Car following model of the distracted driver

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By

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Preface

September 2007 I started my bachelor mechanical engineering at the TU Delft. I had a general interest in technology so I thought this study would suit the best and that I would discover my interest along the way. In the bachelor research project I choose a topic which was focused on research on the human being. I liked this and proceeded with a master in the Biomechanical Design, automotive track. The combination of the human being and the fast development of in vehicle technology and automated driving make it an interesting field to study.

This graduation project is about the effects of distraction on car following performance and traffic flow. The study uses data from a simulator experiment performed at IFSTTAR in 2009. I like to thank Thierry Bellet for the opportunity to conduct further analysis of this data and also for the internship at IFSTTAR. During my internship Jean Charles Bornard helped me with the data and provided me with the details of the experiment.

Many tanks go to Riender Happee who always provided me with constructive feedback. I had some struggles keeping myself motivated, but Riender helped me to see the interesting parts of my research and that kept me moving. In the last part, also Meng Wang helped and reviewed the traffic flow simulation, thank you.

What I learned during this project is that it isn’t always easy to use and interpret data from an experiment that was not designed and conducted by you. I also discovered that it’s hard for me to focus on a single topic. That’s certainly valuable information I learned for my further professional career.

Thomas Vlaar,
Delft February 2015
Summary

More than 500 people die and over 10,000 get injured annually in the Netherlands due to car accidents (SWOV 2014). One of the causes of accidents is distraction by for instance a cell phone or navigation system that are more and more used in the car nowadays. In this study the influence of distraction on the car following task is examined as well as the implications on traffic flow.

For this study, data from a simulator experiment (Bellet and Bornard 2012) is used. In the experiment the participants drove an urban scenario, with a visual, cognitive and without secondary task (ST). With the visual ST participants had to indicate which of three pictograms match a fourth one appearing some seconds later on a display. The cognitive ST consists of indicating whether a letter did already appear in a sequence of letters orally presented to the participants. There were two following conditions, one free following and one constrained following conditions where they needed to keep 0.6s Inter-Vehicular-Time (IVT). Additional feedback was present about whether they were on this value.

The different conditions of this experiment are statistically analysed with a paired t-test. The visual, cognitive and no secondary task scenarios in the free following and constrained condition are compared, which makes a total of 9 t-tests. The average distance to the lead car, average absolute speed difference and average inter vehicular time (IVT) are used as car following performance measures. As expected, the free following and constrained condition are significantly different on all measures. Main result is that with a visual ST in the free following condition, the subjects drive closer to the lead car, with less speed difference, compared to the no ST scenario. In the constrained following condition, this effect is not seen. Even a significant increase in speed difference is seen between the visual and no ST scenarios.

Besides the car following performance, also the control effort of the participants is statistically analysed with a paired t-test. The measures used for control effort are: Root Mean Squared Error (RMSE) of derivative of steering wheel rotation; RMSE of derivative of gas pedal depression; RMSE of derivative of brake pedal depression and the frequency of brake actions. Expected is that the drivers show an intermitted controlling behaviour due to the secondary task. Only a decrease of control effort for the gas pedal, on the straight parts during a secondary task is seen but no discontinuous control is observed. Despite the secondary task, the participants keep on controlling the car continuously with almost the same effort.

The data from the simulator experiment is used to estimate the parameters for the Helly and IDM car following model. These are both continuous models which are expected to describe the distracted behaviour adequate, because no evidence for intermittent control is found in the experimental data. An attempt is made to solve the known problem of the standard Helly model of underestimating the braking phase by introducing an extra gain during the braking phase. Another Helly variant (st-switch) is introduced which estimates a different gain for the velocity input during the secondary task. These models are compared to the standard Helly and IDM model. The brake model does perform slightly better regarding the variance accounted for (VAF), but it is still underestimating the braking phase. The same holds for the IDM model.
The parameters estimated for the visual ST condition capture the distracted behaviour. The higher $k_v$-value indicates the lower speed difference found in the data. The lower $h_v$-value will lead to less distance to the lead car. From the st-switch model, it can be seen that the estimated $k_v$-value during the visual secondary tasks doesn’t differ much from the $k_v$-value during the period where no secondary task is presented. This leads to the conclusion that the participants didn’t change their behaviour during the secondary task. But the fact that a visual secondary task needed to be performed during the driving task made them more vigilant during the whole run.

The multiple resource theory (Wickens 2002) partly describes the effect of an increase of mean speed difference in the visual ST scenario, compared to the no ST scenario in the constrained condition. The multiple resource theory says that a secondary task that draws from the same resources as the primary task will lead to compensatory behaviour in the primary task. This compensatory behaviour is found by several studies in literature (Jamson et al. 2004; Strayer, Drews, and Johnston 2003; Strayer and Drews 2004), where drivers increased the distance to the lead car. In this study, this compensation on distance with a secondary task is not seen. In the free following condition, the mean distance to the lead car, mean speed difference and IVT even decreased in the visual ST scenario compared to the no ST scenario. This is unexpected and can’t be explained with the multiple resource theory. The inverse u theory (Hancock 1989), which describes the relation between workload and performance can explain this increased car following performance. This relation says that in an underload or overload situation, thus when the workload is too low or too high, the performance is not optimal. The free following task was probably too easy and the drivers were in an underload situation. The secondary task increased the workload and made the drivers more vigilant, as a consequence the performance increased with a secondary task compared to the no ST scenario. In the constrained condition, the workload was already high due to the additional task of keeping the vehicle at 0.6s IVT. During the secondary task, the participants keep continuously controlling the vehicle. This can be explained by the use of the internal mental model of the current driving situation to anticipate the future states. The deceleration of the lead car can also be incorporated in this mental model, because the speed difference of the lead car is due to the track layout. It is also possible that the participants perceive the changes of the lead car speed via their peripheral vision and are therefore able to continuously control the car.

To see the influence of distraction on the road capacity a traffic flow simulation will be carried out. The Helly and IDM model describe the distracted behaviour as good as the non-distracted behaviour and can both be used to perform the traffic flow simulation of a distracted driver. This is done by simulating a fleet of vehicles on a single lane road stretch of 4000 m with an increasing inflow from 500 to 4000 veh/h. It is concluded that with a visual secondary task, the road capacity increases compared to the no ST condition, with 33%, from 2250 to 3000 veh/h. The Helly model is less suited for the traffic flow simulation because it only shows the free flow region and gets unstable in the congested region.

A couple of limitations should be considered, first the study is conducted in a simple driving simulator. Therefore the results are not one on one transferable to driving in the real world. The speed variations of the lead car were mainly due to the track layout, so the participants might anticipate on this speed behaviour. This would make the car following task partly a track following task which is not captured in the car following models. Furthermore no additional hazards (crossing children, other cars on an intersection) were presented. Last limitations are the short scenarios of 90 seconds.
The main conclusions of this report are that the effect of a secondary task depends on the primary driving task. In the free following condition, which is a low workload task, the secondary task has a positive effect on car following performance. In the constrained conditions the participants were asked to drive very close (0.6s IVT) to the lead vehicle the secondary task had no effect on the car following performance. Although the participants engaged in a visual and cognitive secondary task, the vehicle is continuously controlled. Therefore the continuous control models can be used to describe this distracted behaviour. This is confirmed by the $k_e$ gain of the model which didn't change during the visual ST. The traffic flow simulation showed an increase of road capacity of 33% for the scenario of visual distraction compared to no distraction.

The results of this study can be interesting for the automated vehicles. When the driver isn't controlling the vehicle, in the automated mode, the ‘driving’ task becomes quite easy and dull. Therefore it is likely that when the driver is reclaiming control, the performance is not optimal. Future studies can focus on the effect of a secondary task in the automated vehicles in a real car experiment. It would be interesting to choose real secondary tasks like sending text messages, engaging in social media contacts or reading a paper. Furthermore it would be interesting if the results of this study also hold when the participants are driving for a longer period of time and engaging in a secondary task.
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Last year 570 people died and more than 10,000 people get injured in the Netherlands due to a car accident (SWOV 2014). These accidents happen due to a variety of reasons. One of the causes of accidents is distraction by for instance a cell phone or navigation system. The use of these devices influences the driving behaviour. With more insight into the effects of distraction on driving behaviour, the number of traffic accidents can be reduced. In this thesis, the effect of distraction on car following will be investigated. By looking at performance measures and a car following model, more insight in the distracted driver will be given. The distracted behaviour may also affect traffic flow, this will also be looked at. First a general introduction will be given about car driving, distraction and driver modelling. This will lead to the research questions formulated for this master thesis. A part of this master thesis is work performed during a two month internship at IFSTTAR (Lyon –Bron).

