Human Factors of Automated Driving: Predicting the Effects of Authority Transitions On Traffic Flow Efficiency.

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Conference paper
Submission date: November, 1st 2014

TRAIL

2nd TRAIL Internal PhD Conference
Delft, 13th November 2014

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Abstract

Automated driving potentially has a significant impact on traffic flow efficiency. Automated vehicles, which possess cooperative capabilities, are expected to reduce congestion levels for instance by increasing road capacity, by anticipating traffic conditions further downstream and also by accelerating the clearance of congestion. However, the effects of automation on traffic flow efficiency may be considerably influenced by human factors such as user acceptance and behavioural adaptations of drivers.

Under certain traffic situations, drivers could prefer to disengage the automated system and transfer to a lower level of automation or are forced to switch off by the system (e.g. in case of sensor failure). These transitions between different levels of automation are called authority transitions and can significantly affect the longitudinal and lateral dynamics of vehicles. Microscopic simulation software packages can be used to ex ante evaluate the impact of automated vehicles on traffic flow efficiency. Currently, mathematical models describing car-following and lane changing behaviour are not able to adequately describe and predict authority transitions.

In order to develop an adequate model of driving behaviour for automated vehicles including these authority transitions, an empirically underpinned theoretical framework is needed where human factors are accounted for. In the proposed research, we aim at developing this theoretical framework, which serves as the basis for the prediction of effects of automated driving on traffic flow efficiency. In order to determine the real-life effect of automation on traffic flow efficiency, firstly, empirical data from Field Operational Test and driving simulation experiments will be collected and analysed. Secondly, microscopic traffic flows models incorporating human factors will be developed: within this framework, authority transitions will be investigated taking into account intra- and inter-driver heterogeneity. Thirdly, the effects of different penetration rates of automated vehicles and different levels of automation on traffic flow efficiency will be investigated.

Key words: automation, authority transitions, human factors, microscopic modelling, traffic flow efficiency.

Front picture: Power companies build for your new electric living. *The Victoria Advocate*, 24 March 1957.

1. Introduction

In recent years, an increasing interest in automated vehicles and systems supporting the drivers in their control task has arisen. Automated vehicles are expected to have a significant impact on traffic flow efficiency, safety levels as well as the environment. Automated vehicles which have cooperative capabilities are expected to reduce congestion levels through an increase in road capacity, through anticipation to the traffic conditions downstream and also through accelerating the clearance of congestion by increasing the outflows from a queue [1]. For instance, these benefits on traffic flow can be attained by reducing the time headways and regulating the speeds.

The introduction of automated vehicles on public roads is likely to be gradual: the functionalities of automated systems are introduced through intermediate steps. In this context, SAE International [2] distinguishes five levels of automation as follows:

- Level 0: manual driving;
- Level 1: driving assistance;
- Level 2: partial automation;
- Level 3: conditional automation;
- Level 4: high automation;
- Level 5: full automation.

According to the above-mentioned definition, these levels differ in terms of automated control tasks and driver supervision of the system. At the driving assistance level, the system takes over either longitudinal or lateral control. In partial automation, the system takes over longitudinal and lateral control, while the driver permanently monitors the system and is expected to resume control at any time. In conditional automation, the system takes over longitudinal and lateral control, while the driver does not have to continuously monitor the system and is expected to resume control in case of an emergency (e.g. sensor failure). In high automation, the system takes over longitudinal and lateral control, even if the driver does not respond adequately to a request to intervene in case of certain roadway and environmental conditions. In full automation, the system full-time takes over longitudinal and lateral control under all roadway and environmental conditions. Moreover, the driver is not required to resume manual control.

In case of certain traffic situations, drivers can prefer to disengage the automated system and transfer to a lower level of automation (or manual driving) [3] or are forced by the system to switch off (e.g. in case of a sensor failure) [4]. These transitions between different levels of automation are called *authority transitions*. These transitions can significantly affect the longitudinal and lateral dynamics of vehicles and are consequently expected to have a significant impact on traffic flow efficiency (e.g. capacity, traffic flow stability).

Mathematical models of driving behaviour of manually driven and automated vehicles [5, 6] can be implemented in microscopic simulation software packages to ex ante evaluate the impact of automated vehicles on traffic flow efficiency at different penetration rates. Currently, mathematical models describing car-following and lane changing behaviour do not account for authority transitions. In addition, it is not clear how authority transitions affect the lateral and longitudinal dynamics of vehicles and to what extent mathematical models of driving behaviour are able to represent these transitions. Therefore, new mathematical models of car-following behaviour and lane changing behaviour are needed. However, in order to do so, insight is required into how authority transitions in automated vehicles affect the lateral and longitudinal dynamics of vehicles. These dynamics may be considerably influenced by human factors such as user acceptance and behavioural adaptations of drivers. Moreover, this insight may be relevant for the design of such systems. Following the definitions proposed by SAE International [2], the foreseen levels of automation which will be investigated in this research are driving assistance, partial automation and conditional automation.

This research proposal is structured as follows. Section 2 presents the literature review that focuses on the effects of authority transitions on driving behaviour and the limitations of current mathematical models. Section 3 describes the research set-up, identifying the knowledge gaps, formulating the research questions and discussing the foreseen research methodology. Section 4

provides the conclusions and recommendations for future research, while also discussing the limitations of the proposed research.

2. Literature review

Before investigating the effects of authority transitions on longitudinal and lateral dynamics, it is essential to investigate the dynamics of the vehicles and discuss the possible motivations that trigger the transitions. In this section, possible reasons for authority transitions between ACC and manual driving are identified based on the available literature. In order to explore the potential effects of the authority transitions on driving behaviour, we introduce an overview of the available research on behavioural adaptations and the changed role of the driver with ACC. In microscopic simulations, a distinction is usually made between the longitudinal vehicle interaction subtask, which is described by car-following models, and the lateral vehicle interaction subtask, which is described by lane-changing models and gap-acceptance models. In order to gain insight into the mathematical models of driving behaviour, a brief overview of the existing car following and lane-changing models is presented. Finally, the knowledge gaps are identified based on the literature review proposed.

