changes in TTCs. Second, '*simulation step*' has direct and dramatic effects on TTC values. A higher simulation step amplifies the TTC values. In contrast to the TTC reproduction, headway formula is $\Delta\mathrm{x}/\mathrm{v}$, the headway change at Figure 5 seems to be more close to a linear trend. However any acceleration change has smaller absolute changes (millisecond) on headways since v value in the headway equation is much higher than $\Delta\mathrm{v}$ in the TTC.

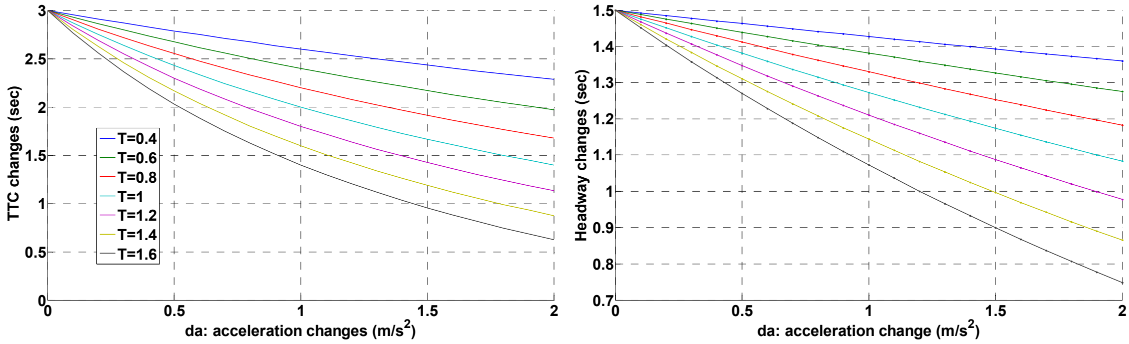
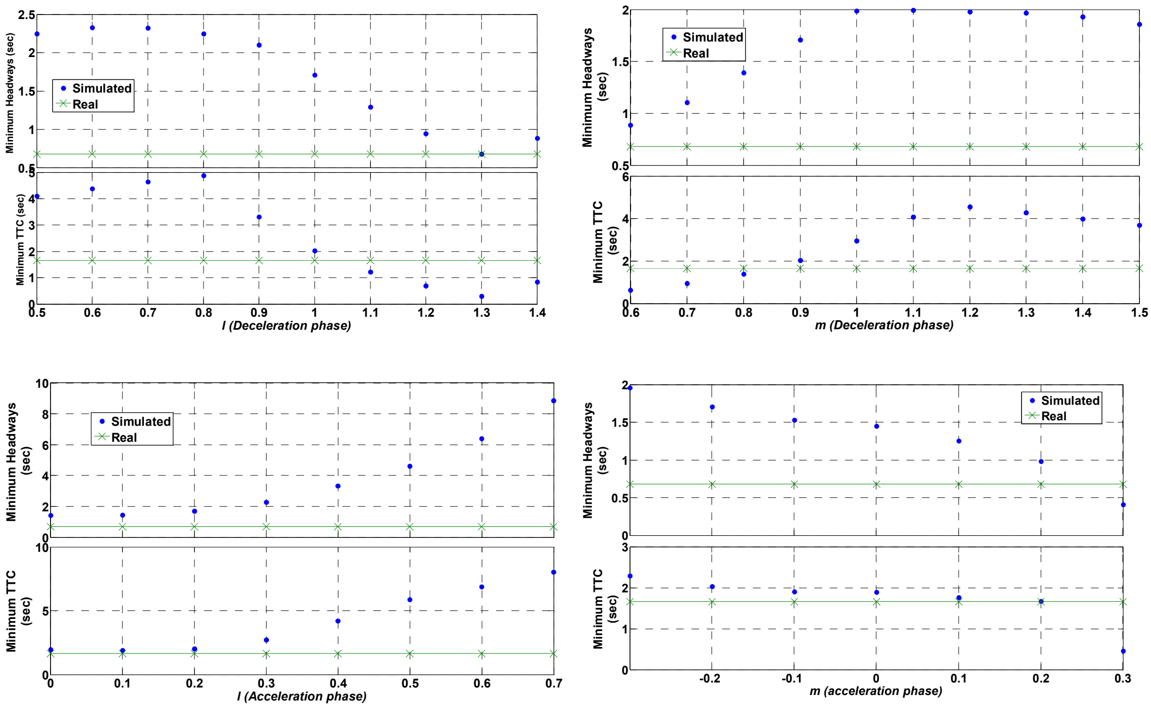


Figure 5: The effect of acceleration change on TTC and headways for different reaction times, m, l and c parameters effects on the safety metrics

To see the effects of m and l on the acceleration and deceleration of the GHR model with the Ozaki parameters, another test is conducted. A couple of following vehicles from NGSIM data is chosen and tested using m and l values proposed in the literature. In this parameter ranges the CF model is stable. Figure 6 illustrates the effects of the changes in the GHR model parameters on the reproduced TTCs and headways.

Figure 6 illustrates that in the deceleration phase $l \propto 1/\mathrm{TTC}$ while $\mathrm{m} \propto \mathrm{headway}$. On the other hand the acceleration phase has $\mathrm{l} \propto \mathrm{TTC}$ and $m \propto 1/\mathrm{headway}$. The coefficient '$c$' = 1.1 as suggested by Ozaki provides shortest TTCs.



