Automated Driving, Traffic Flow Efficiency, and Human Factors

Literature Review

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Automation may be assumed to have a beneficial impact on traffic flow efficiency. However, the relationship between automation and traffic flow efficiency is complex because behavior of road users influences this efficiency as well. This paper reviews what is known about the influence of automation on traffic flow efficiency and behavior of road users, formulates a theoretical framework, and identifies future research needs. It is concluded that automation can be assumed to have an influence on traffic flow efficiency and on the behavior of road users. The research has shortcomings, and in this context directions are formulated for future scientific research on automation in relation to traffic flow efficiency and human behavior.

Road transport is an important part of society. However, the costs of congestion, pollution, and traffic accidents are enormous (*1*). Systems supporting the driver may address these problems. Interest has grown in recent decades about development of technologies that support the driver through automation.

Automation of the driving task has many benefits for traffic flow efficiency. Automated driving is expected to reduce current congestion levels through anticipation of traffic conditions downstream, by reducing the probability of traffic breakdown, and by accelerating clearance of congestion by increasing the outflow of a queue. Additional improvements may be achieved through platooning of vehicles, optimization of the distribution of traffic over lanes, and network traffic management and route guidance strategies.

Movement toward the highest level of automation, fully automated vehicles, and thus toward the realization of the mentioned benefits, is gradual. In the literature, two approaches to analysis of development toward fully automated vehicles can be found: a geographical approach and a functional approach (*2*). In the geographical approach, the implementation of most (if not all) aspects of full automation will take place in one step, and the geographical areas of implementation expand gradually. The functional approach is based on the assumption that the functionality of fully automated vehicles cannot be realized suddenly and so intermediate steps must be identified and optimized. An intermediate step toward full automation can be defined as any discernible functional increment whose realization may encounter considerable difficulties.

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The functional approach best represents the development toward full automation. In this sense, the steps or stages toward full automation have to be identified. Gasser and Westhoff formulated four consecutive levels of automation (*3*), as follows:

- Driver assistance,
- Partial automation,
- High automation, and
- Full automation.

In driver assistance, the driver permanently maintains either longitudinal control (speed choice, car following) or lateral control (lane keeping, merging, lane changing, overtaking). The other task can be automated to a certain extent by an advanced driver assistance system. Partial automation entails the situation in which a system takes over longitudinal as well as lateral control. The driver is required to monitor the system permanently and is required to be prepared to take over control at any time.

In the third level, high automation, the system also takes over longitudinal and lateral control, but the driver is no longer required to monitor the system permanently. Nevertheless, the driver must be prepared to respond adequately to a takeover request by the system. On the highest level, full automation, the system again takes over longitudinal and lateral control. However, in case a takeover request by the system is not carried out, the system will return to a minimal risk condition by itself (*3*).

The current state of driver assistance is illustrated by the presence of systems such as adaptive cruise control (ACC) and lane-keeping assistance. However, assistance is on the verge of the second phase: partial automation. For instance, Google and original equipment manufacturers are testing automated vehicles on public roads. However, these tests focus on the technical aspects of automated driving, neglecting the possible advantages of automated driving for traffic flow efficiency.

The relationship between automation of vehicles and its impact on traffic flow efficiency is complex, as the effect of automation on traffic flow efficiency is assumed to be dependent on many factors. For example, besides the settings of the systems, the effects on traffic flow efficiency may be assumed to be dependent on human factors, for example, user acceptance and behavioral adaptation caused by the changing role of the driver.

However, most studies into the influence of automation on traffic flow efficiency are conducted with (microscopic) simulations (*4*). In these studies assumptions are made about the behavior of drivers of automated vehicles and drivers of the surrounding manually driven vehicles. It can be assumed that automation has a substantial influence on the behavior of drivers of automated vehicles as well as that of drivers of manual vehicles interacting with the automated vehicles. The latter is significant because it can be assumed that the development toward fully automated vehicles will follow the functional approach, leading to a situation in which vehicles with different levels of automation may be present simultaneously (*2*).