2.1. Mandatory and discretionary authority transitions

The authority transitions appear to be strongly related to the characteristics of the driver support system. For example, Field operational Tests (FOTs) [3] investigated driving behaviour with different types of ACC systems that have limited decelerations capabilities and are inactive at speeds below 30 km/h. Drivers prefer to disengage ACC and resume manual control during dense traffic conditions in order to have smaller distance headways. In case of medium dense traffic conditions, drivers tend to deactivate the system to have full control of the vehicle (e.g. in case of overtaking manoeuver). Two types of authority transitions can be distinguished, namely: *discretionary* and *mandatory* authority transitions. In case of *discretionary* authority transitions, the driver disengages the system or switches to a lower level of automation voluntarily. The most common motivations to initiate a discretionary state transition with the above-mentioned types of ACC [5, 7, 8]:

- *Speed adaptation prior to a lane change manoeuver:* The driver plans to make a lane change and the current acceleration is not adequate.
- *Overruling due to defensive or offensive behaviour:* The driver brakes (or accelerates) to create a sufficient (or insufficient) gap for a vehicle in an adjacent lane for merging.
- *Left-lane speed adaptation:* The driver brakes to avoid illegal overtaking on the right and to adapt to the speed of the vehicle in the adjacent lane.

In case of *mandatory* authority transitions, drivers are forced to switch off or switch to a lower level of automation by the system. Possible reasons for mandatory authority transitions are [5, 7, 8]:

- *A sensor failure:* the sensor cannot work properly (e.g. poor visibility due to adverse weather conditions) and the driver has to resume manual control.
- *Reaching the system support constraints in a safety-critical situation:* The system support constraints in speed and acceleration are reached. However, the driver needs to exceed these limits in order to avoid collision or overtake.

No studies were found analysing possible motivations for authority transitions between partial automation, driving assistance and manual driving.

2.2. Behavioural adaptations and changed role of the driver

Adaptations in driving behaviour are defined as the collection of behavioural aspects that arise following a change in the road traffic [9]. Adaptations are defined as *direct* when these behavioural aspects are intentionally realised through system parameters set by the manufacturer of the system, and *indirect* when these behavioural aspects are unintended [9]. For instance, the influence of ACC on the longitudinal driving behaviour of drivers has been extensively investigated since the 90s. In general,

ACC is assumed to reduce driver vigilance, which can result in reduced ability to detect and respond to an emergency situation [10, 11, 12]. For example, while using ACC, drivers may show an impaired ability to respond to emergency situations which require applying the brake pedal [13]. In addition, it appears that ACC systems, which automatically regulate the speed when the vehicle gets too close to the leader, result in higher speeds and shorter time headways [14, 15]. However, little insight was found on the influence of the above-mentioned authority transitions on human driving behaviour.

The effects of ACC on driving behaviour may be related to the changed role of the driver, who is transformed from a manual controller to a supervisor of the system [1]. Indeed, automated vehicles require drivers who are capable to resume control in case of authority transitions. Studies in the field of aviation have suggested that monitoring the system for long periods of time might increase the workload of the driver [16] which can result in a reduction in situation awareness and a failure in the detection of critical changes in the state of the system [17]. In addition, indirect adaptation effects may be due to over-reliance on the system, which is defined as the tendency of human supervisors to place too much trust in automated systems [18]. In the road transport field, similarly, some driving simulator studies have found a reduction in situation awareness [19] and very low levels of self-reported mental workload [20] while driving with ACC.

Stanton et al. [21] validated a driving simulator by comparing responses on a secondary task and driving style questionnaire in both a road car and a driving simulator. After that, they investigated the workload associated with four different levels of automation: manual, ACC, active steering system (AS, i.e. automation of lateral control), and simultaneous usage of ACC and AS. They found that no reduction in workload was associated with ACC over manual driving, while a reduction in workload was associated with AS and further reduction was associated with ACC plus AS. These reductions in workload did not result in adverse effects on normal driving performance.

Recently, Strand et al. [22] analysed driving behaviour during automation failures with ACC and simultaneous usage of ACC and lateral automated system. In their driving simulator experiment, they found that humans are poor monitors of automation and higher levels of automation aggravate this problem.

2.3. Car following models

The development of microscopic traffic flow models started in the fifties with the so-called car-following models that are based on a supposed mechanism describing the process of one vehicle following another [23]. The scope of these mathematical models is to mimic driving behaviour [24]. In recent years, the importance of these models has further increased, with behavioural models forming the basis for the design of advanced vehicle control and safety systems [25]. Indeed, longitudinal vehicle interaction subtasks have been shown to play an important role in the formation and propagation of congestion [24].

In general, car-following models express the acceleration of a vehicle a_i at time t as a function of speed of the vehicle v_i, speed of the lead vehicle v_{i-1}, net distance headway to the lead vehicle s_{i-1} and acceleration of the lead vehicle a_{i-1} as described in Equation 1 [26]:

$$a_i(t) = f_{cf}(v_i, v_{i-1}, s_i, a_{i-1}) \quad (1)$$

Each model of car-following behaviour could be distinguished by its own control objective [26]. In addition, the model can incorporate the driving behaviour of one lead vehicle (simple car-following) or more lead vehicles (multi-anticipative car following models).

In this section, five types of car-following models broadly cited in literature and used in research are discussed:

- Safe-distance models;
- Stimulus response models;
- Psycho- spacing models;
- Fuzzy logic-based models;
- Cellular Automaton models (CA).

Safe-distance car following models describe the dynamics of a single vehicle assuming that the driver maintains a safe distance headway in order to avoid collisions with the lead vehicle in case of emergency manoeuvres. This approach is firstly proposed by Pipes [27], Forbes et al. [28], Kometani and Sasaki [29]: the minimal safe distance is assumed to increase with the velocity of the vehicle. In addition to the original formulation, Gipps [30] includes several mitigating factors, such as a reaction time and maximum braking rate.

Stimulus-response car-following models describe the reaction of a driver (e.g. acceleration and braking) as a function of a stimulus (e.g. changes in relative distance and speed with the leader). This type of model is firstly formulated by Chandler et al. [31] and Helly [32]. Treiber et al. [33] introduced the Intelligent Driver Model (IDM), where the acceleration of the driver is described as a combination of a free-road acceleration strategy and dense traffic condition deceleration strategy.