1.1 Car driving: distraction as cause of accidents

Car driving is a common but complex task. All three levels of cognition, skill, rule and knowledge levels are involved in the driving task (Bellet et al. 2012). In order to drive a car through traffic, a driver needs to perceive and analyse current information; anticipate the current situation into the future and take decisions to interact with other drivers and the environment (Bellet et al. 2009). Trends in new vehicles are that they have more and more in-vehicle safety and support systems, from ABS and ESC to lane departure warning systems and adaptive cruise control. These systems may help the driver in performing its task. But they may also distract the driver, or make the driving task dull and the driver inattentive. Another source of distraction is technologies as cell phones, navigation and infotainment systems. When using these technologies while driving, they draw attention from the driver. Not all secondary tasks may be a distraction from the driving task. For instance an experienced and skilled driver may be able to do another task without compromising on driving performance. It really depends on driving skills, the secondary task and driving context (Young, Regan, and Hammer 2007). The effect of the distraction on driving behaviour may vary due to these factors. Nevertheless distraction from the driving task could have disastrous effects. The relation between distraction and accidents is researched in several studies. Depending on the study, 5% to 25% of the accidents are attributed to distracted driving (Hurts, Angell, and Perez 2011). This leads to 5870 fatalities in the US in 2008 (Hurts, Angell, and Perez 2011) and about 20 to 100 fatalities yearly in the Netherlands (Hagenzieker and Stelling 2013).
These trends in new vehicles and technologies are a potential problem for traffic safety. After implementation of the technologies and deployment on the road, their effect on safety can be assessed. When it turns out that the safety benefit doesn’t outweigh the negative safety aspects, it’s too late because the system is already on the road. It would be great when these effects on safety and distraction can be studied beforehand. In that way, the design can be changed in an early stage. To assess the safety and distraction effects of new technologies, driver models can be used. Next, different driver models and their application will be discussed.

1.2 Driver models

The driver plays a major role in the combined car-driver system. Since the 1960s the first mathematical driver models started to arise (Plöchl and Edelmann 2007). Focus was on the lateral control of the car, with models based on classical control theory. It is only since (Michon 1986), that a cognitive approach is adopted. These models aim at realistically simulate human cognition. That means not only modelling the perception-action loop, but also the higher level of cognition which is among other things responsible for long term memory, resource management, mental representation of the environment, goal initiation and performance monitoring. By simulating these higher levels of cognition, these models are suited for studying driver behaviour. With these cognitive driver models, also the behaviour of drivers, when confronted with new technologies, can be studied. These findings can be used to alter these technologies in the initial design phase, in such a way that the changing driver behaviour doesn’t compromise safety. The main cognitive driver models used today (ACT-R (Budi 2002), QN-MHP (Liu, Feyen, and Tsimhoni 2006) and COSMODRIVE (Bellet et al. 2012)) are all able to simulate lower level of control (action-perception loop) as well as the higher level of cognition.

This thesis focuses on the lower level of control, the more unconscious part of the driving task. The focus will also be on the longitudinal control, which is a key part in all driving conditions. The lower level longitudinal control can be simulated with perception-action models. These driver models mathematically describe the relation between drivers perceived input (speed difference with and distance to lead car) and output (acceleration).

1.3 Research question

From the previous paragraphs it can be concluded that distracted driving potentially leads to accidents and that cell phones and navigation systems are a common source of distraction. With driver models it is possible to quantify effects on driver behaviour and with traffic flow models it is possible to predict effects on road capacity. The main research questions therefore are:

- What is the influence of a secondary task during car following on driving behaviour?
  - Can distracted driving behaviour be accurately described by a car following model?
  - Is the driving behaviour different at the moment the distraction is present?
What is the effect of a secondary task on traffic flow?

These sub-questions are made up to help answer the main research question. To be able to use car following models to investigate and model distracted driving behaviour, it should first be identified if they can describe this behaviour accurately. What is the effect on driving behaviour at the moment of distraction? So will the driver behave different only when distracted or also at the moments between the actual distraction? When the influence on a single driver is known, the last thing to look at is what will happen when multiple drivers are distracted. How will this influence traffic flow? Next the expectations regarding these questions will be discussed.

### 1.4 Expectations of distracted driving

The introduction and growing popularity of cell-phones has led to an increased interest in the effect of distraction (and thus mainly distraction by the cell-phone) on driving behaviour. A lot of research on this specific topic is conducted. With the conclusions of literature on distracted driving, and with the use of theory about human task performance an expectation can be formed regarding distracted driving.

When performing any task, (cognitive) resources are used. In the multiple resource model (Wickens 2002), the different resources are divided into different inputs (visual, auditory, tactual), cognitive processing stages (perception, processing, action) and reasoning types (symbolic, subconscious, linguistic) see Figure 1. With this model one can investigate how two tasks may interfere with each other. For the driving task, which is a highly visual task, another visual task (operating a navigation system) draws from the same resource and will interfere more than for instance a hands free phone call. What can be expected regarding car following is that when a driver is distracted, less resource is allocated to the driving task. Therefore the driver will increase the distance to the lead car in order to safely perform the driving task with less resource.
Whether and how drivers self-regulate their driving to compensate for the decrease in attention to the driving task is seen as a fundamental question (Young, Regan, and Hammer 2007). This research focuses on the operational level of the longitudinal control task where compensatory behaviour consists of decreasing speed and increased distance to the lead car. What can be expected of a distracted driver in a car following task, increasing the distance to the lead car, is found by several studies in literature (Jamson et al. 2004; Strayer, Drews, and Johnston 2003; Strayer and Drews 2004). These studies all looked at the effect of cell phone conversations or speech based e-mail, where the distraction is mainly cognitive. When the drivers increase the distance to the lead car when distracted, it is expected that the road capacity decreases.
The method to answer the research questions posted in 1.4, and check if the expectations are correct is explained in the following chapter. To investigate the behaviour of drivers when distracted, data from a simulator experiment is used. This data is statistically analysed with regard to car following behaviour and control effort. To model the behaviour, different car following models can be used. These will be explained and the most appropriate will be chosen. The method of estimating the parameters is explained. Finally the traffic flow simulation will be discussed. In Figure 2 an overview of the methodology used is given.

2.1 Data simulator experiment

The data for analysis of driver behaviour and estimating model parameters is coming from a simulator experiment performed at IFSTTAR (Bellet and Bornard 2012). An explanation of the experiment will be given.
2.1.1 Simulator study

The study was conducted in a fix-based driving simulator (see Figure 5). A video of the simulator can be found here: https://www.youtube.com/watch?v=TfTvZv7Dkal. There were 19 participants (male and female) in total. In Table 1 the average age, years in possession of driving license and kilometres driven for the participants can be seen.

Table 1: Summary of participant’s properties. Means, with standard deviation in parentheses.

<table>
<thead>
<tr>
<th>Age</th>
<th>Years driving licence</th>
<th>Km</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.2 (7.6)</td>
<td>10.3 (5.9)</td>
<td>120000 (96000)</td>
</tr>
</tbody>
</table>

All 19 participants drove 12 driving scenarios with and without visual secondary task. From this group of 19, 10 drove all scenarios also with a cognitive secondary task (see Table 2). The duration of each scenario was about 1.5 minute. All subjects drove the scenarios in the same order. The scenario’s with a cognitive secondary task is driven 10 to 30 days after the initial 12 scenarios with and without visual secondary task.

The primary task of car following was performed in three different environments:

- highway (130 km/h)
- rural (90 km/h)
- urban (50 km/h)

The highway and rural environment are both a straight road stretch, the urban environment had a different track layout (see right of Figure 3).

There were two following task conditions:

- free following
- constrained at 0.6 sec. Inter-Vehicular-Time (IVT)

During the constrained task participants had visual feedback on whether they were on the desired value of 0.6 sec. IVT. The feedback consisted of a sphere placed at 0.6 s IVT in front of the participants’ car and a bigger sphere at the rear bumper of the lead car. When at (+/- 10%) of the 0.6 s IVT, the spheres were green, else they turned red. Participants were instructed to keep the spheres green. This constrained following behaviour doesn’t reflect normal driving. In this condition the participants are forced to drive dangerously close to the lead car. Also this type of feedback isn’t normally available during driving.

There were two types of lead car behaviours:

- steady
- unsteady

With an unsteady lead car the amplitude of the lead car speed was periodically altered with a frequency of 0.2 Hz and amplitude of +/- 10%. The unsteady lead car shows a very predictable
and artificial behaviour which wouldn’t be found in a real driving context. In Figure 3, the velocity profiles of the lead car in the different experimental conditions can be seen.

Table 2: The test conditions the participants performed. NO-ST = without secondary task (n=19), VST = visual secondary task (n=19) and CST = cognitive secondary task (n=10).

