



Dealing With Uncertainty in Implementing Advanced Driver Assistance Systems: An Adaptive Approach

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ABSTRACT

Much has been written about the technologies of Advanced Driver Assistance Systems (ADAS) – electronic systems that support the driver in controlling his vehicle in a better way. Within this literature, there is usually a focus on specific ADAS technologies and/or specific aspects of ADAS implementation. Broader pictures of ADAS implementation, in which the various ADAS, their possible consequences for transportation system performance, and societal conditions for implementation are treated in an integrated way, are seldom presented. As such, the current value of these studies is highly limited with regard to public policymaking. In this paper, we take a system view of policymaking for ADAS implementation. Within this view, policymaking concerns making choices regarding a system (e.g., the transport system) in order to obtain desired system outcomes. We apply this view to the field of policymaking with respect to ADAS implementation, showing that large uncertainties exist about future transport system contexts, the outcomes of ADAS policy decisions, and the valuation of the outcomes by stakeholders involved in or affected by ADAS policy decisions. In order to deal with these uncertainties, a flexible or adaptive policy is proposed that takes some actions right away and creates a framework for future actions that allow for adaptations over time as knowledge about ADAS accumulates and critical events for ADAS implementation take place. The adaptive approach is illustrated in two contexts: (1) ADAS for road traffic safety, and (2) ADAS for road traffic efficiency.

Keywords: intelligent transportation systems, uncertainty, adaptive policymaking

1. INTRODUCTION

Modern societies are increasingly confronted with the externalities of road traffic, such as congestion, accidents, consumption of scarce space, use of energy, and vehicle emissions. About 43,000 people are killed and 3,500,000 injured every year due to road accidents in the European Union [1]. In addition, if no actions are taken, increased traffic congestion and related environmental stress due to vehicle use is expected in the coming decades (see, for example, [2, 3]). Public authorities aiming to control these externalities are currently considering several types of measures. These measures include economic incentives (e.g., charging for vehicle use), regulations (e.g., restricted lane use to specific groups, speed limitations under certain traffic conditions), and the implementation of new transport technologies to make the (road) transport system more ‘intelligent.’ Measures in the last category are often given the label ‘Intelligent Transportation Systems’ (ITS). ITS refers to the combination of information and communication technologies through which (road) traffic data are collected,

processed and transmitted to transport users and/or operators. A variety of ITS measures have been proposed and gradually implemented in order to improve the use of road infrastructure. Emphasis has been placed on traffic management and travel information measures, such as route guidance, ramp metering, dynamic speed regulation, flexible lane use, dynamic park and ride, and incident warning systems. The ITS measures currently implemented within the field of traffic management and travel information appear to be effective [4]. However, it has been argued that these measures will reach a point of saturation beyond which traffic performance improvements will not be possible anymore [5]. Further improvements in traffic performance might be achieved through the use of Advanced Driver Assistance Systems (ADAS), the technologically most advanced category of ITS, since these systems intend to take the driver out of the driving loop. ADAS aim at improving vehicle control by the automation of the driver’s acceleration, braking and steering tasks.

The range of ADAS already researched and developed is wide, varying from systems that support the driver in one

specific driving task (e.g. proper distance keeping, blind spot obstacle warning, lane keeping) up to highly advanced systems in which the driver's steering, acceleration, and braking tasks are totally taken over (e.g. the autopilot). In these (and other) studies, ADAS proved to have potential for improving road traffic efficiency and safety significantly. For instance, it has been estimated that the use of systems that support the driver in keeping a proper distance to the nearest vehicle ahead (adaptive cruise control) could increase road capacity by up to 25% [6]. The large-scale implementation of collision avoidance systems, which support the driver in case of imminent crash danger with vehicles or obstacles, could reduce collisions by up to 50% [7]. Another type of ADAS measure involves the application of intelligent speed adaptation. These systems take into account the local speed restrictions and warn the driver in case of speeding or even automatically adjust the maximum driving speed to the posted maximum speed. The use of full-automatic speed control devices could lead to as much as a 40% reduction in injury accidents [8] and a 59% reduction in fatal accidents [9]. These results imply high potential individual and societal advantages. Consequently, the policy focus is shifting from technology development towards ADAS implementation on a large scale.