In general, the above mentioned models assume that the driver reacts to very small changes in the relative velocity with the lead vehicle and does not react when the difference in velocity is equal to zero. In addition, the magnitude of the response is the same for small and large distance headways.

In order to overcome these limitations, the so-called psycho-spacing models which include insights from perceptual psychology are introduced by Michaels [34] and Todosiev and Barbosa [35]. They point out that drivers are characterized by certain limits in the perception of the stimuli to which they react (perceptual thresholds). The car following behaviour is described on a relative speed-spacing plane (DV, DX). In these models, the fundamental behavioural rules introduced assume that, in case of large distance headways, the driver does not respond to velocity differences. Similarly, in case of distance headways smaller than a certain threshold, the driver does not perceive and respond to relative velocities smaller than a boundary value.

Fuzzy-logic based methods are firstly applied to car-following models by Kichuchi and Chakroborty [36], Yikai et al. [37]. The aim is to describe accurately driving behaviour rather than trying to model the traffic system mathematically. The input variables are divided into a number of overlapping “fuzzy sets” describing to what extent a variable (e.g. distance headway) fits the description of a “term” (e.g. “close”) and are processed according to fuzzy “if-then” rules (e.g. IF “close” THEN “brake”). The results of the individual rules are averaged and weighted into one single output decision.

CA-models represent the traffic system by using cells of equal size and describe the movement of vehicles from cell to cell in a discrete way. These models are introduced by Nagel [38], Wu and Brilon [39]. The size of the cells is chosen such that a vehicle driving with a velocity equal to one moves to the next cell during one time step. CA- models consider a minimal set of driving rules: vehicles accelerate when the velocity is lower than the maximum velocity and decelerate when the distance to the leader is smaller than minimum distance gap or spontaneously with a given probability.

For a more detailed overview, it can be referred to Brackstone and McDonald [25].

In order to include automated longitudinal control tasks into microscopic simulations, car-following models need to be extended. For instance, ACC can be implemented considering a different vehicle class where speeds and headways are regulated following specific rules [5] and calibrating the parameters of the model separately [6].

2.4. Lane-changing models

Lane changes have been shown to influence traffic flow efficiency substantially. For instance, Ahn and Cassidy [40] claim that lane change is the main cause for traffic breakdowns.

Lane change models predict when lane changes are performed taking into account different motivations. Gipps [41] proposed one of the earliest frameworks for lane-changing decision in an urban driving environment: drivers aim in travelling from A to B in a safe and comfortable manner. Most of the models proposed [41, 42, 43] distinguish between mandatory and discretionary lane-changes. Mandatory lane changes (MLCs) occur when the driver is forced to change lane in order to follow a specific route. Discretionary lane changes (DLCs) occur when the driver perceive that the lane change provide better traffic conditions. However, Toledo et al. [44] demonstrated the potential shortcomings of assuming that lateral and longitudinal interaction subtasks are independent processes. They proposed an integrated driving behaviour model assuming that drivers develop short terms plans in order to accomplish short terms goals. Driving behaviour is explained through the inclusion of

variables related to lane proximity, trip plan, network knowledge and driving style. Treiber and Kesting [45] introduced an integrated lane change model (MOBIL) where the acceleration from the car-following model is used to evaluate the desire and safety of lane changes. However, this model only considers the lane-change reason of speed. In order to overcome these limitations, Schakel et al. [46] introduced the Lane Change model with Relaxation and Synchronisation. Drivers are assumed to prepare for a lane change by selection gaps for merging and synchronizing speed. In addition, the lane change process may influence the car following subtask: drivers accept smaller headways during and after lane changes (i.e. relaxation).

In order to include automated lateral control tasks into microscopic simulations, lane-changing models need to be extended, introducing specific rules and calibrating the parameters of the model separately.

2.5. Effects of automation on traffic flow efficiency

Several studies are available on the influence of automation on traffic flow efficiency in terms of capacity, capacity drop and traffic flow stability. However, these studies mainly focus on the influence of automation on the longitudinal control task on highways through ACC and Cooperative Adaptive Cruise Control (CACC), not considering the influence of authority transitions. Studies on the effects of automation of the lateral control task on traffic flow efficiency are currently missing.

Capacity is the maximum flow rate per lane. Microscopic simulations studies [47, 48, 49, 50] suggested that a beneficial effect for capacity could be achieved through automated platooning of vehicles (i.e. ACC and CACC). However, Klunder et al. [5] pointed out that these effects could be considerably influenced by the possibility to switch on and off the ACC.

The *capacity drop* indicates the difference between the maximum upstream inflow (i.e. capacity) and the maximum downstream outflow from traffic congestion (i.e. *dynamic capacity*). This drop is caused by the larger headways maintained by drivers after congestion. The capacity drop can be considered as an indicator of the performance of a highway during congested conditions. Studies analysing the capacity drop in relation to automation are scarce. However, Kesting et al. [51] observed that capacity increases linearly and dynamic capacity increases over-proportionally when the penetration level of ACC vehicles increases and the driving strategies are adapted to the traffic conditions in terms of maximum acceleration and time headways. They suggested that the faster increase in dynamic capacity compared to capacity can be explained as an ‘obstruction effect’ caused by slower drivers which hinder faster ACC vehicles.

Three types of stability can be identified [52]: *local stability, string stability* and *flow stability*. Local stability refers to two vehicles in a car-following situation. The car-following process is defined to be stable if the magnitude of the disturbance decreases with time. String stability is related to a platoon of vehicles and focus on the propagation of disturbances between the vehicles in the platoon. A platoon is considered stable when the disturbance decreases while propagating upstream. Traffic flow stability can be considered related to a series of platoons, characterized by platoon sizes and inter-platoon gaps. Traffic flow is stable when a disturbance of a platoon is transferred to upstream platoons while decreasing in magnitude. Dealing with automation, it can be assumed that the string composed by ACC vehicles is not stable [53]. However, CACC vehicles can result in a more stable traffic flow [54]. Schakel et al. [55] pointed out that in mixed traffic conditions the presence of CACC vehicles leads to limited effects on traffic flow stability and substantial consequences for the characteristics of shock-waves.

It can be concluded that the available studies are based on simulations and use relatively simple mathematical models of driving behaviour for ACC and CACC. Moreover, the influences of the automation of the lateral control task and the authority transitions on traffic flow efficiency are not analysed.