For formulating a theoretical framework and identifying the needs for scientific research, combined insight is needed into what is known about the impact of vehicle automation on traffic flow efficiency and what is known about changes in behavior of drivers of vehicles having various levels of automation. This paper discusses what is known about the influence of automation on traffic flow efficiency and the influence of automation on (driving) behavior of the drivers of automated vehicles and of the manually driven vehicles interacting with the automated vehicles.

The next section discusses the available research into the influence of automation on several aspects of traffic flow efficiency: capacity, capacity drop, and traffic stability. This section is followed by a presentation of the available literature on (changes in behavior) of individual road users following the implementation of automated vehicles. Next is a synthesis of the findings, as well as the formulation of a theoretical framework and identification of research needs.

INFLUENCE OF AUTOMATION ON TRAFFIC FLOW EFFICIENCY

This section discusses the influence of automation on several indicators of traffic flow efficiency: the influence of automation on capacity, the capacity drop, and traffic stability. The discussion starts with the influence of automation on freeway capacity. Several studies described the influence of automation on the indicators of traffic flow efficiency. However, these studies largely focused on the effect of automation of the longitudinal control task through ACC and cooperative ACC (CACC). No studies were found on the influence of automation of the lateral control task on traffic flow efficiency.

Capacity

It is assumed that the capacity for manually driven vehicles is between 1,800 and 2,200 vehicles per hour per lane (vphpl). A substantial amount of research has been performed on the influence of automation on freeway capacity. For instance, Karaaslan et al. proposed that automation can be assumed to have a substantial influence on freeway capacity through automated platooning of vehicles (*4*). Through microscopic simulations, they determined that, dependent on platoon size, flow maximizing speed, free speed, and separation between vehicles, a substantial benefit for capacity could be achieved through automation. They determined in this context that a capacity can be achieved that is substantially higher that can be achieved when only manually driven vehicles are present.

Ioannou also investigated the potential impacts of longitudinal automation of vehicles on freeway capacity, that is, platooning with coordinated braking (*5*). Ioannou's simulations assumed a typical maximum deceleration level based on test data for the estimation of capacity. Furthermore, Ioannou made a distinction between three scenarios: autonomous platoons, free agent infrastructure-supported platoons, and free agent infrastructure-managed platoons. In the autonomous vehicles scenario, the vehicles were assumed to operate independently with their own sensors, with the infrastructure providing basic traveler information. In the free agent infrastructure-supported platooning scenario, the vehicles operated autonomously but also were able to receive information from other vehicles as well as from the infrastructure. The infrastructure did not have the authority to issue direct control commands in this scenario. Finally, in the free agent infrastructure-managed platooning scenario, the infrastructure had the authority to issue direct control commands. In addition to these three, scenarios with and without mixed traffic (passenger vehicles, buses, heavy trucks) were studied, as were various road surface conditions. In that study's simulations, capacity was reduced by 30% to 40% in the case of wet road surface conditions, irrespective of scenario. Mixing of classes of vehicles also reduced capacity by 11% to 23%, depending on the percentage of buses and heavy trucks. Platooning, especially with coordinated braking, yielded the highest capacity. For 10-vehicle platoons, capacity was up to 7,489 vehicles per hour (vph), which is a substantial increase compared with normal traffic.

VanderWerf et al. also investigated the influence on freeway capacity of the automation of the longitudinal driving task (*6*). That study showed that a CACC system leads to a substantial improvement in traffic flow efficiency and an increase in lane flow from 2,100 vphpl on a 100% manual highway to 2,900 vphpl on a 20% manual, 20% ACC, 60% CACC-equipped highway. No other vehicle classes were incorporated (e.g., trucks). Overtaking was not allowed in the simulations.

Van Arem et al. investigated the effect of CACC-equipped vehicles on overall traffic flow performance (*7*). That study revealed that CACC has a potential positive impact on the traffic throughput. In addition, CACC appears to increase highway capacity near a lane drop. The impact of a dedicated CACC lane (i.e., a lane strictly operated by CACC-equipped vehicles) was studied, and it was shown that with a low CACC penetration (<40%), the effect will lead to a degradation of traffic performance. The positive effect of longitudinal automation (i.e., ACC and CACC) on capacity was confirmed in more recent studies. Arnaout and Bowling explored the effect of CACC on a multilane freeway without any perturbations (no obstacles, ramps, lane drops) (*8*). The study showed that CACC had a positive impact on capacity, especially in the case of high traffic densities. Furthermore, the study confirmed that penetration rate is an important contributing factor in the impact of longitudinal automation on traffic flow efficiency.