However, policy development regarding ADAS is hindered by large uncertainties about the outcomes of large-scale ADAS implementation and the valuation of the outcomes by stakeholders involved in or affected by implementation decisions [10]. Until now, the development of ADAS has been strongly technology driven and the performance and impacts of most ADAS prototypes have been assessed only in experiments under strictly controlled conditions, implying limited real-world validity [11]. For instance, in these experiments, the contribution of ADAS implementation to general transport policy goals is based on the assumptions that all vehicles are equipped with perfectly functioning systems, and that drivers use the systems exactly as they were designed to be used. Yet, only very few vehicles have been equipped with ADAS, different systems have been developed by different suppliers, systems have malfunctioned, and drivers have behaved in unexpected ways when using ADAS. These developments raise serious questions about the estimated positive impacts cited above. ADAS technology development and its impacts are strongly related to the societal conditions that have to be fulfilled for implementation. For instance, it might be necessary to change legal regulations in the context of liability and third-party insurance for ADAS that take drivers out of the driving loop [12]. Another uncertainty involves societal acceptance. It is often argued that drivers will reject ADAS, since it reduces their freedom and their responsibilities for making their own decisions [13].

Thus, there are major uncertainties surrounding ADAS technology implementation. Current policymaking is often characterised by a 'sit and wait' attitude in response to these

uncertainties, allowing developments to be largely determined by market forces. This relatively uninvolved approach could actually slow down ADAS development or could lead to the implementation of ADAS that serve producers' and individual consumers' interests only, not more general transport policy goals. Hence, there is a need for an ADAS policy course that recognises the existence of uncertainties without neglecting the possibilities and responsibilities of public authorities with respect to general transport policy goals. In this paper, such a course is presented by focussing on identifying and handling relevant uncertainties within the context of ADAS policymaking. In general, this approach involves a flexible or adaptive policy, which allows adaptations in time as knowledge about ADAS proceeds and critical events for ADAS implementation take place. In Section 2, an integrated view on policymaking is specified. This view forms the basis for the definition of the adaptive policymaking process, which is explained in Section 3. In Sections 4 and 5, the adaptive policy is applied to the field of ADAS implementation. We draw some conclusions in Section 6.

2. THE NEED FOR INNOVATIVE POLICYMAKING

Strategic planning with respect to the implementation of ADAS requires focusing on the transport policymaking process. Over the years, most transport policy analysis has been focused on the transport system itself. In the literature, several views (and related models) of transport systems can be found, differing in the transportation problem the researcher encounters and the aims of the study. Infrastructure network models, for instance, are oriented to the physical components of the transport system, i.e., roads and traffic flows, whereas transport economists focus their views and models on the tensions between transport supply and transport demand. These different views may be useful but too limited from a public policy perspective. These models typically focus on the physical part of road transportation, i.e., infrastructure and traffic, and hardly or not at all on the decisions made by individuals and organisations involved in transportation processes [14]. Public policy is concerned with intervening at various points in the transport system in a way that takes into account both the interaction among the physical elements of the transport system and the behavioural mechanisms underlying this interaction. Policy analyses and their related models rarely reflect this perspective. In this paper, therefore, we specify a view on policymaking in general and apply this to the domain of traffic and transport.