2.6. Knowledge gaps

Based on the literature review proposed, the main knowledge gaps are identified as follows.

1. *Empirics of automated driving in case of authority transitions*
   The studies available in literature on authority transitions between ACC and manual driving are generally based on FOTs and it is not clear how authority transitions affect the lateral and

longitudinal dynamics of vehicles. No studies based on FOTs were found exploring the effects of authority transitions between conditional automation, partial automation and manual driving.

2. *Human factors of automated driving in case of authority transitions*
   No studies based on FOTs were found analysing possible motivations for authority transitions between conditional automation, partial automation and manual driving. The relationships between authority transitions, human factors and human driving performances have never been explored explicitly. In addition, an underpinned theoretical framework defining the relationships between authority transitions, human factors and traffic flow conditions is missing.

3. *Modelling of automated driving in case of authority transitions*
   Most mathematical models describing car-following and lane changing behaviour do not account for authority transitions and for this motivation there is no clear view to what extent parameter values and model performances of current models are affected by authority transitions.
   The available studies on the effects of automation on traffic flow efficiency are based on simulations and use relatively simple mathematical models of driving behaviour for ACC and CACC. To the best of our knowledge, no mathematical models describe driving behaviour in case of conditional automation and partial automation.

4. *Effects of automated driving on traffic flow in case of authority transitions*
   No studies were found on the effects of authority transitions between ACC and manual driving on traffic flow efficiency in terms of capacity drop and traffic flow stability.
   The influences of the AS and authority transitions between AS and manual driving on traffic flow efficiency (i.e. capacity, capacity drop and traffic flow stability) have never been investigated. Similarly, the effects of conditional automation on traffic flow have never been explored.

3. Research set-up

In this section, the research objectives and the research hypotheses are formulated based on the knowledge gaps identified and the expected outcome of the research. Next, the research hypotheses are translated into a set of research questions. Finally, the research approach and the proposed research methodology are discussed addressing the formulated questions.

3.1. Research objectives

For each knowledge gap identified, the main objectives of this research are formulated as follows.

1. *Empirics of automated driving in case of authority transitions*
   To gain insight into the longitudinal and the lateral dynamics of automated vehicles in case of authority transitions.

2. *Human factors of automated driving in case of authority transitions*
   To propose a theoretical framework that explores the relationships between authority transitions, human factors and traffic flow characteristics.

3. *Modelling of automated driving in case of authority transitions*
   To develop a mathematical model of driving behaviour that accounts for authority transitions and implement it into a microscopic traffic flow simulation.

4. *Effects of automated driving on traffic flow in case of authority transitions*
   To evaluate the effects of authority transitions on traffic flow efficiency and investigate potential consequences in terms of traffic safety and policy analysis.

3.2. Research hypotheses

Defined the main research objectives, research hypotheses are formulated as follows.

1. *Empirics of automated driving in case of authority transitions*

- Under certain traffic situations, drivers could prefer to disengage partial automation and transfer to driving assistance or manual driving.
- Authority transitions cause significant changes in the longitudinal dynamics (e.g. speed, acceleration and time headway) and in the lateral dynamics of automated vehicles (e.g. lateral positioning and lane changing).
- Comparing different levels of automation, there are significant variations in the drivers' behavioural adaptations before/during/after authority transitions per each level.

2. *Human factors of automated driving in case of authority transitions*
   - Discretionary and mandatory authority transitions are strongly related to the driver support system and traffic flow characteristics.
   - There are significant variations between and within drivers in terms of motivations to voluntary disengage the system and reactions to mandatory authority transitions.
3. *Modelling of automated driving in case of authority transitions*
   - Current mathematical models are not adequate in representing authority transitions between different levels of automations and manual driving.
   - Continuous lateral positioning is a prerequisite for modelling lane-changing behaviour.
   - Incorporating human factors it will be possible to formulate mathematical models which are suitable to represent authority transitions between different levels of automation and manual driving.
   - These models outperform current mathematical models.
4. *Effects of automated driving on traffic flow in case of authority transitions*
   - Authority transitions affect traffic flow efficiency considerably in terms of capacity, capacity drop and traffic flow stability.
   - Authority transitions have significant consequences in terms of safety and policy analysis (e.g. mode choice) that should be further investigated with specific studies.

3.3. Research questions

Formulated the research hypothesis, the research questions are identified as follows.

1. *Do authority transitions influence the lateral and longitudinal dynamics of automated vehicles?*
   - How do drivers react to mandatory authority transitions?
   - What are the behavioural adaptations of drivers before/during/after mandatory and discretionary authority transitions in different levels of automation?
2. *How does human driving behaviour vary during authority transitions?*
   - What are the motivations that lead drivers to switch off/on the system voluntarily?
   - How can the reactions of drivers during mandatory authority transitions be explained?
   - What are the variations within and between drivers and how these variations can be related to the support system, driver characteristics and human factors?
3. *How can human driving behaviour during authority transitions be modelled?*
   - What microscopic modelling approaches have been proposed in literature for authority transitions between different levels of automation and what are the limitations?
     How can current model performances be evaluated in relation to authority transitions?
   - What are the most suitable modelling approaches and mathematical formulations to incorporate authority transitions between different levels of automation?
   - How can the new mathematical model be calibrated and what are the model performances? How can the model be validated?
4. *What are the effects determined by the introduction of automated vehicles on public roads?*
   - Does automated driving improve traffic flow efficiency (e.g. capacity, the capacity drop and traffic flow stability) in mixed traffic conditions and to what extent?

- Are there undesirable effects and how these effects could be mitigated? Are there beneficial effects and how these effects could be further improved (e.g. system design)?

3.4. Research approach and research methodology

3.4.1. Empirics of automated driving in case of authority transitions

The aim is to investigate driving behaviour (i.e. longitudinal and lateral control) in vehicles of different levels of automation (i.e. driver assistance, partial automation, conditional automation) during authority transitions, exploring variations within drivers and differences between drivers. The data will be collected through different methods as follows:

- Field Operational Tests;
- Driving simulator experiments.