Overall, it can be assumed that automation has a substantial influence on capacity. In the next section the influence of automation on a more dynamic aspect of capacity, namely, the capacity drop, is discussed.

Capacity Drop

Capacity drop is the phenomenon by which, when congestion occurs, drivers maintain larger headways than before the speed dropped. This leads to a reduction in capacity. Research has shown that some of the traffic flow mechanisms trigger these capacity drops. The mechanisms are triggered, for example, by high traffic densities, which arise in an individual lane and then gradually spread over the carriageway. From research it follows that the capacity drop, represented by the difference between the free capacity $C_{\text{max}}^{\text{free}}$ and the outflow from congestion Q_{out}, has a magnitude ranging between 5% and 30% (*9, 10*).

Research into the influence of automated vehicles on this traffic flow phenomenon is scarce. As for research into the influence of automation on capacity, most studies focus on the influence of automation of the longitudinal driving task on this traffic flow phenomenon.

Kesting et al., for example, investigated the dynamic capacity after a traffic breakdown in relation to the presence of vehicle equipped with ACC (*9*). That study simulated a traffic breakdown through an increase in the inflow. They concluded that the increase in capacity is not linear and is dependent on the penetration rate. At more than approximately 50% ACC vehicles, the capacity increased faster than at lower percentages. This was confirmed later by Kesting and others in a simulation study of a two-lane highway with an on-ramp (*11*). Automated driving strategies were adapted to the following five discrete traffic conditions:

- Free flow,
- Upstream jam front,
- Congested traffic,
- Downstream jam front, and
- Bottleneck sections.

In the study each traffic condition was associated with a different parameter setting of the car-following model, for example, the intelligent driver model (*12*). The study distinguished between several penetration rates and the percentage of trucks. By calculating the difference between the free capacity C^{free} and the outflow from congestion Q_{out}, the authors observed that the value of the relative capacity drop was between 2% and 12% when adaptation of driving strategies to traffic conditions by automation was not applied. This outcome is well illustrated in Figure 1, which shows that the capacity drop increases when the penetration level increases. The figure also shows that the capacity drop is dependent on the percentage of trucks.

These studies addressing the influence of automation of the driving task on capacity and the capacity drop show that automation could have a beneficial impact on these aspects of traffic flow efficiency. In most of the discussed studies, capacity increased dependent on the penetration rate of the automatic vehicles, and the capacity drop decreased. However, the studies have some drawbacks.

First, these studies relied solely on simulations, which raises the question of validity, especially for studies in which the effect of mixed traffic was considered. It is not yet known to what extent the behavior of manually driven vehicles is affected by the presence of automated vehicles (especially in platoons). Adaptation effects in driving behavior of these vehicles may have a negative effect on the assumed impact automated vehicles have on capacity. Most studies assume that drivers of automated vehicles accept small headways. However, acceptance of handing control to a system is low in the case of small headway settings. The human factor of automated driving is insufficiently considered in the preceding studies.

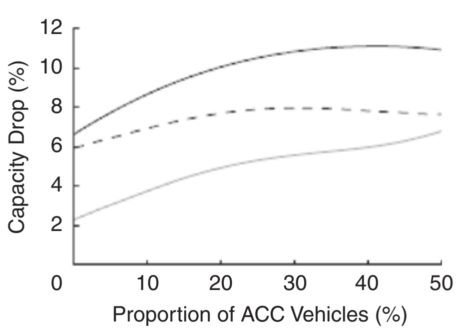

FIGURE 1 Capacity drop, that is, difference between maximum free flow and dynamic capacity as function of penetration rate (*11*). Black line represents 0% trucks; dashed and gray lines represent 10% and 20% trucks, respectively.