For the purposes of this paper, we assume that policymaking, in essence, concerns making choices regarding a system in order to change the system outcomes in a desired way (see Fig. 1) [15]. At the heart of this view is the system comprising the policy domain, in our case the transport system. It is important (1) to define its boundaries, and (2) to

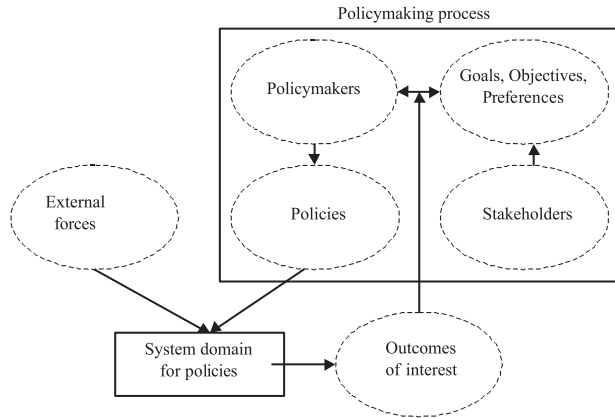


Fig. 1. An integrated view on policymaking.

define its structure (that is, the elements and relationships among them). In general, from a policy point of view, a transport system can be defined by distinguishing physical components of transportation and their interactions [16]. These physical components include the subjects of transportation (people or goods), the means of transportation (vehicles or transport units), and infrastructure. Furthermore, interactions exist among these components that can be regarded as markets. The results of these interactions (the system outputs) are called *outcomes of interest*. Outcomes of interest refer to the characteristics of the system that are considered relevant criteria for the evaluation of policy measures. For transport policies, these criteria involve, among others, the level of emissions by motor vehicles, the number of road casualties, the amount of noise nuisance, and the amount of congestion on the road network [17].

Two types of forces act on the system: *external forces* and *policies*. Both types of forces are developments outside the system that can affect the structure of the system (and, hence, the outcomes of interest to policymakers and other stakeholders). *External forces* refer to forces that are not controllable by the decisionmaker but may influence the system significantly, i.e. exogenous influences. Well-known external forces on the transport system involve demographic, economic, spatial, social, and technological developments in society. For instance, factors which have affected the daily pattern of travel include the increase of female participation in the labour force, more flexible office hours and opening hours of shops, and changing land-use patterns [18]. *Policies* are the set of forces within the control of the policymakers related to the system. In other words, a policy is a set of actions taken to control the system, to help solve problems within it or caused by it, or to help obtain benefits from it. In speaking about national policies, the problems and benefits generally relate to broad national goals. For instance, in the Netherlands, the national transport policy goals include the maintenance and improvement of accessibility, increased traffic safety, reduction in harmful emissions and noise pollution, and slowing down the fragmentation of the countryside [19].

Applying this view on policymaking to ADAS development and implementation shows the following uncertainties (see [20] for a full discussion). First, the possible influence of external forces, including ADAS technology development, is uncertain. This has been almost completely ignored up until now, although the importance of exogenous events for the development of ADAS, like urban sprawl, dispersion of work centres, working flexibility, etc., has been argued. Most ADAS implementation studies assume that technological progress will drive the implementation process, neglecting the likely co-evolution of ADAS technology and society. Second, the outcomes from ADAS implementation are uncertain. The way ADAS implementation might affect transport system performance is currently unknown, since the key-relationships determining transport system performance from ADAS implementation are very uncertain. The current knowledge is restricted to evaluating the intended impacts of specific ADAS, often assuming optimal technological performance of ADAS, drivers who do not adapt their behaviour to supportive systems, and optimal traffic conditions. As such, figures on traffic performance improvements by means of ADAS implementation are hardly more than indicative. Finally, the valuation of the outcomes from ADAS implementation is uncertain. Stakeholders tend to have different opinions about the severity of future traffic problems. This results in different, often conflicting, needs regarding ADAS implementation. As such, the willingness of stakeholders to accept (or reject) outcomes of ADAS implementation is uncertain.

Summarising, large uncertainties exist about external developments, the outcomes of ADAS policy decisions, and the valuation of the outcomes by stakeholders involved in or affected by ADAS policy decisions. Up until now, policymakers have dealt with these uncertainties in one of two ways [21]. The most common approach is to neglect or ignore the above mentioned uncertainties, assuming that the future world will be more or less the same as the current world. While this may be the easiest option for the short term, it means in fact accepting large uncertainty with respect to, for instance, ADAS policy outcomes. This could lead to a serious policy failure. For instance, although ADAS intends to improve traffic efficiency (or at least not to reduce road capacity), there are studies that forecast some capacity decreases for certain penetration degrees and specific operating characteristics of some systems [22]. Furthermore, the safety benefits could be outweighed by countervailing behavioural responses by drivers [23]. These negative efficiency and safety impacts may increase in case of a mixed situation of vehicles with different systems, each having its specific type of support and performance. Implementing an ADAS without considering the possible negative impacts could lead to policy failure.