Data collection methods

The validity of data collected in a FOT can be considered relatively high while the level of controllability is limited [56]. Indeed, in a FOT it is not possible to present exactly the same conditions to all the participants and therefore precisely control for potential confounding variables. Vice-versa, driving simulators possess a high degree of controllability. Presenting exactly the same traffic flow and environmental conditions to all the participants, driving performances can be assessed objectively [57]. Since reality is represented virtually, driving simulator experiments can result in a reduction in validity. However, recent findings [58] have suggested that driving simulator studies possess relative validity, which means that the observed behavioural response converges in the same direction as in real life. Most of the studies on the changed role of the driver in relation to automation have been performed using driving simulator studies or have been conducted in the field of aviation [59]. Based on available literature, FOTs and driving simulator experiments seem to be useful and complementary instruments to analyse the dynamics of vehicles.

In addition, the data collected include personal characteristics of drivers (e.g. age, gender, driving experience, education, and nationality), driving styles (e.g. aggressive/prudent driving behaviour) and human factors (e.g. mental workload and situation awareness). This information is collected by using a questionnaire expressly designed and self-reported measures.

Data analysis methods

The distributions of speed, acceleration and time headways are analysed in order to study the longitudinal dynamics of vehicles in case of authority transitions. The lateral positioning inside the lane and the lane changing are analysed to investigate the lateral dynamics. The behavioural hypothesis we would like to test is that the authority transitions between different levels of automations and manual driving cause significant changes in speed, acceleration, time headway, lateral positioning and lane-changing. The characteristics of mandatory switching off are investigated in terms of time needed to resume manual control after sensor failure and the consequent speed drop. Similarly, the characteristics of discretionary switching on actions after the sensors are functioning again are analysed. Discretionary authority transitions are explored comparing the longitudinal dynamics of vehicles before and after the voluntary switching on and off.

Detailed analysis of the driving behaviour of single drivers is discussed in-depth by using a relative speed-spacing (DV, DX) plane to identify possible changes in the perceptual thresholds in case of authority transitions. When the vehicle crosses one of these thresholds, the driver will perceive a change in either relative space or relative speed and respond with a constant acceleration or deceleration [60]. In this research proposal, this point in the (DV, DX) plane is defined as an *action point*.

3.4.2. Theoretical framework for human factors of automated driving in case of authority transitions

Based on the main findings of the previous phase, an empirically underpinned theoretical framework for automated driving in case of authority transitions is developed where human factors are accounted for. In this context, Figure 1 presents the relationships between authority transitions, human factors and traffic flow conditions. This theoretical framework represents the basis for identification of the main variables and relationship that will be included in the microscopic traffic flow model.

Data analysis methods

In order to define the position of the action points in the (DV, DX) plane, a data analysis technique which aims at identifying periods of constant acceleration is used [61]. It is assumed that a trajectory can be represented by non-equidistant periods in which the acceleration is constant and consequently the speed can be represented by a continuous piecewise linear function of time. The actions points are defined as the time instants at which the acceleration changes.

After that, a Multivariate Regression Analysis is performed to determine the extent to which the perceptual thresholds vary in vehicles equipped with different levels of automation and during authority transitions. In addition, the relationships between perceptual thresholds, driver characteristics, driving styles and human factors are explored by using Multiple Regression Analysis.