Second, most of the simulation studies used relatively simple mathematical models of driving behavior [for example, Arnaout and Bowling used fixed values for key parameters (*8*)].

Third, the reviewed studies focused on automation of the longitudinal driving task (driver assistance). Although studies on the implementation of control algorithms for lane changing were found, no studies addressed the influence of automation of lane changing on capacity and the capacity drop.

Finally, no studies were found on the influence of so-called transient maneuvers (e.g., merging, splitting, entry and exit of platoons, switching from manual to automated control and vice versa) on capacity and the capacity drop.

Traffic Stability

At increasing traffic volumes, the risk of traffic breakdown increases. A stable dynamic system is one that, when perturbed from an equilibrium state, tends to return to its equilibrium state. Following an extensive review, Kesting and Treiber identified the following three types of traffic flow stability (*13*):

- Local,
- String, and
- Flow.

Local stability entails a pair of vehicles in a car-following situation. The car-following process is assumed to be stable if the magnitude of the disturbance decreases over time. String stability, also referred to as asymptotic stability or platoon stability, entails a platoon of following vehicles and focuses on the propagation of the disturbance from one vehicle to another vehicle in the platoon. A platoon is assumed to be stable if the disturbance dampens when propagating upstream.

There are several approaches to traffic flow stability. In this paper it is assumed that traffic flow stability concerns a traffic flow consisting of a series of platoons, characterized by platoon sizes and interplatoon gaps. A traffic flow is assumed to be unstable if the disturbance of a platoon is transferred to upstream platoons while growing in magnitude.

Eyre et al. investigated the influence of automation on (string) stability (*14*). They proposed a simple framework in which a platoon is viewed as a linear mass–spring–damper system. The transfer functions were used to determine the string stability properties of a platoon operating under a given control scheme. That study showed that implementing a fixed-time headway controller had a substantial influence on traffic stability.

Darbha and Rajagopal, however, proposed that a constant-time headway policy leads to unacceptable characteristics for automated traffic flow (*15*). In their study they performed simulations by using a single section of 1,000 m with a single lane and an on-ramp. Time headways of 1 s as well as a gain factor of $\lambda = 1$ were implemented in the simulation. The simulations showed that a constant time headway policy leads to traffic flows with undesirable stability characteristics. Furthermore, they conjectured that stability can be guaranteed only up to the peak density when automated vehicles have negligible actuation and sensing delays.

These findings were contradicted by Li and Shrivastava, who studied traffic flow stability induced by a constant time headway on a circular road (*16*). The study showed that traffic is stable when this control strategy is used. Swaminathan and Li studied traffic flow stability induced by an arbitrary ACC policy on a circular road (*17*). They found that any arbitrary ACC policy is exponentially stable if the policy is monotonous in spacing. Arnaout and Bowling explored the effect of CACC on traffic flow efficiency and concluded that in addition to a substantial increase in capacity, CACC systems lead to more stable traffic flows (*8*).

Finally, Schakel et al. determined the influence of CACC on traffic flow stability in mixed traffic (*18*). Using simulations, they assessed the shock wave dynamics to determine traffic flow stability. That study concluded that the increase in headway variability caused by the presence of mixed traffic had only a small effect on traffic flow stability. Schakel et al. observed that an increase in the penetration rate of CACC vehicles had substantial consequences for the characteristics of shock waves (*18*). When the penetration rate increased, the duration of the shock waves was shortened and the range was lengthened. A rapid increase in the shock wave speed was observed.

These studies showed that automation may have a beneficial influence on traffic flow stability, although some contradictory results were found. However, the discussion about the influence of automation on capacity and the capacity drop holds for the research on the influence of automation on traffic stability. Overall, the studies

- Predominantly made use of simulations,
- Did not consider behavioral adaptations of the surrounding manually driven vehicles,
- Mainly used relatively simple mathematical models in their simulations,
- Focused on the influence of automation of the longitudinal control task, and
- Did not consider the influence of the so-called transient maneuvers.