The second approach to deal with these uncertainties is more enlightened. It focuses on identifying uncertainties and developing a policy that takes these uncertainties into

account. It assumes that the range of future worlds can be specified well enough to determine robust policies that will produce favourable outcomes in most of them. These future worlds are described by means of scenarios. The best policy is the policy that produces the most desired outcomes across different scenarios. Scenarios enable the policymaker to act consciously in the presence of uncertainty. Although this approach has been successful in the past, the problem is that if the range of assumptions about the future turns out to be wrong, the negative consequences might be as large as the total ignorance of uncertainties. Traditionally, the construction of scenarios in the field of transportation has been mostly based on trend extrapolations [14]. Serious trend breaks are often not included. Events like serious transport accidents and the explosive growth of mobile technology implying substantial changes in activity and mobility patterns are often not taken into account. The question is: In this rapidly changing world, is it feasible to develop and analyse a full set of plausible, future scenarios? It remains difficult, if not impossible, to get sufficient knowledge about the external factors influencing transportation performance. Furthermore, most of (levels of) these factors are inherently unpredictable in the long term [24].

Hence, traditional approaches have serious shortcomings in handling uncertainties regarding ADAS policymaking in an appropriate way. The challenge for enlightened ADAS policymaking is to develop other, innovative approaches to handle these uncertainties. Instead of focussing on the identification of all feasible ADAS technologies and development paths, which would be a waste of resources, an approach is needed that adapts to the future course of events and fully exploits knowledge that becomes available as time proceeds [24].

3. THE ADAPTIVE APPROACH

Walker et al. [25] have developed an “adaptive” approach to policymaking that allows policymakers to cope with the uncertainties that confront them by creating policies that respond to changes over time and that make explicit provision for learning. The approach makes adaptation explicit at the outset of policy formulation. Thus, the inevitable policy changes become part of a larger, recognised process and are not forced to be made repeatedly on an ad hoc basis. Adaptive policies are devised not to be optimal for a best estimate future, but to be robust across a range of plausible futures. Such policies combine actions that are time urgent with those that make important commitments to shape the future and those that preserve needed flexibility for the future. Under this approach, significant change in the surface transportation system would be based on a policy analytic effort that first identifies system goals, and then identifies tactics and strategies designed to achieve those goals, but that specifies ways of modifying those tactics and

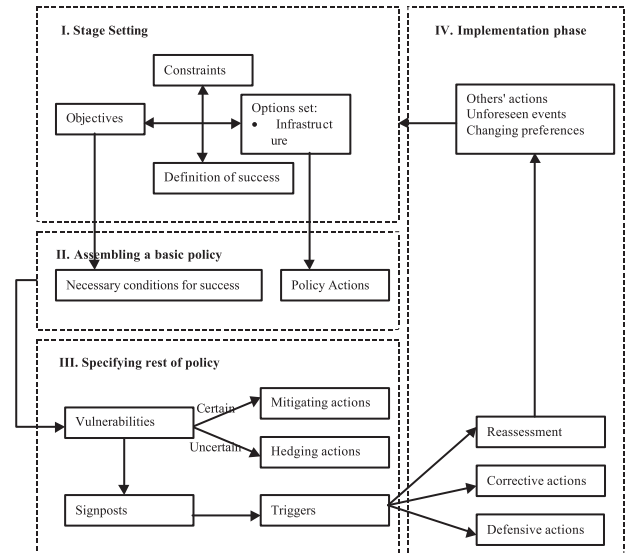


Fig. 2. The adaptive policymaking procedure.

strategies as conditions change. Within the adaptive policy framework, individual actors would carry out their activities as they would under normal policy conditions. But policymakers, through monitoring and mid-course corrections, would try to keep the system headed toward the original goals. Figure 2 illustrates the adaptive policy process. In particular, the following steps summarise the process for creating and implementing an adaptive policy.