<table>
<thead>
<tr>
<th></th>
<th>130 km/h</th>
<th></th>
<th>90 km/h</th>
<th></th>
<th>50 km/h</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steady</td>
<td>Unsteady</td>
<td>Steady</td>
<td>Unsteady</td>
<td>Steady</td>
<td>Unsteady</td>
</tr>
<tr>
<td>Free following</td>
<td>NO-ST</td>
<td>NO-ST</td>
<td>NO-ST</td>
<td>NO-ST</td>
<td>NO-ST</td>
<td>NO-ST</td>
</tr>
<tr>
<td>VST</td>
<td>VST</td>
<td>VST</td>
<td>VST</td>
<td>VST</td>
<td>VST</td>
<td>VST</td>
</tr>
<tr>
<td>CST</td>
<td>CST</td>
<td>CST</td>
<td>CST</td>
<td>CST</td>
<td>CST</td>
<td>CST</td>
</tr>
<tr>
<td>Imposed at 0.6</td>
<td>NO-ST</td>
<td>NO-ST</td>
<td>NO-ST</td>
<td>NO-ST</td>
<td>NO-ST</td>
<td>NO-ST</td>
</tr>
<tr>
<td>IVT</td>
<td>VST</td>
<td>VST</td>
<td>VST</td>
<td>VST</td>
<td>VST</td>
<td>VST</td>
</tr>
<tr>
<td></td>
<td>CST</td>
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</tbody>
</table>

Figure 3: Velocity plot of the different experimental conditions (left) track layout (right).

The two secondary tasks were constructed to interfere with the driving task on different resources according to the multiple resource model (Wickens 2002). The visual secondary task (VST) mainly interferes on the visual perception resource, which is very important because driving is mainly a visual-motor task. The cognitive secondary task (CST) interferes with the cognitive processing resources (see Figure 4). The two tasks will be described below. All participants drove the 12 scenarios with and without visual secondary task. The cognitive secondary task is driven by 10 subjects.
Figure 4: Wickens’ multiple resource model with the parts where the visual secondary task (red) and cognitive secondary task (green) interfere with the primary driving task.

The visual secondary task consisted of three pictograms which appeared on a display, see Figure 5. This display was positioned at the place where normally the radio would be. Three to four seconds after the three pictograms appeared, a fourth one appeared under the three pictograms. Participants had to use a 3 button input device to indicate which pictogram matched this fourth one.

Figure 5: Display for the visual secondary task: Matching the fourth pictogram with the three above. (Left). Driving simulator (right).

The cognitive secondary task consisted of a sequence of letters auditory presented to the participant while driving. The participant had to detect whether a certain letter was already presented before (‘n-back’ method). The more letters occur between two same letters, the more difficult the task gets.
2.2 **Analysis of behaviour**

The data from the simulator study of IFSTTAR will be analysed. This will give insight in the car following performance and the control effort put into controlling the car.

2.2.1 **Car following performance**

Car following is the task of following the car in front. The speed of the following car depends on the preceding car. To show the performance regarding car following, the following measures are used:

- Average distance to lead car [m] (front to rear bumper)
- Average absolute speed difference of lead and ego car [m/s]
- Average inter vehicular time (IVT) [s]

The first measure, average distance to the lead car, indicates how well the subject is trying to follow the lead car. The average absolute speed difference indicates how well the participants actually follow the speed of the lead car. The average inter vehicular time indicates the safety margin the participant adopt. Furthermore the parameters of the Helly model, see 2.3.1, will be used to give more insight in the sensitivity of the driver to speed difference or distance to the lead car.

2.2.2 **Control effort**

To see whether the subjects put more effort into controlling the vehicle when faced with a secondary task, the following control effort measures are used:

- RMSE of derivative of steering wheel rotation []
- RMSE of derivative of gas pedal depression []
- RMSE of derivative of brake pedal depression []
- Frequency of brake actions [1/s]

The derivative is used because this will indicate if the subjects are actually rotating the steering wheel or moving the gas/brake pedal. The RMSE is used because the direction of movement is not important. With the first three measures, it can be assessed how many effort is put into lateral and longitudinal control of the vehicle. The last measure indicates if more brake actions are performed. Brake action is defined as an increase of brake pedal depression from 0 to nonzero.

2.3 **Car following models**

The driving task of car following typically concerns the interaction between adjacent vehicles in the same lane. So the model tries to describe the behaviour of drivers following each other. In general form, a car following model can be described as follows:
The acceleration ($a$) of the following vehicle is a function of distance to the preceding vehicle ($\Delta x$) minus some desired distance ($D(v)$), which is speed dependent and the speed difference ($\Delta v$) between the vehicles. Different car-following models will be presented and a choice will be made to which will be used for the modelling of distracted driving behaviour.

### 2.3.1 Helly model

The Helly model, first published in (Helly 1959) is used to describe the car following behaviour. The model equation and its parameters will be explained. The Helly model is a linear car following model. Input for the model is the speed difference and distance between ego and lead car. With these two values, and five parameters which have to be set, it calculates the acceleration of the ego car. The ego acceleration is computed as follows:

$$ a_i(t) = a_i(t) = f(\Delta x - D(v), \Delta v) $$

2.3-1

$$ a_i(t) = K_v \Delta v_i(t - \tau) + K_d \{\Delta x_i(t - \tau) - h_i(t)\} $$

2.3-2

$$ h_i(t) = h_0 + h_v v_i(t) $$

2.3-3

The five parameters of the model which need to be set are:

- $K_v$ = corrective feedback gain controlling relative speed
- $K_d$ = corrective feedback gain controlling following distance
- $h_0$ = desired distance at standstill
- $h_v$ = additional THW representing the dependency of desired distance on the speed
- $\tau$ = visuomotor delay

The desired free velocity in this model is set to a high value. This results in a model which always accelerates till it is within the desired distance to the lead car. The gains $K_v$ and $K_d$ can be seen as a measure of how well the velocity profile of the lead car and desired distance profile will be followed. In the left picture of Figure 6, the velocity response of the ego car can be seen for high and low values of $K_v$. With a high $K_v$, the lead car velocity profile is, after delay $\tau$, followed almost perfectly. With low $K_v$, the behaviour is looser and has an overshoot. The same difference, but than on the following distance profile, is seen with a high and low following distance gain $K_d$, see right picture of Figure 6.
2.3.2 Intelligent Driver Model (IDM)

The intelligent driver model uses the same inputs (relative speed and distance to the lead car) as the Helly model. It has a non-linear response to speed difference (Treiber, Hennecke, and Helbing 2000).

$$
\dot{v} = a \left[ 1 - \left( \frac{v}{v_0} \right)^\delta - \left( \frac{s^*(v, \Delta v)}{s} \right)^2 \right]
$$

The desired minimum gap ($s^*$) is:

$$
s^*(v, \Delta v) = s_0 + T v + \frac{v \Delta v}{2 \sqrt{ab}}
$$

- $\dot{v}$ = acceleration of ego car
- $\Delta v$ = speed difference between lead and ego car
- $\Delta x$ = following distance of ego car
- $v$ = speed of ego car
- $s$ = distance to lead car
- $s^*$ = desired distance of ego car

The model parameters are:

- $a$ = maximum acceleration
- $b$ = desired deceleration
- $v_0$ = desired velocity
- $\delta$ = acceleration component
- $T$ = safe time headway
- $s_0$ = desired distance at standstill
According to (Treiber, Hennecke, and Helbing 2000), the IDM model has different driving modes, depending on traffic conditions. In equilibrium traffic, the model keeps a velocity dependent equilibrium gap. At very low density traffic, the model accelerates with parameter $a$ to the desired velocity. When the gap ($s$) is smaller than the desired distance ($s^*$) and the velocity difference $\Delta v$ is very high, the deceleration approaches $b$. With low approach rates, the $s_0 + T v$ term dominates.

### 2.3.3 Action-perception threshold models

The action-perception thresholds are based on the presence of perceptual thresholds. The human perception is limited and not all changes in relative speed or distance to the lead vehicle will be noticed. When the changes are within these thresholds, the driver will maintain a constant acceleration. With crossing one of the thresholds, the driver will adjust its acceleration (Brackstone and McDonald 1999).

### 2.3.4 Conclusion

The use of thresholds makes the action-perception threshold model less appropriate to use for the data available, see Figure 3. Due to the large speed variation in the data, the thresholds will be crossed very often and an almost continuous model will occur. Therefore the Helly and IDM model are more suitable to model the data from the experiment. According to Hoogendoorn (Hoogendoorn et al. 2010), the Helly model performs slightly better and the parameters are more intuitive. It should be noted that the model describes low acceleration patterns quite well but when the magnitude of acceleration fluctuations is increased significant errors occur (Brackstone and McDonald 1999). To assess if the Helly model can be used, and if the IDM model performs better with regard to this known problem of the Helly model, in 3.3.3 a comparison between these models will be made.