This section discussed the possible influence of automation on traffic flow efficiency. It can be assumed that automation may have a beneficial influence on capacity, the capacity drop, and traffic stability. However, the surveyed studies did not consider some crucial aspects of automated driving. The next section discusses the behavioral aspects of automated driving in more detail.

HUMAN FACTORS ASPECTS OF AUTOMATION

The studies discussed in the previous section addressed the possible impact of automation on traffic flow efficiency. These studies, which primarily focused on automation of the longitudinal control task, used simulation. However, the impact of automation on traffic flow efficiency may be assumed to be dependent on human factors. For instance, headways may be assumed to strongly influence capacity and the capacity drop, and variability in speed and reaction time may influence traffic stability. The possible positive effects of automation on traffic flow efficiency may be mitigated by human factors (*19*). Therefore this section addresses the possible human factors aspects in relation to the implementation of automation.

In the literature, a broad distinction is made between direct and indirect behavioral adaptation in relation to the driving task. According to Martens and Jenssen, direct adaptation effects in driving behavior entail the effects in driving behavior that are realized through system parameters set by the manufacturer of the system (*20*). These effects are intended by the designers of the system and follow from the functional specifications of the system. It could be argued that the simulation results discussed in the previous section largely consider these direct adaptation effects. However, simulation studies usually assume headway settings that are smaller than drivers would choose in reality (*21*).

Research on behavioral adaptation in relation to automation mostly refers to indirect adaptation effects in driving behavior. These are unintended effects (or side effects) of the system. Indirect effects have an adverse effect on the efficiency of the system, resulting in negative effects for traffic flow, safety, and the environment. In addition to a distinction between direct and indirect adaptation effects in driving behavior, a distinction can be made between the several types, such as changes in perception, cognitive changes, changes in driving performance, attitudinal changes, and changes in the adaptation to environmental conditions (*20*).

Adaptation effects in behavior may be caused by the changed role of the driver and user acceptance. In this section the changed role of the driver and user acceptance are discussed in more detail, following a review of the available empirical research on behavioral adaptation in relation to automation of the driving task.

Empirics of Behavioral Adaptation and Automation

As in the case of the influence of automation on traffic flow efficiency, most research on behavioral adaptation in relation to automation focuses on automation of the longitudinal driving task. For instance, Brown conjectured that ACC might reduce the attention and vigilance of drivers, leading to driver distraction and a failure to detect and respond to critical situations (*22*). Hoedemaeker and Brookhuis concluded that drivers rate driving with ACC as less effortful than driving without ACC (*23*). This attitude could lead to situations in which drivers engage more often in secondary tasks (*24*).

Research indicates that driving performance may deteriorate when ACC is used. For instance, lane position variability has been shown to increase during ACC use (*23*). Drivers tend to brake harder and more often while using ACC (*25*). This braking behavior may indicate how much attention a driver is allocating to the driving task. As drivers allocate less attention, their ability to respond to critical situations in which they must operate the brake themselves may be impaired (e.g., in case of a sensor failure in automated vehicles). It has been shown that in response to a braking lead vehicle, drivers in vehicles equipped with ACC begin braking later (*26*) and only if the minimum time distance without intervention would have been shorter than 0.7 s (*27*). Driving simulation studies investigating driver responses to critical events have found that drivers using ACC took longer to react to a stationary queue (*28*) and collided more often with a stationary queue than did unsupported drivers (*29*).

Dragutinovic et al. performed a meta-analysis of the behavioral adaptation effects in driving in relation to ACC (*30*). Using the concept of effect sizes, their analysis of speed concluded that the use of ACC did not have a significant effect on average driving speed. However, a more detailed analysis revealed that the studies could be clustered into two groups: one with a positive effect and one with a negative effect. In experiments showing a positive effect, an assisting type of ACC was applied; when a more bare type of speed control system was applied, negative effects on speed were observed. The more advanced types of ACC led to a substantial increase in speed. The studies that showed a positive effect on speed also showed a substantial reduction in headway.