The first activities constitute the *stage-setting* step in the policymaking process. This step involves the specification of objectives, constraints, and available policy options. This specification should lead to a definition of success, i.e. the specification of desirable outcomes.

In the next step, a *basic policy* is assembled, consisting of the selected policy options and additional policy actions, together with an implementation plan. It involves (a) the specification of a promising policy and (b) the identification of the conditions needed for the basic policy to succeed. These conditions should support policymakers by providing an advance warning in case of failure of policy actions.

In the third step of the adaptive policymaking process, the *rest of the policy* is specified. These are the pieces that make the policy adaptive. This step is based on identifying in advance the (uncertain) conditions or events that could make the policy fail (its ‘vulnerabilities’), and specifying actions to be taken in anticipation or in response to them. This step involves (a) identification of the vulnerabilities and actions to be taken and (b) translation of the necessary conditions for success into signposts that should be monitored in order to be sure that the underlying analyses remain valid, that implementation is proceeding well, and that any needed policy interventions are taken in a timely and effective manner. Hence, in this step two types of analyses are needed.

First, vulnerabilities should be identified and analysed. Vulnerabilities can reduce the acceptance of a policy to a

Table 1. Differences between traditional policymaking and adaptive policymaking.

Characteristic	Policymaking approach	
	Adaptive policymaking	Traditional policymaking
Consideration of goals	Stakeholders participate in forums to develop and identify the diversity of goals.	Stakeholders pursue their own goals, cooperating at their own initiative
Treatment of uncertainty	Forums explicitly elicit key uncertainties and contingent plans for addressing them	Individual stakeholders ignore uncertainty or address uncertainty based on rigid assumptions.
Potential for radical system change	Radical system changes may be promoted through cooperative action	Individual preferences enable only incremental system changes
Response to unexpected events	Pre-specification of defensive/corrective actions (if needed), reducing avoidable surprises	Individual stakeholders respond 'ad hoc' to surprises
Monitoring of outcomes	Coordinated monitoring of outcomes as a part of the implementation process.	Limited monitoring, mainly on an <i>ex-post</i> basis.

point where the policy is no longer successful. Both certain and uncertain vulnerabilities can be distinguished. Certain vulnerabilities can be anticipated by mitigating actions – actions taken in advance to reduce certain adverse effects of a policy. Uncertain vulnerabilities are associated with hedging actions – actions taken in advance to reduce or spread the risk of possible adverse effects of a policy. The second analysis is the definition of signposts that contain information whether additional actions are needed to guarantee the progress and success of a basic policy. In particular, critical values of signpost variables (triggers) should be specified in this analyses, beyond which actions should be implemented to ensure policy progress in the right direction and proper speed.

Once the above policy is agreed upon, the final step involves *implementation*. In this step, the events unfold, signpost information related to the triggers is collected, and policy actions are started, altered, stopped, or extended. The adaptive policymaking process is suspended until a trigger event is reached. As long as the original objectives and constraints remain in place, the responses to a trigger event have a defensive or corrective character – that is, they are adjustments to the basic policy that preserve its benefits or meet outside challenges. Under some circumstances, neither defensive nor corrective actions might be sufficient. In that case, the entire policy might have to be reassessed and substantially changed or even abandoned. If so, however, the next policy deliberations would benefit from the previous experiences. The knowledge gathered in the initial adaptive policymaking process on outcomes, objectives, measures, preferences of stakeholders, etc., would be available and would accelerate the new policymaking process.

Table 1 gives an overview of the differences between traditional and adaptive policymaking. Although both types of policymaking emphasize the importance of adaptation as a situation unfolds, there are two key differences. First, there is the presence or absence of a common goal among stakeholders, which adaptive policymaking sees as instrumental and traditional policymaking views as potentially dysfunctional, since it might slow down decisionmaking.