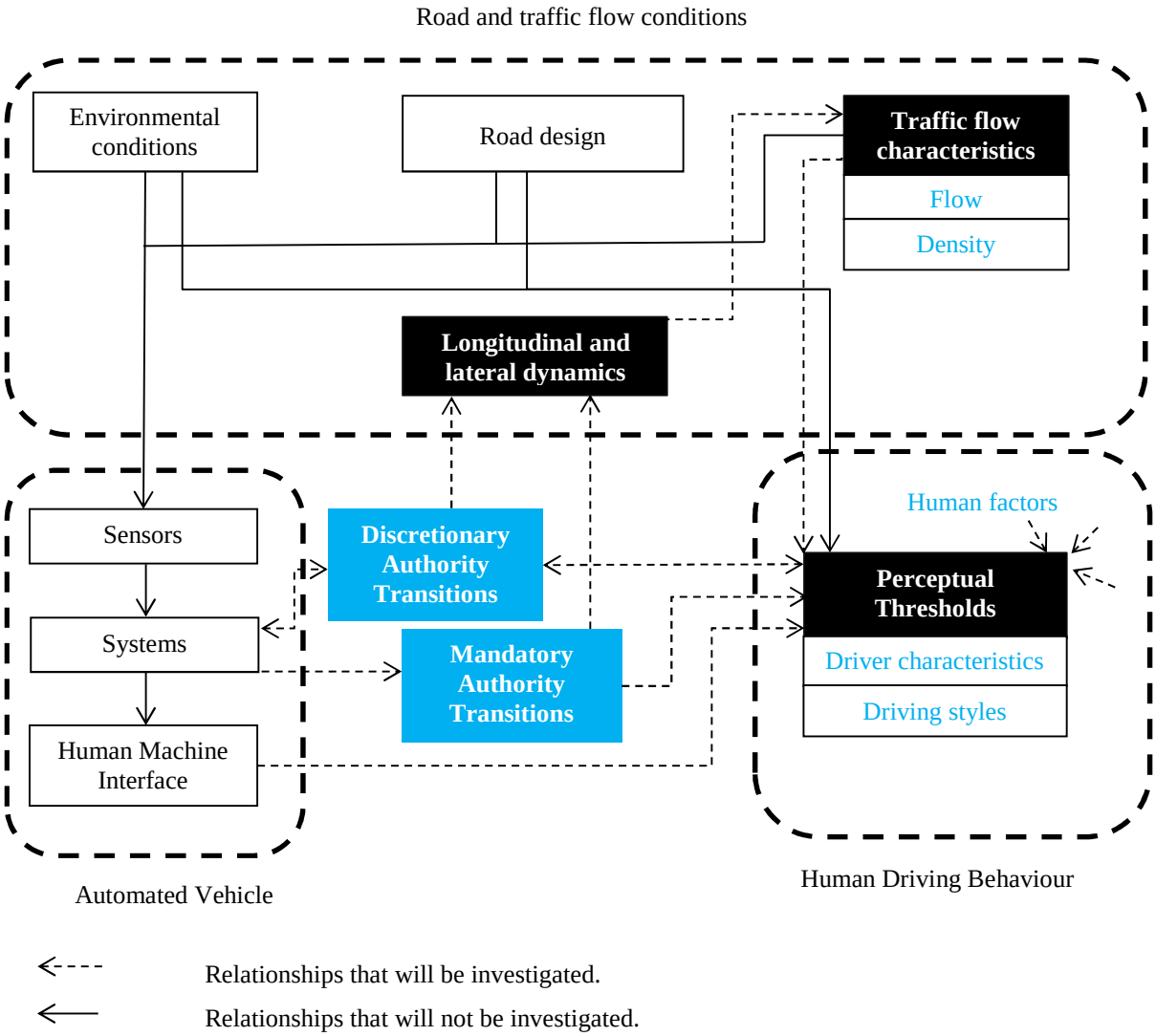

Figure 1 **Theoretical framework of relationships between authority transitions, human factors and traffic flow conditions.**

3.4.3. Modelling of automated driving in case of authority transitions

The limitations of current mathematical models of car following and lane-changing behaviour are investigated. The scope of this phase is to develop new mathematical models of driving behaviour that incorporate authority transitions and could be implemented into microscopic traffic flow simulations.

Data analysis methods
The parameter value fluctuations and performance of current mathematical models for car-following (e.g. IDM, Helly, etc.) and lane changing behaviour (e.g. MOBIL) are evaluated in relation to authority transitions between different levels of automation and manual driving. The models are calibrated using a calibration approach for joint estimation proposed by Hoogendoorn and Hoogendoorn [62]. A Maximum Likelihood approach is used to estimate the parameters, where the joint likelihood is determined through the observation of the trajectories analysed in the experiment.

Microscopic traffic flow simulations
A new mathematical model which incorporates perceptual thresholds in relation to automation is developed. The model requirements are defined based on the main findings of the previous stages. Potential requirements of this model are listed as follows:

- Representation of driving behaviour in different levels of automation (i.e. manual driving, driving assistance and partial automation) by using specific driving rules;
- Dynamic changing of the driving rules in order to represent authority transitions;
- Continuous lateral and longitudinal positioning;
- Integrated car-following and lane-changing behaviour.

The most suitable modelling approach is selected based on the requirements defined and the literature review. After that, the model is formulated in mathematical terms and implemented in an appropriate microscopic simulation package. This model is calibrated combining empirical data from FOTs and driving simulator experiments. The parameter value fluctuations and model performance are evaluated in relation to authority transitions between different levels of automation and manual driving. These results are compared to the performance of current mathematical models.

3.4.4. Effects of automated driving on traffic flow in case of authority transitions

Several penetration rates of automated vehicles are explored and the effect of automated driving on traffic flow efficiency in mixed traffic conditions are evaluated using the microscopic traffic flows models developed in terms of capacity, capacity drop and traffic flow stability. For this purpose, an assessment framework is developed and applied.

Data analysis methods
The distributions of time and distance headway, speed, acceleration, traffic density and traffic flow are analysed simulating several penetration rates of automated vehicles. The effects of automation on traffic flow efficiency are thoroughly discussed. Specific studies are suggested in order to investigate the effects of authority transitions on safety and policy analysis. Finally, suggestions are proposed for the design of new automated systems maximizing the benefits on traffic flow efficiency.

3.5. Potential cooperation within HF Auto

The present research is developed in the context of the project HFAuto–Human Factors of Automated Driving, a Multi-Partner Initial Training Network (ITN) composed by thirteen Early Stage Researchers (ESRs) and an Experienced Researcher (ER). This research plan is organised for being independent from the work of the other researchers in the network. However, potential collaborations which can be very useful to gain a deeper insight into the research questions proposed and can be discussed during the project are indicated as follows:

ER1. Design of the questionnaire on personal characteristics of drivers, driving styles and human factors; prediction of the potential policy impact of automation;

ESR2. Analysis of the motivations that lead drivers to switch off/on the system voluntarily;

ESR4. Analysis of the system setting and mandatory authority transitions;

ESR10. Analysis of the behavioural adaptations of drivers in case of authority transitions;

ESR11. Analysis of the variations within drivers in case of authority transitions;

ESR12. Analysis of the variations between drivers in case of authority transitions.

4. Conclusions

Authority transitions between automation and manual driving are expected to have significant effects on traffic flow efficiency in terms of capacity, capacity drop and traffic flow stability. The available literature indicates that drivers may prefer to disengage ACC and resume manual control in dense traffic conditions and to perform manoeuvres such as lane changing. However, these studies rely on data collected in FOTs and driving simulator experiments expressly analysing authority transitions in a much more detailed way are missing. Moreover, no FOT studies were found exploring authority transitions in case of partial automation. Therefore, it is not clear how authority transitions affect the lateral and longitudinal dynamics of vehicles. No studies were found on the relationship between authority transitions and human driving behaviour and an underpinned theoretical framework defining the relationships between authority transitions, human factors and traffic flow conditions is currently missing. Mathematical models describing car-following and lane changing behaviour do not account for authority transitions and there is no clear view to what extent these models are able to represent authority transitions. No studies were found on the effects of authority transitions on traffic flow efficiency in terms of capacity drop and traffic flow stability.

In this research proposal, a research plan is drafted in order to fill the knowledge gaps identified. First, the effects of authority transitions between partial automation, driving assistance and manual driving on longitudinal and lateral dynamics will be investigated. Data collected in driving simulator experiments and FOTs will be analysed by using statistics. Insight will be gained into the relationship between human driving behaviour and authority transitions. Second, an empirically underpinned theoretical framework for authority transitions including human factors will be developed. Third, this framework will be used to develop mathematical models of driving behaviour that incorporate authority transitions. Potential requirements for these models are the representation of driving behaviour in different levels of automation, dynamic changing of the driving rules, continuous lateral and longitudinal positioning, integrated car-following and lane-changing behaviour. The performances of the resulting models will be analysed and compared to these of current mathematical models. Fourth, the effects of authority transitions on traffic flow efficiency in mixed traffic conditions will be investigated by using the traffic flow simulations developed. Finally, directions for future research will be discussed, outlining the potential consequences of automation on traffic safety and policy analysis.