The research in this section shows that automation may have a substantial influence on driver behavior. Increases in reaction times caused by a reduction in attention (driver distraction) were observed. However, these studies have limitations. Most important is that they focus on automation of the longitudinal driving task. No research was found into the influence of automation of the lane changing task and transient maneuvers on human behavior, and none was found into the influence of the presence of automated vehicles on the behavior of manually driven vehicles.

The assumed effects on the behavior of drivers of automated vehicles may be caused by the changed role of the driver and user acceptance. The next subsection discusses the consequences of these human aspects.

Changed Role of the Driver

Automated driving requires a capable driver who can resume control, for instance, in complex traffic situations or in case of system failure. Automation is not all-or-nothing, as indicated by the description of the functional approach toward full automation by van Arem and Tsao (*2*). Automation cannot be assumed to substitute the human driver seamlessly, nor can it be assumed that the human driver can safely accommodate the limitations of automation (*31*). An analogy can be made with aviation: the flight deck has evolved from the manual control of an aircraft to an airborne office where many tasks are automated and information about the state of the system is not directly available to pilots (*32*).

The previous subsection discussed how an increase in reaction time may be caused by the change in the role of the driver from a manual controller to a supervisor of a system. It has been suggested that the more advanced a system, the higher the need for adequate human monitoring (*33*).

In continuous monitoring of one function, reaction times are normally restricted to 1 s; if more functions are to be monitored, awareness of the situation must be refreshed more often (*34*). Furthermore, drivers may have to determine whether a system fails and determine the origin of this failure. Many studies have shown that monitoring a system for prolonged periods could increase the workload of the driver (*35*).

This increased workload may lead to reduced situation awareness. There is a long history of system supervisors who were unaware of failures of automation and did not detect critical changes in the state of the system (*36*). Parasuraman concluded that vigilance effects can be found in complex monitoring and that humans are poor passive monitors of automated systems (*37*).

In addition to an increase in driver workload, indirect adaptation effects in behavior may be causes by overreliance on the system. Overreliance in the literature has been associated with the tendency of human supervisors to place too much trust in automated systems (*38*). Supervisors may choose to neglect the automated system in favor of other tasks through a shift in attention, resulting in reduced situation awareness (*35*).

With automation, drivers are transformed from active processors of information to passive observers. Evidence suggests that passive processing may be inferior to active processing (*39*). Endsley and Kiris found that subjects' situation awareness was lower under fully automated and partially automated conditions than under normal performance in a vehicle navigation task (*40*). They concluded that drivers, although aware of low-level data, had less comprehension of what the data meant in relation to their operational goals, especially, according to Endsley and Kiris, because drivers were more passive in their decision-making process.

This subsection described possible consequences of the changed role of the driver in automation. One of the significant consequences of this changed role is the increase in reaction time following a reduction in situation awareness and attention, which could have a substantial impact on the influence of automation on traffic flow efficiency. However, the cited studies have some limitations. Few studies focused on the effect of the changed role of the driver in actual automated vehicles. Most of the studies used (driving) simulations or focused on systems other than automated driving. Furthermore, drivers of manually driven vehicles are assumed to be affected by situation awareness and driver workload when automated vehicles are in the vicinity. However, no research has been available on this topic.

In addition to the changed role of the driver, human behavior in relation to automation may also depend on user acceptance. The final subsection discusses user acceptance of vehicle automation.

User Acceptance

An important issue in the implementation of vehicle automation is user acceptance; that is, users must give up aspects of direct control over the vehicle. If automation of vehicles is not accepted and users refrain from using the technology, the impact of automation on traffic flow efficiency is mitigated.

Nilsson et al. established that takeover of control in the case of short headways was less accepted than warning suggestions of the appropriate action in a test of types of collision avoidance systems (*41*). Hoedemaeker (*42*) and Hoedemaeker and Brookhuis (*23*) found that handing over control to a device and an automated braking function is evaluated as a negative aspect of driver assistance systems.

In a large survey reported by Bekiaris et al. in the context of the SAVE project, the driver population was reluctant to release vehicle control but was willing to accept it in an emergency (*43*). Finally, De Vos and Hoekstra found that a short headway was considered less comfortable and less acceptable than larger headways (*44*).