Second, there is a big difference in the treatment of uncertainties. Adaptive policy analysis is based on identifying *in advance* the uncertain conditions or events that could make the policy fail (its 'vulnerabilities'), and specifying actions to be taken in anticipation or in response to them. Hence, the adaptive policy allows *pre-specified* and *pre-agreed* adaptations in time as knowledge accumulates, learning proceeds, and critical events take place during implementation.

Hence the adaptive policymaking approach seems promising for surface transportation system development in terms of how, in the face of uncertainty, policymaking can and should occur. In the following sections the concept of adaptive policymaking described above will be illustrated for developing innovative transport policies regarding ADAS implementation.

4. ADAPTIVE POLICYMAKING FOR ADAS IMPLEMENTATION I: ROAD TRAFFIC SAFETY

The first step in designing an adaptive policy involves the specification of objectives, constraints, and available policy options. A major objective in transport policies involves the improvement of road traffic safety. For instance, in the Netherlands, national targets have been set at a 25% reduction in road fatalities and hospitalised injuries for 2010 [19]. On a European level, the road safety objectives are even higher. The European Commission has formulated the objective to reduce road fatalities by 50% within the European Union by 2010 [3]. In general, outcomes of interest for policymakers might be reductions in accident fatalities, injuries and material damage, as well as minimising the secondary consequences of accidents (secondary accidents, congestion, etc.). The constraints could be those imposed by costs, vehicle-throughput, travel time, comfort, convenience, etc. Next to more traditional, preventive measures, like driver-educational campaigns and legislation, today's policy options could include measures that directly intervene in vehicle driving tasks, i.e., the first generation of

ADAS or, as we will call them hereafter, ‘safety-ADAS.’ Safety-ADAS that are (nearly) entering the market nowadays involve:

- **speed headway keeping:** the driver is supported in keeping a safe distance to the nearest vehicle ahead by accelerator and, possibly, brake control;
- **front obstacle collision avoidance:** the driver is warned and/or his vehicle temporarily, controlled if he comes too close to an obstacle in front;
- **side obstacle collision avoidance:** the driver is warned and/or the vehicle is temporarily controlled in case of collision danger during lane changing and merging;
- **lane departure avoidance:** the driver is warned and/or the vehicle is temporarily controlled when the vehicle is drifting out of its lane;
- **intelligent speed adaptation:** the driver is warned and/or his vehicle speed temporarily adapted based on local speed regulations.

In the next step, a basic policy is assembled. A promising basic policy might be to implement specific safety-ADAS for ‘unsafe’ drivers (e.g., younger drivers) on ‘unsafe roads’ (e.g., urban roads) under ‘unsafe’ traffic conditions (e.g., fog, darkness, snow). Accident statistics might be of use in specifying unsafe ‘traffic scenarios’ in this context. For illustration, in Table 2, the potential safety benefits of selected safety-ADAS are presented for different road types in the Netherlands [26]. It was assumed that speed headway keeping could only be applied at driving speeds exceeding 40 km/h. Therefore, safety benefits of this application on roads with speed limits lower than 50 km/h were not taken into account. Furthermore, in estimating the safety benefits of the support services, both market penetration and utilisation factors of the systems were left out of consideration. It was assumed that these factors do not affect the *relative* sizes of the potential safety benefits. Also, it was assumed that future technology developments would minimise system-reliability and human-machine interaction problems. However, these assumptions will be monitored closely as implementation develops.

The figures show that lane departure avoidance could contribute most to a (relative) reduction of fatalities and injuries on roads with 100–120 km/h speed limits, closely followed by front obstacle collision avoidance systems. In addition, for roads with speed limits within the 50–90 km/h range, intelligent speed adaptation is of interest. This application also scores best on low-speed roads (0–50 km/h) followed by front obstacle collision avoidance systems. Hence, in terms of implementation, these types of figures should be used to guide policymakers in choosing promising systems from a safety point of view.