### 2.4 Parameter estimation

In order to reflect the observed behaviour (of the participants and the vehicle together) in certain experimental conditions, the parameters for the car following models in these conditions need to be estimated. The same method as in (Saffarian, de Winter, and Happee 2013) is used. By an iterative optimization process, the model parameters are altered such that the error between predicted model and observed participant’s acceleration and following distance is minimized. It tries to find a model response which fits best on the participant’s response, see Figure 7. This is done with a nonlinear least squares estimate. The squared error between the model and the observed acceleration and following distance is minimized. The error criterion is weighted in such a way that the error of acceleration and following distance both contribute for about 50% for optimal accuracy (Saffarian, de Winter, and Happee 2013). In Figure 7, the difference of the initial model and optimized model is shown. It can be seen that the optimized model better reflects the observed behaviour.
2.5 Traffic flow simulation

To see the influence of a distracted driver on the road capacity, a traffic flow simulation will be carried out. To simulate the traffic flow, the Helly and IDM model are used to simulate multiple vehicles on a single lane. The individual estimated model parameters are used as input for the traffic flow simulation. The parameters are randomly assigned to the vehicles in the simulation. In this way a heterogeneous flow is simulated. A single lane road stretch of 4000 m. is used with a time step of 0.1s and a simulation time of 250s. The maximum velocity is set to 120 km/h.

The inflow of vehicle's $q_{in}$ is increased in steps of 100 veh/h from 500 to 4000 veh/h. The initial conditions are an empty road stretch. The speed of the vehicle entering the network is set to the current speed of the vehicle which entered the network before him with a THW of $3600/q_{in}$.

When one vehicle's position is further than the position of its predecessor, the simulation is stopped. The intensity, density and mean speed are calculated using Edie’s (Edie 1965) definition. The equations are respectively:

\[ q = \frac{\sum_i x_i}{X T} \quad 2.5-1 \]

\[ k = \frac{\sum_i t_i}{X T} \quad 2.5-2 \]

\[ u_M = \frac{q}{k} \quad 2.5-3 \]

The spatial resolution used in the simulation is 250 m. the temporal resolution is 10 s.

To quantify the traffic flow, the mean variance of the speed over the whole road stretch is calculated. Therefore the mean speed per segment is averaged for the whole simulation time. The variance of these mean speeds per segment is then calculated.
The data of the simulator experiment at IFSTTAR is used to analyse the behaviour of the subjects when they perform a secondary task. This will give insight in how the behaviour changes when a secondary task is performed. The data is then used to estimate parameters for different Helly models and compare them to see to what extent the models can be used to simulate distracted behaviour. With this car following models, a traffic flow simulation can be performed in order to see what the effect of distracted drivers has on the traffic flow.

### 3.1 Selecting suitable data

The Helly and IDM model both use velocity difference and distance as input. For a good estimation of the parameters, the velocity should vary. In Figure 8, the lead car velocity profiles can be seen for the three different environments (steady and unsteady lead car behaviour). From this figure the usable data can be identified. In the urban environment, all the data is usable for the estimation, the speed of the lead car is almost continuously varying. For the steady lead car in the rural and highway environment only the acceleration and deceleration phase can be used. For all experiments, the amount of data in these initial and final stages is small (from 9 to 25 seconds).
The unsteady lead car behaviour is also analysed. Because the lead car velocity is continuously varied this data could potentially be used to estimate the model parameters. This unsteady lead car behaviour is not well reflected in the observed behaviour of the driver. This means that it is not suitable for the parameter estimation. To evaluate that this behaviour is not reflected, the coherence between lead and ego car velocity at 0.2 Hz (the frequency of the applied variation to the lead car velocity) is calculated over the period where the 0.2 Hz variation is applied to the lead car velocity, see Table 3. It is observed that in the constrained following condition, the unsteady lead car behaviour is much better reflected, the difference in coherence is indeed significant (p < 0.01).

Table 3: Mean coherence of lead and ego car velocity at 0.2 Hz with std deviation in parentheses

<table>
<thead>
<tr>
<th>Coherence at 0.2 Hz</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsteady free following</td>
<td>0.35 (0.23)</td>
</tr>
<tr>
<td>Unsteady constrained</td>
<td>0.71 (0.19)</td>
</tr>
</tbody>
</table>

This difference is illustrated in Figure 9. In the left picture, the response of the subject (green line) to an unsteady lead car (blue line) is shown for the free following condition. In the right picture, the response in the constrained condition is shown. It can be seen that in the constrained condition the unsteady lead car behaviour can also be seen in the subject behaviour. That the subjects hardly respond to the unsteady lead car in the free following condition can be because the speed difference and variation in distance is not big enough to evoke an action by the subjects. In the constrained condition, the subjects drive much closer to the lead car and a reaction to the unsteady behaviour might be needed to keep driving safe. Furthermore to keep the car at 0.6 s. IVT, the subjects need to respond to the unsteady lead car behaviour.
3.2 Analysis of performance and control effort

To study the influence of a secondary task on the car following performance of the subjects, the data of the simulator experiment is analysed. In 2.2, the measures used for this analysis are explained. These measures are distance to lead car, speed difference between lead and ego car and inter vehicular time (IVT). The three measures are calculated directly from the data of the simulator experiment. Last it is examined if the driver uses the same effort to control the vehicle with and without secondary task.

3.2.1 Statistical analysis of simulator data

In the simulator experiment, three variables are changed in the different conditions. These three variables are:
1. Lead car behaviour Steady and unsteady lead car
2. Following task Free following and constrained at 0.6 s IVT
3. Secondary task Without secondary task (NO-ST), with visual secondary task (VST) and cognitive secondary task (CST)

In total the participants drove 12 runs in the urban environment. For more explanation about the different test conditions, see paragraph 2.1.1. To look at the driver performance, the mean distance to the lead vehicle, the mean absolute speed difference and the IVT are compared. In Table 5, the mean and standard deviation of the 12 conditions can be seen.

Table 5: Mean and standard deviation of the different conditions. ff = free following; NO-ST = no secondary task; VST = visual secondary task; CST = cognitive secondary task.

<table>
<thead>
<tr>
<th>Lead car behaviour</th>
<th>Following task</th>
<th>Secondary task</th>
<th>Distance (m)</th>
<th>Speed difference (m/s)</th>
<th>IVT (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>steady</td>
<td>NO-ST</td>
<td></td>
<td>23.40 (11.05)</td>
<td>2.24 (0.70)</td>
<td>2.44 (1.22)</td>
</tr>
<tr>
<td></td>
<td>VST</td>
<td></td>
<td>15.96 (6.76)</td>
<td>1.75 (0.55)</td>
<td>1.66 (0.73)</td>
</tr>
<tr>
<td></td>
<td>CST</td>
<td></td>
<td>16.70 (7.79)</td>
<td>1.91 (0.64)</td>
<td>1.71 (0.69)</td>
</tr>
<tr>
<td>constrained</td>
<td>NO-ST</td>
<td></td>
<td>8.61 (1.69)</td>
<td>1.16 (0.26)</td>
<td>0.81 (0.17)</td>
</tr>
<tr>
<td></td>
<td>VST</td>
<td></td>
<td>9.27 (2.91)</td>
<td>1.35 (0.37)</td>
<td>0.91 (0.32)</td>
</tr>
<tr>
<td></td>
<td>CST</td>
<td></td>
<td>8.72 (2.23)</td>
<td>1.26 (0.39)</td>
<td>0.86 (0.22)</td>
</tr>
<tr>
<td>unsteady</td>
<td>NO-ST</td>
<td></td>
<td>24.07 (13.66)</td>
<td>2.52 (0.73)</td>
<td>2.49 (1.53)</td>
</tr>
<tr>
<td></td>
<td>VST</td>
<td></td>
<td>17.27 (6.69)</td>
<td>2.21 (0.44)</td>
<td>1.77 (0.70)</td>
</tr>
<tr>
<td></td>
<td>CST</td>
<td></td>
<td>20.22 (7.30)</td>
<td>2.40 (0.64)</td>
<td>1.95 (0.78)</td>
</tr>
<tr>
<td>constrained</td>
<td>NO-ST</td>
<td></td>
<td>9.17 (3.26)</td>
<td>1.66 (0.42)</td>
<td>0.86 (0.30)</td>
</tr>
<tr>
<td></td>
<td>VST</td>
<td></td>
<td>9.39 (2.95)</td>
<td>1.85 (0.39)</td>
<td>0.93 (0.33)</td>
</tr>
<tr>
<td></td>
<td>CST</td>
<td></td>
<td>9.19 (3.32)</td>
<td>1.68 (0.40)</td>
<td>0.87 (0.32)</td>
</tr>
</tbody>
</table>

The different conditions are driven by all participants therefore they are compared with a paired t-test see Table 6. In order to correct for the multiple comparison problem the significance level is adjusted with a Bonferroni correction. For the 9 statistical test, an alpha level of $\alpha = 0.006$ is adopted.