User acceptance may be assumed to play an important role in the effect of automation on traffic flow efficiency. The reviewed studies show that user acceptance is generally low because drivers are reluctant to hand over control to a system. However, most studies focused on collision avoidance systems and other systems aimed at longitudinal control. It is not yet clear to what extent higher levels of automation are accepted by users and to what extent user acceptance influences the use of the system; thus, the impact on traffic flow efficiency also is not clear.

SYNTHESIS, DISCUSSION, AND IDENTIFICATION OF RESEARCH NEEDS

An overview was provided of the available research into the influence of automation on traffic flow efficiency. It was conjectured that automation may have a beneficial effect on traffic flow efficiency through anticipation of traffic conditions farther downstream, reduction of the probability of the occurrence of a traffic breakdown, and accelerated clearance of congestion because of an increase in the outflow of a queue. For instance, traffic flow simulations suggest a congestion delay reduction of 30% or 60% when 10% or 50% of the vehicles are driving automatically in congestion because of increased throughput (*45*). Automated driving may be able to cut congestion by 50%. This percentage could go up when vehicle-to-vehicle or vehicle-to-infrastructure communication is used.

It was concluded from available research on the influence of automation on capacity, the capacity drop, and traffic stability that automated vehicles may have a beneficial influence on these indicators of traffic flow efficiency. However, it was also conjectured that the relationship between automation and traffic flow efficiency is more complex than assumed in those studies because this relationship may be moderated by many factors. Figure 2 is a theoretical framework for this complex relationship. In the figure, the impact of automation on traffic flow efficiency is dependent on the system settings, that is, the desired time headway and speed choice. The figure shows that these settings influence car-following behavior, lane choice, and lane changing behavior. These behaviors are also assumed to incorporate the behavior of manually driven vehicles and vehicles in which, for