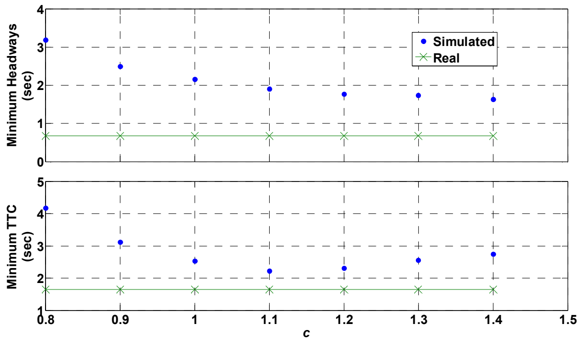


Figure 6: The effects of the changes in the GHR model parameter (m, l, c) in both acceleration and deceleration phases on the reproduced TTC and headway

PROPOSED PARAMETERS WITH THE BETTER ABILITY TO REPRODUCE SAFETY INDICATORS

Hamdar and Mahmassani (2008) altered the constant parameter 'c' as a normally distributed variable to make the model create crashes. The reproduction of safety indicators, not creating crashes is the focus in this study, so another approach is applied to modify the model. Additionally the Ozaki parameters function better than the Chandler model and use different parameters for acceleration and deceleration. The results of the sensitivity analysis indicates that in deceleration phase of the GHR model, to get smaller TTCs, should have a higher 'l', for example 1.2. Furthermore 'm' needs to be smaller than the Ozaki suggested value (0.9). According to Figure 6 'm' is fixed to 0.7 in deceleration phase to reproduce the smaller TTCs and headways. On the other hand, in the acceleration phase, Figure 6 illustrates that, the parameters l and m respectively should be 0.1 and 0.2. Constant 'c' is the same as Ozaki values fixed to 1.1. Table 3 illustrates the final recommended parameter sets.

Table 3: The proposed parameter for reproduction of safety indicator

Parameter		Value
Deceleration phase	l	1.2
	m	0.7
Acceleration phase	l	0.1
	m	0.2
In any phase of driving	c	1.1

The entire 251 NGSIM trajectories for our recommended parameters in Table 3 are simulated. The results are presented in the Figure 7. Table 2 illustrates that TTC reproduction is 19% better than the original Ozaki parameter sets. Short headways RMSE in Table 2 are lower as well. Although we have achieved a good improvement in the TTC reproduction, the reproduction of short headways in the GHR model cannot be achieved by only parameter changing and needs further research. The idea of using a different reaction time and different 'c' values as variables might be a construct as was introduced by (Ozaki 1993) too. It is obvious that the proposed parameters are not a perfect match with reality, however, the proposed direction towards getting the GHR model performs better in terms of reproduction of safety metrics and particularly TTCs empowers the current GHR model versions.

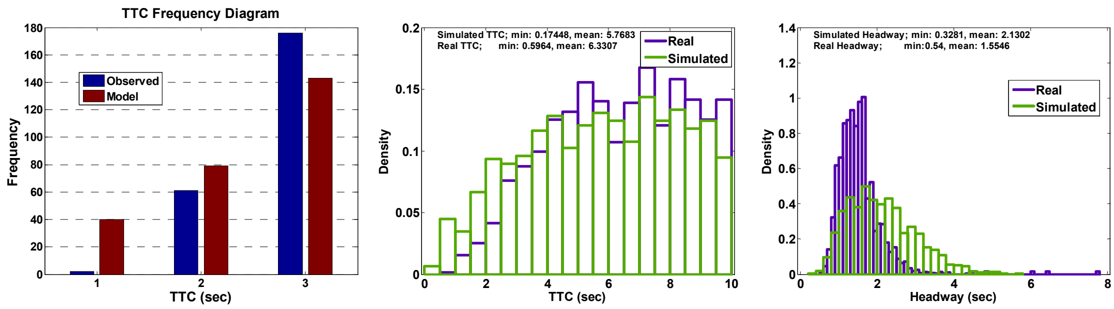


Figure 7: The level of robustness of GHR model with the modified parameters sets for GHR model for better representation of the TTC and short headways

Although the proposed parameters does not perfectly match with reality, the proposed parameters, improve the GHR model to simulate safety metrics more accurately.

CONCLUSION

The GHR CF model represents driver behaviour in a fairly good manner. However, this model is still far away from being well-designed in terms of the necessary level of precision for traffic safety studies. This model was examined by implementing sensitivity tests on the model parameters and tracking the safety indicators within the model structure. As a result ideas developed to explore how the model can be improved for safety study purposes.

This study therefore proposed a new set of parameters () for the GHR CF model and established a calibration procedure that improves the GHR CF model, which can be used for investigating safety measures. The new parameter sets specifically are proposed in Table 3. Additionally this paper highlights the areas that any model should address to be able to more realistically simulate traffic flow for the purpose of safety studies.

Simulations in aggregate and individual level were used to support experiments in this paper. The GHR model with the new parameter sets demonstrates better capabilities to simulate unsafe vehicle movements with short TTCs and Headways. The new GHR model parameter set makes the simulated models potentially able to be used to specifically evaluate near rear-end crashes events. The outcomes of this research assist to proactively evaluate safety via microscopic simulation models. For future work of this research, the GHR model should be tested in a platoon of vehicles and its accumulation effects like shockwaves behaviour need to be further investigated. Meanwhile the results of this study needs to be validated against the Australian traffic data sets. The effects of the other external factors such as changes to speeds, road geometry, traffic density on likely safety outcome needs to be further investigated.

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