Table 6: p-values of the paired t-test performed between the different conditions. Bold values are significant with a Bonferroni correction for multiple testing, $\alpha = 0.006$.

<table>
<thead>
<tr>
<th></th>
<th>Distance (m)</th>
<th>Speed difference (m/s)</th>
<th>IVT (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>steady ff NO-ST vs. steady ff VST</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>steady ff NO-ST vs. steady ff CST</td>
<td>0.003</td>
<td>0.021</td>
<td>0.009</td>
</tr>
<tr>
<td>steady ff VST vs. steady ff CST</td>
<td>0.734</td>
<td>0.977</td>
<td>0.696</td>
</tr>
<tr>
<td>steady constrained NO-ST vs. steady constrained VST</td>
<td>0.175</td>
<td>0.001</td>
<td>0.064</td>
</tr>
<tr>
<td>steady constrained NO-ST vs. steady constrained CST</td>
<td>0.550</td>
<td>0.644</td>
<td>0.873</td>
</tr>
<tr>
<td>steady constrained VST vs. steady constrained CST</td>
<td>0.023</td>
<td>0.025</td>
<td>0.059</td>
</tr>
<tr>
<td>steady ff NO-ST vs. steady constrained NO-ST</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>steady ff VST vs. steady constrained VST</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>steady ff CST vs. steady constrained CST</td>
<td>0.011</td>
<td>0.006</td>
<td>0.004</td>
</tr>
</tbody>
</table>

When looking at the following task (free following vs. constrained), it can be seen that all measures are significantly different between the two conditions, see last three rows of Table 6. The free following task and constrained task can be considered as very different tasks. The free
following condition can be seen as normal driving behaviour when following a lead car, where the constrained condition doesn't reflect normal driving. Indeed normally you don't drive that close to a vehicle and neither have visual feedback whether you are at 0.6 s. IVT or not. In this constrained condition the car following performance is much more precise. The participants drive closer to the lead car, with less speed difference and smaller IVT.

The secondary tasks in the free and constrained following conditions are compared, see top six rows of Table 6. For the free following condition the average distance, speed difference and IVT are all significantly different between NO-ST and VST conditions. A significant difference of the average distance is seen between the NO-ST and CST task. The cognitive secondary task and visual secondary task do not give a difference in car following performance.

The effect of secondary task on the following task is graphically shown in Figure 10. There it can be seen that the effect of the secondary task is different in the free following condition compared to the constrained following condition. In the free following the average distance, average absolute speed difference and IVT all decrease with a secondary task. This effect is significant for the visual secondary task compared to the no secondary task condition and for the average distance also the CST is significantly different compared to the NO-ST condition. For the constrained following condition the secondary tasks do not interfere with the car following performance. The effect of the secondary task is thus dependent on the following condition.

This can be explained by the limited amount of resources of the human driver and the theory of (Hancock 1989). This states that when the workload is too low, the performance of an operator is not optimal. When the workload is too high, performance will also drop. The free following task without secondary task is probably so easy that the participants didn't perform as well as they can. By engaging in a secondary task, the workload increases, they become more vigilant and the performance increases. In the constrained condition, the participants are effectively doing a secondary task besides car following. They are asked to constrain their following behaviour at 0.6s IVT, which is a very small time gap. On top of that, the secondary task draws from the available resources. The car following performance slightly decreases, only significant for the speed difference in the visual secondary task condition. The constrained condition with secondary task was subjectively reported as the most difficult by the participants.
3.2.2 Influence of a secondary task on control effort

To further investigate the influence of the secondary task on the behaviour, the runs with a secondary task are divided into segments where this task is actually present and parts where no secondary task is presented to the subjects. Also the data is split up in straight and curved track parts to see the influence of secondary task in the different track parts. It is observed in the raw data that the measures sometimes go to zero in one time step and back to the value it was on (see Figure 11). Therefore a low-pass moving average filter with a window size of 5 is used to smooth out these irregularities.

The measures used to compare the driver control effort in the different parts are:

- RMSE of derivative of steering wheel rotation (RMSE dTheta)
- RMSE of derivative of gas pedal depression (RMSE dGaspedal)
- RMSE of derivative of brake pedal depression (RMSE dBrakepedal)
- Frequency of brake actions (Freq. brake action)

The first three measures give an indication about the control effort of the subjects on steering, acceleration and braking. The last measure indicates the number of brake actions.
Figure 11: Raw data of gas pedal depression. At 44.6 s the measure goes to zero and back to its original value in 1 time step.

In Table 7, the top 6 rows compare the whole run with and without secondary task. In the bottom 6 rows is a comparison of the run with secondary task, which is divided into parts of no secondary task and secondary task and curved and straight parts.

The secondary and no secondary task conditions are compared using a paired t-test. Because this analysis consists of 24 t-tests a Bonferroni correction is applied which sets the $\alpha$-value at 0.002.

Table 7: Comparison of whole run with and without secondary task (top rows). Comparison of straight and curved parts with and without secondary task (bottom rows). Both are in the urban environment, free following with steady lead car behaviour. Significance level with a Bonferroni correction is set to $\alpha = 0.002$.

<table>
<thead>
<tr>
<th></th>
<th>RMSE dTheta</th>
<th>RMSE dGaspedal</th>
<th>RMSE dBrakepedal</th>
<th>Freq. brake action</th>
</tr>
</thead>
<tbody>
<tr>
<td>VST</td>
<td>0.3162</td>
<td>0.3783</td>
<td>1.0779</td>
<td>0.0543</td>
</tr>
<tr>
<td>NO-ST</td>
<td>0.3232</td>
<td>0.4203</td>
<td>0.9690</td>
<td>0.0572</td>
</tr>
<tr>
<td>p-value VST</td>
<td>0.536</td>
<td>0.237</td>
<td>0.241</td>
<td>0.514</td>
</tr>
<tr>
<td>CST</td>
<td>0.3121</td>
<td>0.4012</td>
<td>1.2787</td>
<td>0.0497</td>
</tr>
<tr>
<td>NO-ST</td>
<td>0.3436</td>
<td>0.3339</td>
<td>0.9440</td>
<td>0.0422</td>
</tr>
<tr>
<td>p-value CST</td>
<td>0.028</td>
<td>0.099</td>
<td>0.092</td>
<td>0.399</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Straight</th>
<th>Curved</th>
<th>Straight</th>
<th>Curved</th>
<th>Straight</th>
<th>Curved</th>
</tr>
</thead>
<tbody>
<tr>
<td>VST</td>
<td>0.0553</td>
<td>0.6648</td>
<td>0.3638</td>
<td>0.3925</td>
<td>1.0998</td>
<td>1.1760</td>
</tr>
<tr>
<td>NO-ST</td>
<td>0.0741</td>
<td>0.6456</td>
<td>0.5181</td>
<td>0.4440</td>
<td>1.1556</td>
<td>1.2617</td>
</tr>
<tr>
<td>p-value VST</td>
<td>0.017</td>
<td>0.804</td>
<td>&lt;0.001</td>
<td>0.109</td>
<td>0.392</td>
<td>0.484</td>
</tr>
<tr>
<td>CST</td>
<td>0.0496</td>
<td>0.4691</td>
<td>0.3947</td>
<td>0.3958</td>
<td>1.2298</td>
<td>-</td>
</tr>
<tr>
<td>NO-ST</td>
<td>0.0624</td>
<td>0.4506</td>
<td>0.4800</td>
<td>0.5434</td>
<td>1.1858</td>
<td>1.3256</td>
</tr>
<tr>
<td>p-value CST</td>
<td>0.396</td>
<td>0.481</td>
<td>0.191</td>
<td>0.012</td>
<td>0.669</td>
<td>-</td>
</tr>
</tbody>
</table>

In the top rows, it can be seen that the difference between no secondary task and a visual or cognitive secondary task is inconclusive and not significant. The same amount of effort is put into controlling the car in the secondary task conditions compared to the no secondary task condition.

When further specified, in the bottom rows, it can be seen that control effort with a secondary task on the straight parts is less than without a secondary task. For the gas pedal control ($p <$
0.001) this is significant. Although in Figure 12 it can be seen that the participant is distracted from the driving task, no intermittent control is found in the analysis of the control effort. During the distraction, the participants still controls the vehicle.

![Subject is distracted when the secondary task is present.](image)

**Figure 12: Subject is distracted when the secondary task is present.**

### 3.3 Modelling the distracted driver

In the previous paragraph the behaviour of a driver when performing a secondary task is studied. It was concluded that a secondary task has influence on the car following performance and that the participants keep continuously controlling the vehicle. This makes it valid to use a continuous car following model to describe and further analyses the distracted driver. By using different parameters, the difference between a distracted and non-distracted subject can be simulated. The Helly model has some limitations, which will be discussed, and possible solutions are put forward. By estimating parameters for a Helly model which makes a distinction between the parts where a secondary task is presented and not, the difference in behaviour during a secondary task can be analysed. Finally the parameters for individual subjects will be simulated in order to see the between driver differences.