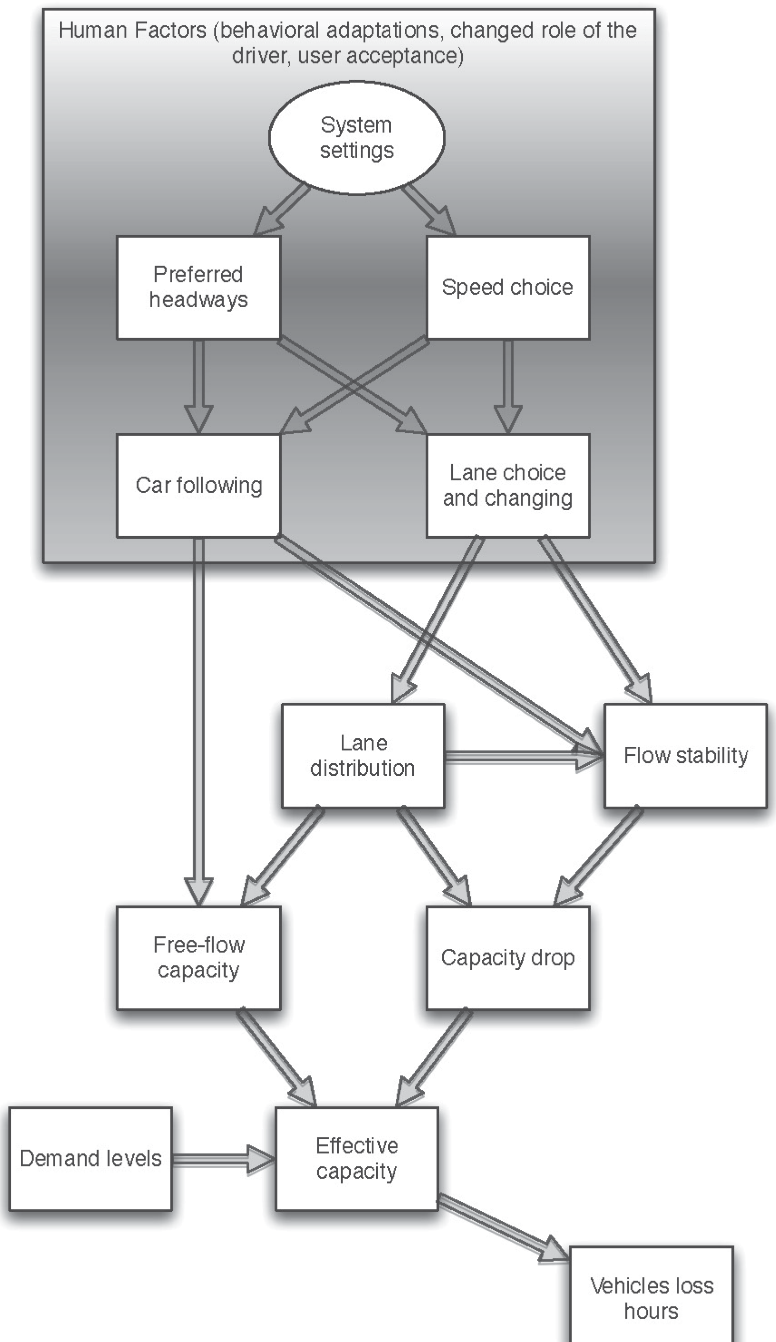

FIGURE 2 Conceptual relation between automated vehicles and traffic flows.

example, only car following is automated (e.g., ACC), accounting for the situation in which vehicles with differing levels of automation will be present on the roads simultaneously. [van Arem and Tsao provide a functional approach toward full automation (*2*).]

However, human factors may significantly influence the effect of automation on traffic flow. In the theoretical framework it is assumed that human factors may influence the system settings (*21*) and may affect driving behavior (*46*). Human factors may also influence the behavior of drivers in vehicles of all different levels of automation.

The available research indicates that automation has a substantial influence on human behavior. This influence may be due to the changed role of the driver as the role is transformed from active controller of the vehicle to passive supervisor of the system. It is assumed that these effects on behavior may have a substantial influence on the impact of automation on traffic flow efficiency. User acceptance also may have a substantial influence on the impact of automation on traffic flow efficiency. User acceptance of automation may be assumed to be low, with possibly an impact on traffic flow efficiency. Finally, in the theoretical framework it is assumed that car-following behavior as well as lane choice and lane changing behavior influence capacity, the capacity drop, traffic stability, and ultimately vehicle loss hours.

The findings of this study and the assumptions made in the theoretical framework suggest research needs. The changed role of the driver may have a substantial influence on driver workload and situation awareness with, for instance, an increase in reaction time as a result. However, to what extent the levels of automation, as described in the introduction, actually influence these determinants of driving behavior still needs to be investigated. Experiments that use actual automated vehicles can be used to determine the influence of the levels of automation on situation awareness, measured with eye tracking, and driver workload, measured with physiological indicators of workload. Because user acceptance may have a substantial influence on the efficiency of automation, research is needed to determine user acceptance of the levels of automation and also determine which factors influence user acceptance.

It was hypothesized that changes in the behavior of drivers of automated vehicles, as well as the behavior of drivers of manually driven vehicles in the vicinity of automated vehicles, substantially influence the impact of automated vehicles on traffic flow efficiency. Although the influence of automation on driving behavior may be assumed, the available research has some limitations. For instance, available research focuses on automation of the longitudinal control task. No research was found on behavioral adaptation in relation to automation of the lateral control task. Also, no research was found on behavioral adaptation in relation to transient maneuvers, such as merging, splitting, entry and exit of platoons, and transfers from automated driving to manual driving and vice versa. What changes in behavior can be observed for drivers of manually driven vehicles surrounding automated vehicles? For instance, how do drivers of manually driven vehicles react to platoons of automated vehicles?

The influence of automation on traffic flow efficiency largely has been investigated with microscopic simulations; future research on the influence of automated vehicles (on various levels of automation) on traffic flow efficiency should use actual automated vehicles. Most of the current studies considered only automation of the longitudinal control task. Research is needed in which the influence of automated lateral control is also considered. Finally, simulation studies have mainly used simple mathematical models of driving behavior. The findings from the empirical studies of the influence of automation on traffic flow efficiency, including behavioral adaptations, should be used to construct new models that can adequately capture this new reality.

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