Acknowledgments

The research has been performed in the project HFAuto – Human Factors of Automated Driving (PITN-GA-2013-605817). The authors would like to thank Marjan Hagenzieker and Haneen Farah (Delft University of Technology) for their valuable comments which contributed to improve the quality of this paper.

5. References

[1] Hoogendoorn, R. G., B. van Arem and S. P. Hoogendoorn. Automated Driving, Traffic Flow Efficiency And Human Factors: A Literature Review. In *Annual Meeting of the Transportation Research Board*, Washington D. C., 2014.

[2] SAE International. *SAE International's Draft Levels of Automation for On-Road Vehicles*. 2014.

[3] Viti, F., S. P. Hoogendoorn, T. P. Alkim and G. Bootsma. Driving behavior interaction with ACC: results from a Field Operational Test in the Netherlands. In *IEEE Intelligent Vehicles Symposium*, Eindhoven, 2008.

[4] Nilsson, J., N. Strand and P. Falcone. Driver performance in the presence of adaptive cruise control related failures: Implications for safety analysis and fault tolerance. In *2013 43rd Annual IEEE/IFIP Conference on Dependable Systems and Networks Workshop (DSN-W)*, 2013.

[5] Klunder, G., M. Li and M. Minderhoud. Traffic Flow Impacts of Adaptive Cruise Control Deactivation and (Re)Activation with Cooperative Driver Behavior. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2129, 2009, pp. 145–151.

[6] Kesting, A. *Microscopic Modeling of Human and Automated Driving: Towards Traffic-Adaptive Cruise Control*. Saarbrücken: Verlag Dr. Müller, 2008.

[7] Pauwelussen, J. and M. Minderhoud. The Effects of Deactivation and (Re)Activation of ACC on Driver Behaviour Analyzed in Real Traffic. In *IEEE Intelligent Vehicles Symposium*, Eindhoven, 2008.

[8] Pauwelussen, J. and P. J. Feenstra. Driver Behavior Analysis During ACC Activation and Deactivation in a Real Traffic Environment. *IEEE Transactions On Intelligent Transportation Systems*, Vol. 11, No. 2, 2010, pp. 320 – 338.

[9] Martens, M. H. and G. D. Jenssen. *Behavioral Adaptation and Acceptance*. London: Springer Verlag, 2012.

[10] Nilsson, L. Safety Effects of Adaptive Cruise Control in Critical traffic Situations. In *2nd World Congress of Intelligent transport Systems*, Tokyo, 1995.

[11] Brown, C. The concept of behavioural adaptation: Does it occur in response to lane departure warning? In *International Conference on traffic and transport psychology*, Berne, 2000.

[12] Stanton, N. A., M. Young and B. McCaulder. Drive-by-wire: The case of driver workload and reclaiming control with adaptive cruise control. *Safety Science*, Vol. 27, 1997, pp. 149-159.

[13] Hoedemaker, M. and M. Kopf. Visual sampling behaviour when driving with adaptive cruise control. In *Ninth International Conference on Vision in Vehicles*, Australia, 2001.

[14] Ward, N., S. Fairclough and M. Humphreys. The Effect of Task Automatisation in Automotive Context, a Field Study of an AICC System. In *International Conference on Experimental Analysis and Measurement of Situation Awareness*, Florida, 1995.

[15] Dragutinovic, N., K. A. Brookhuis, M. P. Hagenzieker and V. Marchau. Behavioural effects of Advanced Cruise Control Use – a meta-analytic approach. *European Journal of Transport and Infrastructure Research*, Vol. 5, No. 4, 2005, pp. 267-280.

[16] Parasuraman, R., M. Mouloua and R. Molloy. Effects of adaptive task allocation on monitoring of automated systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, Vol. 38, No. 4, 1996, pp. 665-679.

[17] Ephrath, A. R. and L. R. Young. Monitoring vs. man-in-the-loop detection of aircraft control failures. In *Human detection and diagnosis of system failures*, Springer, 1981, pp. 143-154.

[18] Danaher, J. W. Human error in ATC system operations. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, Vol. 22, No. 5, 1980, pp. 535-545.

[19] Stanton, N. A. and M. Young. Driver behaviour with adaptive cruise control. *Ergonomics*, Vol. 49, 2005, pp. 1294-1313.

[20] Saffarian, M., R. Happee and J. De Winter. Why do drivers maintain short headways in fog? A driving-simulator study evaluating feeling of risk and lateral control during automated and manual car following. *Ergonomics*, Vol. 55, 2012, pp. 971-985.

[21] Stanton, N. A., M. S. Young, G. H. Walker, H. Turner and S. Randle. Automating the Driver's Control Tasks. *International Journal of Cognitive Ergonomics*, Vol. 5, No. 3, 2001, pp. 221-236.

[22] Strand, N., J. Nilsson, I. Karlsson and L. Nilsson. Semi-automated versus highly automated driving in critical situations caused by automation failures. *Transportation Research Part F* (Forthcoming), 2014.

[23] Hoogendoorn, S. P. and P. H. Bovy. State-of-the-art of vehicular traffic flow modelling. *Journal of Systems and Control Engineering*, Vol. 215, No. 4, 2001, pp. 283-303.

[24] Boer, E. Car following from a driver perspective. *Transportation research Part F: Traffic*

Psychology and Behaviour, Vol. 2, No. 4, 1999, pp. 201-206.

[25] Brackstone, M. and M. McDonald. Car-following: a historical review. *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 2, No. 4, 1999, pp. 181–196.

[26] Hoogendoorn, R. *State-of-the-Art Driving Theory and Modeling in case of Adverse Conditions*. Delft University of Technology, Delft, 2010.

[27] Pipes, L. An Operational Analysis of Traffic Dynamics. *Journal of Applied Physics*, Vol. 24, No. 1, 1953, pp. 274-287.

[28] Forbes, T., H. Zagorski, E. Holshouser and W. Deterline. Measurement of Driver Reactions to Tunnel Conditions. In *Highway Research Board*, Vol. 37, 1958, pp. 345-357.

[29] Kometani, E. and T. Sasaki. Dynamic behaviour of traffic with a nonlinear spacing-speed relationship. In *Symposium on Theory of Traffic Flow*, New York, 1959.