#### 3.3.1 The Helly model underestimation

As already mentioned in paragraph 2.3.4, the Helly model performs less good when estimating high magnitude accelerations. This high magnitude acceleration is especially present in the braking phase, see Figure 13 at 18, 38, 60 and 72 seconds. The Helly model is clearly not able to follow this sudden deceleration and underestimates the magnitude. A similar mismatch is found in (Saffarian, de Winter, and Happee 2013) and mentioned in the review of (Brackstone and McDonald 1999). In the next part a Helly model variant is introduced which makes a distinction between deceleration (braking) and acceleration. This model is compared together with the IDM model to see which performs best in describing the data from this experiment, regarding the VAF's (variance accounted for). It should be noted that in a driving simulator higher braking rates are found, up to 2 times the rate of braking in real driving (Boer, Girshick, and Yamamura 2000).
3.3.2 Enhanced Helly models

In the previous sub-paragraph, it was showed that the Helly model underestimates the braking phase of the subjects’ acceleration pattern. To overcome this problem, an enhanced Helly model is proposed. To investigate the behaviour during the secondary task, another Helly variant is created, see enumeration below. These models are, together with the IDM model compared to each other to see which give the best fit on the data from the experiment.

- **Standard:** Helly model interacting with linear car model (see paragraph 2.3.1).
- **Brake:** Helly model with different gain when braking (effectively scaling up $K_d$ & $K_v$) interacting with non-linear car model.
- **ST-switch:** Helly model with a sixth parameter $K_{vST}$ replacing $K_v$ when a secondary task is performed.
- **ST-switch brake:** Combination of ‘ST-switch’ and ‘brake’ model.

In the next two sections, the brake and ST-switch model will be further explained.

The standard Helly model determines a desired acceleration, which doesn’t take into account whether the subject is accelerating or decelerating. In Figure 13 it can be seen that when the subjects decelerate, the model isn’t able to simulate this accurately. It is assumed that a model which takes braking into account will better fit the acceleration curve. This is achieved by introducing a new model parameter $k_b$, which is only applied when the drivers brake. At the moments the subjects are braking, the value of $k_b > 1$. Effectively this results in multiplying $k_v$ and $k_d$ with $k_b$ and thus a better tracking of the velocity and distance profile. When the values of $k_v$ or $k_d$ become too high, the model becomes unstable. This ‘brake’ model is mathematically shown in equations 3.3-1 and 3.3-2. The brake model takes the movement time of the foot from gas to brake pedal into account. A movement time of 0.5 seconds is used, based on (Green 2000; Triggs and Harris 1982) which estimates the movement time between 0.2 and 0.5 seconds. During this period in which the gas and brake pedal are not applied, the car slows down due to the aerodynamic drag. Therefore a velocity dependent acceleration is implemented to model this drag.
The ST-switch model is used to make a distinction between the parts where a secondary task is present and where this is not present. This will give more insight in the performance during a secondary task.

3.3.3 Comparison of the IDM and standard and enhanced Helly models

The four different Helly models and the IDM model are now compared. The comparison is graphically shown in Figure 14. Here it can be seen that the brake variant of the Helly model and the IDM model still underestimate the braking phase. Although the brake model has a slightly quicker response no major improvement regarding the braking phase is achieved.

In Table 8 the model parameters are shown without secondary task, with a visual secondary task (VST) and cognitive secondary task (CST). The different model parameters are compared with a paired t-test. From the top two rows it can be concluded that without ST the brake model performs better than the standard Helly model. The VAFa and VAFv are significantly higher for the brake model (p = 0.02 and p = 0.002). The IDM model without ST doesn’t perform better than the Helly model. In Figure 14, the model fits for acceleration and velocity
are plotted. The small difference between the brake and standard Helly model can be seen at the braking peaks. There the brake model responds quicker, but participants maximum braking of 5.5 m/s is still underestimated by the model. The estimated value of parameter $k_v$ in the without ST task, is 1.90 with a standard deviation of 0.9. The braking behaviour differs thus substantially between participants. Some will have severe braking peaks where others accelerate and decelerate with the same amount.

The next four rows are results for the visual secondary task runs. First, the visuomotor delay for all four models with VST is much lower than for the no secondary task condition. Subjects respond quicker with a secondary task, probably because they are in a more vigilant state. The subjects with the highest delay in the without ST run, are especially responding more quickly in the VST condition. The higher $k_v$ values also indicate a state where subjects respond more in accordance to the lead car behaviour. When looking at the different models, the brake-model performs slightly better than the standard Helly model with regard to the VAF’s, see top two rows. For the switch model in the VST condition, the value of $K_{ST}$ is almost the same as $K_v$. This indicates that the behaviour during the visual secondary task doesn’t differ from that when the secondary task is not present. In the cognitive secondary task condition, the $K_{ST}$ value differs more from the $K_v$ but this is not significant.

From these parameters a difference between the visual secondary task and cognitive secondary task can be observed. With a visual secondary task, the subjects are more vigilant and perform the following task better. The $K_v$ value is higher than in the without ST condition. This behaviour is present during the whole run, regardless whether the visual secondary task is present. With a cognitive secondary task, the subjects also perform the following task better but this effect is not as big as with a visual secondary task. Furthermore the bigger difference between $K_v$ and $K_{ST}$ indicates that during the presence of the cognitive secondary task, the behaviour is different than when the secondary task is not present.

Table 8: Parameters for the standard, brake, ST-switch and combined Helly models and for the IDM model in the urban environment, free following and steady lead car. Values are means with stdv between parentheses.

<table>
<thead>
<tr>
<th>ST model</th>
<th>VAF Δx (m)</th>
<th>VAFa (m)</th>
<th>VAFv (m)</th>
<th>$k_v$ (1/s)</th>
<th>$k_d$ (1/s²)</th>
<th>$τ$ (s)</th>
<th>$h_i$ (s)</th>
<th>$h_b$ (m)</th>
<th>$k_b$ (-)</th>
<th>$K_{ST}$ (1/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>no brake</td>
<td>0.63 (0.25)</td>
<td>0.54 (0.13)</td>
<td>0.87 (0.06)</td>
<td>0.30 (0.17)</td>
<td>0.12 (0.09)</td>
<td>0.54 (0.66)</td>
<td>1.60 (1.30)</td>
<td>2.46 (3.73)</td>
<td>1.90 (0.90)</td>
<td>-</td>
</tr>
<tr>
<td>no standard</td>
<td>0.62 (0.24)</td>
<td>0.52 (0.11)</td>
<td>0.86 (0.06)</td>
<td>0.42 (0.29)</td>
<td>0.12 (0.09)</td>
<td>0.50 (0.69)</td>
<td>1.57 (1.32)</td>
<td>4.58 (4.59)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>VST brake</td>
<td>0.59 (0.25)</td>
<td>0.57 (0.11)</td>
<td>0.88 (0.06)</td>
<td>0.52 (0.23)</td>
<td>0.19 (0.30)</td>
<td>0.29 (0.14)</td>
<td>0.90 (0.83)</td>
<td>3.09 (3.21)</td>
<td>1.66 (0.64)</td>
<td>-</td>
</tr>
<tr>
<td>VST standard</td>
<td>0.58 (0.24)</td>
<td>0.55 (0.12)</td>
<td>0.87 (0.06)</td>
<td>0.70 (0.34)</td>
<td>0.12 (0.10)</td>
<td>0.31 (0.15)</td>
<td>0.83 (0.86)</td>
<td>5.21 (4.60)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>VST st-switch brake</td>
<td>0.62 (0.23)</td>
<td>0.56 (0.11)</td>
<td>0.88 (0.06)</td>
<td>0.71 (0.37)</td>
<td>0.11 (0.11)</td>
<td>0.34 (0.14)</td>
<td>1.09 (0.84)</td>
<td>3.79 (3.25)</td>
<td>-</td>
<td>0.74 (0.42)</td>
</tr>
<tr>
<td>CST brake</td>
<td>0.60 (0.28)</td>
<td>0.57 (0.11)</td>
<td>0.88 (0.05)</td>
<td>0.56 (0.31)</td>
<td>0.13 (0.13)</td>
<td>0.31 (0.13)</td>
<td>1.00 (0.79)</td>
<td>2.60 (1.62)</td>
<td>1.60 (0.53)</td>
<td>0.54 (0.22)</td>
</tr>
<tr>
<td>CST standard</td>
<td>0.67 (0.28)</td>
<td>0.47 (0.16)</td>
<td>0.87 (0.07)</td>
<td>0.48 (0.39)</td>
<td>0.10 (0.07)</td>
<td>0.49 (0.65)</td>
<td>0.85 (0.56)</td>
<td>2.62 (1.89)</td>
<td>2.23 (1.13)</td>
<td>-</td>
</tr>
<tr>
<td>CST st-switch</td>
<td>0.65 (0.26)</td>
<td>0.50 (0.15)</td>
<td>0.87 (0.07)</td>
<td>0.57 (0.36)</td>
<td>0.10 (0.08)</td>
<td>0.43 (0.41)</td>
<td>0.71 (0.48)</td>
<td>7.86 (6.37)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CST st-switch brake</td>
<td>0.69 (0.25)</td>
<td>0.49 (0.14)</td>
<td>0.88 (0.06)</td>
<td>0.61 (0.36)</td>
<td>0.08 (0.06)</td>
<td>0.35 (0.14)</td>
<td>0.81 (0.59)</td>
<td>7.60 (7.10)</td>
<td>-</td>
<td>0.78 (0.50)</td>
</tr>
<tr>
<td>no IDM</td>
<td>0.60 (0.24)</td>
<td>0.52 (0.13)</td>
<td>0.85 (0.07)</td>
<td>2.00 (0.61)</td>
<td>9.46 (12.70)</td>
<td>0.21 (0.21)</td>
<td>1.59 (1.01)</td>
<td>5.44 (6.33)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>VST IDM</td>
<td>0.56 (0.25)</td>
<td>0.57 (0.11)</td>
<td>0.87 (0.06)</td>
<td>1.97 (0.63)</td>
<td>4.15 (4.35)</td>
<td>0.14 (0.18)</td>
<td>1.09 (0.71)</td>
<td>3.24 (2.88)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CST IDM</td>
<td>0.68 (0.26)</td>
<td>0.45 (0.18)</td>
<td>0.87 (0.07)</td>
<td>1.66 (0.41)</td>
<td>13.36 (27.36)</td>
<td>0.12 (0.12)</td>
<td>0.86 (0.47)</td>
<td>4.61 (3.81)</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
There are no big differences between the Helly variants and the IDM model. The standard Helly model can be used to describe the distracted driver. No evidence of different behaviour during the secondary task is found. All models perform less well in describing the braking phase, but they will describe real world driving probably better because subjects adopt less higher braking rates in real world driving (Boer, Girshick, and Yamamura 2000). When looked at the model parameters, see Table 9, from literature, it can be seen that the parameters in this study are not very different. In the no secondary task condition, the $k_v$ and $k_d$ value are lower, in the visual secondary task condition the $k_v$ value is higher. For the IDM model, there is a bigger difference between the values of $a$ and $b$ found in this study and the one used by Treiber (Treiber, Hennecke, and Helbing 2000), but the parameters of Wu (Wu and Lu 2011) are more in the same range. So the estimated model parameters are in accordance to the ones in literature.

### Table 9: Model parameters from literature: Helly model average from 6 studies (Brackstone and McDonald 1999). IDM model typical parameters of (Treiber, Hennecke, and Helbing 2000) and parameter estimation of (Wu and Lu 2011).

<table>
<thead>
<tr>
<th></th>
<th>$k_v$</th>
<th>$k_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helly</td>
<td>0.51 (0.03)</td>
<td>0.38 (0.63)</td>
</tr>
<tr>
<td>a</td>
<td>0.73</td>
<td>1.67</td>
</tr>
<tr>
<td>b</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>T</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>$s_0$</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IDM (Treiber)</td>
<td>0.66 (0.46)</td>
<td>4.29 (3.69)</td>
</tr>
<tr>
<td>IDM (Wu)</td>
<td>2.34 (1.32)</td>
<td>2.41 (1.50)</td>
</tr>
</tbody>
</table>

#### 3.3.4 Simulation of individual behaviour

While in 3.3.3 the average model is presented, it is also interesting to see the variation of the subjects. Therefore the individual model parameters are simulated, see Figure 15. There the reaction to a ramp decrease of the lead vehicle speed is plotted, for the standard and brake Helly model with and without a VST. It can be seen that individual differences are larger than differences between the two models. In Figure 16, the same models are simulated for a ramp increase of the lead vehicle speed. Here the individual differences are also larger than the differences between the models. The variance in the acceleration and deceleration are similar. Furthermore an overshoot of the brake model in the deceleration is seen, due to the $K_b > 1$. As expected, this is not present in the acceleration, see top left of Figure 16. This overshoot is most noticeable for the subjects with high $K_b$, for the subjects with $K_b$ close to 1 the braking model only results in a delay of 0.5 s. The overshoot seen in the brake action may affect the traffic flow, more severe braking lead to congestion. When the $K_b$ value becomes too high, the model can also become unstable.
Figure 15: Comparison of acceleration (top) and velocity (bottom) of the standard and brake model and NO-ST and VST task, in reaction to a ramp decrease of speed. The parameters for the standard and brake-model comparison are both for the VST. Lines are simulations of individual subjects.

The switch from gas to brake pedal and vice versa can be seen in the brake model behaviour. The influence of the $k_b$ value is seen in the overshoot on the step from 0 to $-4 \text{ m/s}^2$, where the overshoot is bigger for the brake model than for the standard Helly model. Although the brake model describes the subjects’ acceleration and velocity better, the VAFa and VAFv are significantly higher, the difference between the standard and brake model in the reaction to a ramp decrease of speed of the lead car is very small. The difference between NO-ST and VST is more noticeable. It can be seen that the subjects with a VST are braking earlier and more severe. The consequence is that they track the velocity profile of the lead car better than in the NO-ST condition. The variance in behaviour in the VST condition is less than in the NO-ST condition. This may have a positive effect on the throughput in traffic flow simulation.
3.4 Traffic flow

In the previous paragraph, the influence of a secondary (visual or cognitive) task is discussed. The individual driving behaviour is compared and it can be seen that with a secondary task the drivers respond more vigilant to the speed changes of the lead vehicle. This change in behaviour will also influence the traffic flow when a fleet of cars is considered. The models did simulate the distracted driver well, so it is appropriate to use them for a traffic flow simulation of distracted drivers.

A non-homogenous set of vehicles is simulated on a single lane road stretch, see 2.5 for details. In Figure 17, the fundamental diagram of the IDM and Helly model with two different conditions (with and without visual secondary task) can be seen. The maximum capacity of the visually distracted drivers (3000) is higher than for the not distracted drivers (2250). That’s a capacity increase of about 33%. Furthermore the difference between the linear Helly model and non-linear IDM model can be seen in Figure 17. For the Helly model without a secondary task only the free flow part is present, when the density is too high, the model gets unstable.
Table 10: Speed variance of the traffic flow in the NO-ST and visual-ST condition

<table>
<thead>
<tr>
<th>Speed variance</th>
<th>NO-ST</th>
<th>Visual-ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed variance</td>
<td>50.6</td>
<td>38.4</td>
</tr>
</tbody>
</table>

To quantify the effect on traffic flow of the visual secondary task compared to the no secondary task condition, the variance of the speed of the road stretch is calculated (see Table 10). For the visual-ST condition the speed variance is smaller than for the no secondary task condition. That indicates a more homogenous traffic flow for the distracted cars. This was to be expected from the statistical analysis of the car following performance. The capacity increase for the visual secondary task can be explained by the findings of the individual behaviour. The subjects with a visual secondary task drive closer to the lead vehicle so more vehicles can drive per km road. They also drive with less speed difference, so they are able to track the speed profile of the lead car more accurate. This combination makes that the road capacity can increase in the visual ST condition.

Figure 17: Fundamental diagram of the traffic flow. IDM (left) and Helly (right) with and without visual secondary task.

The difference between the IDM and Helly model as well as the difference between the visual secondary task and no secondary task conditions can also be seen in the velocity-density plots, see Figure 18. For the IDM model, the velocity in the no secondary task condition decreases at lower densities than for the visual secondary task conditions.
Figure 18: Density, velocity relation of the IDM (left) and Helly model (right), with and without visual secondary task.
4 Discussion and conclusion

4.1 Research findings

The following research questions are answered in the thesis. The main conclusions about these research questions will be formulated hereafter.

- What is the influence of a secondary task during car following on driving behaviour?
  - Can distracted driving behaviour be accurately described by a car following model?
  - Is the driving behaviour different at the moment the distraction is present?
- What is the effect of a secondary task on traffic flow?

In this study, it is found that the influence of a secondary task depends on the driving task (free following or constrained) in this study. These driving tasks correspond to a low and high workload situation. In the free following condition, with a visual ST the participants drove closer to the lead vehicle with less speed difference compared to the no ST condition (see Table 5 and Table 6). When the subjects performed a more demanding following strategy (keeping a constant IVT of 0.6 s) this effect is not seen. The speed difference even increased with a visual secondary task in this constrained following condition. The effect of the secondary task in the free following condition is unexpected. In literature (Jamson et al. 2004; Strayer, Drews, and Johnston 2003; Strayer and Drews 2004) the opposite is found, the drivers increased the distance to the lead car when engaged in a secondary task. When the IVT found in this study for no ST (2.4 s) and visual ST scenario (1.66 s.) is compared to the values (1.66 s and 1.32 s respectively) found by (Strayer and Drews 2004) it can be seen that especially in the no ST condition the values differ quite much.