[30] Gipps, P. G. A behavioural car following model for computer simulation. *Transportation Research Part B*, Vol. 15, 1981, pp. 105-111.

[31] Chandler, R. E., R. Herman and E. W. Montroll. Traffic Dynamics: Studies in Car Following. *Operations*, Vol. 6, No. 2, 1958, pp. 165-184.

[32] Helly, W. Simulation of Bottlenecks in Single Lane Traffic Flow. In *Proceedings of the Symposium on Theory of Traffic Flow*, New York, 1959.

[33] Treiber, M., A. Hennecke and D. Helbing. Congested traffic states in empirical observations and microscopic simulations. *Physical Review E*, Vol. 62, No. 2, 2000, pp. 1805–1824.

[34] Michaels, R. M. Perceptual factors in car following. In *Second International Symposium on the Theory of Road Traffic Flow*, Paris, 1963.

[35] Todosiev, E. P. and L. C. Barbosa. A Proposed Model for the Driver-Vehicle System. *Traffic*, Vol. 34, 1964, pp. 17-20.

[36] Kikuchi, C. and P. Chakroborty. Car following model based on a fuzzy inference system. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1365, 1992, pp. 82-91.

[37] Yikai, K., J. I. Satoh, N. Itakura, N. Honda and A. Satoh. A fuzzy model for behaviour of vehicles to analyze traffic congestion. In *Proceedings of the International Congress on Modelling and Simulation*, Perth, 1993.

[38] Nagel, K. Particle Hopping Models and Traffic Flow Theory. *Physical Review E*, Vol. 53, 1996, pp. 4655-4672.

[39] Wu, N., and W. Brilon. Cellular Automata for Highway Traffic Flow Simulation. In: *Proceedings of the 14th International Symposium on Transportation and Traffic Theory*, 1999, pp. 1-18.

[40] Ahn S. and M. Cassidy. Freeway traffic oscillations and vehicle lane-change manoeuvers. In *International Symposium of Transportation and Traffic Theory*, Amsterdam, Elsevier, 2007, pp. 691-710.

[41] Gipps, P. G. A Model for the Structure of Lane-Changing Decisions. *Transportation Research Part B*, Vol. 20, No. 5, 1986, pp. 403-414.

[42] Yang, Q. and H. Koutsopoulos. A microscopic traffic simulator for evaluation of dynamic traffic management systems. *Transportation Research Part C*, Vol. 4, No. 3, 1996, pp. 103-114.

[43] Zhang, Y., L. Owen and J. Clark. Multiregime approach for microscopic traffic simulation. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1644, 1998, pp. 103-114.

[44] Toledo, T., H. Koutsopoulos and M. Ben-Akiva. Estimation of an integrated driving behaviour model. *Transportation Research Part C*, Vol. 17, No. 4, 2009, pp. 365-380.

[45] Treiber, M. and A. Kesting. Modeling Lane-Changing Decisions with MOBIL. In *Traffic and Granular Flow '07*, Berlin, Springer Berlin Heidelberg, 2009, pp. 211-221.

[46] Schakel, W. J. V., Knoop and B. Van Arem. Integrated lane change model with relaxation and synchronization. *Transportation Research Record: Journal of the Transportation Research*

Board, Vol. 2316, 2012, pp. 47–57.

[47] Karaaslan, U., P. Varaiya and J. Walrand. Two proposals to improve traffic flow. In *American Control Conference*, 1991, pp. 2539-2544.

[48] Ioannou, P. *Automated Highway Systems*. Springer, 1997.

[49] VanderWerf, J., S. Shladover and M. A. Miller. *Conceptual development and performance assessment for the deployment staging of advanced vehicle control and safety systems*. UC Berkeley: California Partners for Advanced Transit and Highways (PATH), 2004.

[50] Van Arem, B., C. van Driel and R. Visser. The impact of cooperative adaptive cruise control on traffic-flow characteristics. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 7, No. 4, 2006, pp. 429-436.

[51] Kesting, A., M. Treiber and D. Helbing. Enhanced intelligent driver model to access the impact of driving strategies on traffic capacity. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Vol. 368, No. 1928, 2010, pp. 4585–4605.

[52] Treiber, M. and A. Kesting. *Traffic Flow Dynamics*. Berlin: Springer-Verlag, 2013.

[53] Pueboobpaphan, R. and B. van Arem. Driver and vehicle characteristics and Platoon and Traffic Flow Stability. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2189, 2010, pp. 89–97.

[54] Arnaout, G. and B. Bowling. Towards reducing traffic congestion using cooperative adaptive cruise control on a freeway with a ramp. *Journal of Industrial Engineering and Management*, Vol. 4, No. 4, 2011, pp. 699-717.

[55] Schakel, W. J., B. van Arem and B. D. Netten. Effects of cooperative adaptive cruise control on traffic flow stability. In *13th International IEEE Conference on Intelligent Transportation Systems*, Funchal, 2010.

[56] Anund, A. and K. Kircher. *Advantages and disadvantages of different methods to evaluate sleepiness warning systems*. Swedish National Road and Transport Research Institute, Linköping, 2009.

[57] De Winter, J., P. Wieringa, J. Kuipers, M. Mulder, M. Van Paassen and J. Dankelman. Driver assessment during self and forced-paced simulation-based training. In *Driving Simulation Conference Europe*, Paris, 2006.

[58] Yan, X., M. Abdel-Aty, E. Radwan, X. Wang and P. Chilakapati. Validating a driving simulator using surrogate safety measures. *Accident Analysis & Prevention*, Vol. 40, No. 1, pp. 274–288, 2008.

[59] Sheridan, T. B. *Humans and automation: System design and research issues*. New York: John Wiley & Sons, 2002.

[60] Montroll, E. W. Acceleration and clustering tendency of vehicular traffic. In *Symposium on theory of traffic flow*, Detroit, 1959.

[61] Hoogendoorn, S., R. Hoogendoorn and W. Daamen. Wiedemann Revisited. New Trajectory Filtering Technique and Its Implications for car-Following Modeling. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2260, 2011, pp. 152-162.

[62] Hoogendoorn, S. and R. Hoogendoorn. Generic calibration framework for joint estimation of car-following models using microscopic data. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2188, 2010, pp. 37–45.