With the RMSE of derivative of steering wheel rotation, RMSE of derivative of gas pedal depression, RMSE of derivative of brake pedal depression and the frequency of brake actions the control effort of the participants is analysed. Expected is that the drivers show an intermitted controlling behaviour due to the secondary task. Although the control effort decreases for the gas pedal, on the straight parts during a secondary task no discontinuous control is seen. Despite the secondary task, the participants keep on controlling the car continuous with almost the same effort.
The participants show continuous control and therefore the continuous car following models can be used to model the drivers in this experiment. The data from the simulator experiment is used to estimate the parameters for the Helly and IDM car following model. These models are compared with each other by looking at the VAFs (variance accounted for) for the position, speed and acceleration. The differences between the models are small. All models have trouble describing the steep deceleration of the braking phase. Introducing an extra braking gain in the ‘brake’ variant of the Helly model improves the model slightly at the braking phase. It should be noted that this high braking rates are especially found in driving simulators (Boer, Girshick, and Yamamura 2000) and the Helly model will better describe real world driving. The models are all capable of describing the distracted behaviour. The VAFs of the distracted models don’t differ substantially from the ‘no secondary task’ model. The parameters estimated for the Helly and IDM model are in line with the ones found in literature (Brackstone and McDonald 1999; Treiber, Hennecke, and Helbing 2000; Wu and Lu 2011). So the models can be used for the traffic flow simulation of distracted drivers. The driving behaviour at the moment of the distraction is assessed using the Helly model variant which estimates a different parameter for $k_v$ at the moment of distraction. The $k_v$ changes the most between ‘no secondary task’ condition and the ‘secondary task’ condition and therefore chosen as indicator of behaviour. The estimated value during the visual secondary task doesn’t differ much from the value when no secondary task is presented. Therefore it is concluded that during the distraction the behaviour doesn’t change.

The secondary task also influences the behaviour of a whole fleet of cars in a traffic flow simulation. The subjects with a secondary task drive closer to each other with less speed difference, which leads to an increased capacity of the road. This is confirmed by the traffic flow simulation, the capacity increases with more than 33%. From the variance of the speed in the visual ST and no ST simulation, it is seen that the traffic flow is more homogenous in the visual ST simulation.

The effect of a secondary task in the free following condition can be explained by the theory of (Hancock 1989) see Figure 19. The performance of an operator is optimal when the task requires a certain amount of workload. When a task requires almost no workload, a very dull task, the performance of the operator will not be maximal. When a task requires too much workload it will be difficult and the performance will also drop. In this experiment, the free following task without any secondary task is probably too easy and the drivers are in an underload situation, the performance is not optimal (red part of the inverted U). With a secondary task, the workload of the subjects is increased and as a result the performance is also increased. The constrained following task is more difficult and therefore more demanding (blue part of the inverted U). With a secondary task, the workload becomes higher and the performance drops. That only the speed difference increased in the constrained condition with visual ST is probably due to the fact that the participants had feedback on whether they kept the car at the requested 0.6 s IVT. Although this is an unnaturally close following distance the feedback probably made the impact of the secondary task less big.

The multiple resource theory (Wickens 2002) doesn’t describe all effects of a secondary task found in this study. Only the results in the constrained following condition support the multiple resource theory. For the effects in an overload situation this model is appropriate.
The effect of the visual secondary task is captured in the estimated parameters of the Helly model. With a visual ST the $k_v$-value (gain on speed) is higher, which will lead to a more accurate tracking of the velocity profile and thus less speed difference. The lower $h_v$ (velocity depended distance) leads to a shorter following distance.

When looked at the control effort, the continuous control during the visual secondary task can be explained by the use of the internal mental model. During the distraction, the participants keep controlling the car via this mental model they have of the current driving situation. Because the speed variations of the lead car depend on the track layout, the participants can anticipate on these speed differences. This can explain why they are able to continuous control the vehicle. Another explanation is that they still perceive the driving situation via their peripheral vision. In that way the participants are also able to keep a continuous controlling behaviour. The cognitive secondary task doesn't interfere with the perception of the driver therefore no discontinuous control is observed.

### 4.2 Limitations

Driving simulators are used extensively to study driving behaviour because it’s a controllable environment, and data collection is easy. There are also limitations to the validity of the simulator regarding driver behaviour on the real road. In (Reed and Green 1999), it is concluded that the simulator had a good absolute validity regarding speed control and good relative validity regarding the effects of a secondary task. The results from the simulator study are an indication of real driving behaviour, but can’t be translated directly to real driving.

The car following models used to model the distracted behaviour do all have the general form:

$$a = f(\Delta x - D(v), \Delta v)$$

The acceleration is based on distance to the lead car and relative speed. In the experiment, the subjects were instructed to follow the lead car. The speed variation of the lead car in the urban environment was due to the track layout (see Figure 3). It may be that the subjects did not base
their behaviour solely on the lead car, but also on the track layout. They could anticipate on the 
behaviour of the lead car because of the upcoming corners and roundabouts. This may 
compromise the fit of the car following model.

In this study no hazards are presented to the subjects. The driving task of following the lead car 
was continuous. During this following task no additional hazards (crossing children, other cars 
on an intersection) were presented. Without a secondary task, the driving task was thus very 
easy.

Another limitation of this study was the short driving scenarios of about 1.5 minute. The long 
term effects of the secondary tasks on driving behaviour remain unclear.

### 4.3 Conclusion

This thesis aimed at gaining more insight into distracted driving behaviour. Distraction is one 
of the causes of traffic accidents. Cell phones, navigation and infotainment systems are a 
common source of distraction. In most research, and the common opinion, distraction while 
driving has a negative effect on driving behaviour. When distracted, the drivers pay less 
attention to the driving task and as a consequence take more distance to the lead car. In this 
study the opposite effect is seen. The drivers who are performing a secondary task while doing 
a simple car following task are following their lead car closer with less speed difference 
compared to the condition where they didn’t perform a secondary task. So the distracted driver 
performs their car following task better. This doesn’t mean that everyone now should engage 
in secondary tasks while driving to improve their performance. Two important remarks should 
be made regarding the study. The first one is that this research is performed in a simple driving 
simulator. Low cost driving simulators are able to give insight in the effect of distraction of in-
vehicle systems. In order to get more detailed insights in the effect and nature of distraction an 
on road test is needed (Santos et al. 2005). The second remark is about the primary car 
following task which was not very difficult. Probably it wasn’t necessary to perform this task at 
best to still drive safely. When performing the secondary task, the subjects become more 
vigilant and performed the car following task better. The effect of the distraction is clearly 
dependent on the difficulty of the primary driving task. This is seen when the primary driving 
task is keeping the distance to 0.6s. IVT, which is more effortful than just following a lead car, 
the secondary task doesn’t have a positive effect on the car following performance anymore. 
This constrained following condition is also a very artificial driving condition. In normal 
driving, you won’t drive constantly so close to the lead car. And you certainly have no visual 
feedback on the IVT. This constrained condition can be seen as an attempt to increase the 
driver workload, which was subjectively reported as the hardest condition.

Nowadays, in vehicle technology does take over the driving task more and more. The vehicle 
can keep a safe distance to the lead car and keeps the car in the driving lane. This makes the 
‘driving’ task very easy and possibly dull. As long as the vehicle drives automatically, this 
shouldn’t be a problem. But when the driver takes over control (or needs to take over) the 
performance may not be optimal. With a secondary task, the attention level of the driver can 
be raised which could result in better driving performance at the moment the control is handed 
back to the driver. When the performance increases, the maximum capacity of the road will 
also increase.
Future research can be focused on the transition phase of automated driving, from automated to manual control. It is interesting to see if a secondary task during automated driving keeps the driver alert and vigilant and has a positive effect on the driver performance just after the driver reclaimed control. For the secondary task it would be more appropriate to use real world tasks like sending text messages, engaging in social media or reading a newspaper. The scenarios in this study were quite short, it would be interesting to see if the same effect on car following performance is seen in a longer driving scenario. It could be that due to the secondary task the drivers get tired sooner than when they only perform the driving task than the positive effects are undone.


Hoogendoorn, Raymond, Serge P. Hoogendoorn, Karel Brookhuis, and Winnie Daamen. 2010. “Mental Workload, Longitudinal Driving Behavior, and Adequacy of Car-Following Models for Incidents in Other Driving Lane.” *Transportation Research Record: Journal of the Transportation Research Board* 2188 (-1) (December 1): 64–73.