There are several necessary conditions for the success of this basic policy. An essential condition is the availability of reliable and accurate technologies for the selected safety-ADAS. For intelligent speed adaptation, for instance, this implies the need for reliable and accurate beacons for speed control. For collision avoidance applications, next to reliable and accurate sensing devices, this implies the need for appropriate decision making by the system when an obstacle is detected [27]. Another important condition involves a basic level of willingness among drivers to use the systems as they were intended to be used. A last, often mentioned, condition involves the availability of proper legislation in the context of liability and third-party insurance, as soon as drivers are taken out of the driving loop [12].

In the third step of the adaptive policymaking process, the remainder of the policy is specified. It involves the identification of vulnerabilities of the basic policy and the translation of necessary conditions for success into signposts that warn in case undesired developments. Different safety-ADAS show different vulnerabilities. For instance, regarding intelligent speed adaptation, a vulnerability of the new policy might be a lack of reliability in the speed control technology in case of incidental speed limits (work-zones, accidents, etc.). An action to mitigate the negative effects of this situation on the success of the policy would be to build in some redundancy, by providing temporary vehicle-roadway communication around incidents. For collision avoidance applications, a vulnerability might be the lack of reliable and accurate detection and recognition of more

Table 2. Relative safety benefits (fatalities, injuries, other injuries) of safety-ADAS.

Road type	Roads with 100–120 km/h speed limits(%)			Roads with >50–90 km/h speed limits(%)			Roads with 0–50 km/h speed limits(%)		
	Fatal	Injur.	Other	Fatal	Injur.	Other	Fatal	Injur.	Other
Speed headway keeping	14	21	36	4	7	18	n.a.	n.a.	n.a.
Front obstacle coll. avoidance	28	13	13	26	20	18	29	26	22
Lane departure avoidance	35	36	24	33	25	16	12	9	7
Side obstacle coll. avoidance	2	9	11	1	1	2	2	2	3
Intelligent speed adaptation	10	8	n.a.	30*	24*	n.a.	38	30	n.a.

Note. *For intelligent speed adaptation, only accident statistics on roads with 80 km/h speed limits have been considered, which is the most common speed limit for roads with speed limits between 50 and 90 km/h in the Netherlands.

general obstacles than only vehicles by in-vehicle sensing devices [27]. This obstructs the application of these systems, particularly in secondary road networks. A mitigating action in this context might involve the provision of vehicle-to-vehicle and/or vehicle-to-roadway communication for those networks on which obstacles other than vehicles are likely to appear.

Another vulnerability involves low driver acceptance for ADAS, especially with regard to systems that actively intervene in the vehicle driving task [10]. Driver education programs might be undertaken to hedge against this vulnerability. Education is essential for societal support and for successful marketing. Consumers could be educated on the potential and the risks of safety-ADAS. This should support consumers to interpret and evaluate safety-ADAS in a proper way. Such education could be performed in several ways including demonstrations, pilots, strategic niche management, etc. Appropriate use of safety-ADAS might become part of driving tests.

A more uncertain vulnerability involves the adverse driving behaviour that speed adaptation devices might induce. Experimental results indicate that, with speed adaptation devices implemented, drivers exhibit riskier gap-acceptance, loss of vigilance, increased frustration, and increased impatience [28]. Therefore, the driving behaviour of drivers with speed adaptation should be monitored closely. “Triggers” should be defined that would implement corrective policy actions when certain pre-defined levels of risky driving behaviour develop. Currently, procedures are being developed to specify such triggers [29]. Another uncertain vulnerability is related to the confusion among drivers as, per type of accident, different systems are developed by different suppliers. In general, for all safety ADAS, there is the need for developing performance standards for system operation and human machine interface in order to avoid confusion among drivers as a consequence of using different alternative ADAS measures. Standards should at least include obstacle detection distance, timing of alerts, human factors guidelines such as mode and type of warning or intervention [30].

A major (highly uncertain) vulnerability of safety-ADAS, but one with large consequences, is a serious technological failure. Accidents with safety-ADAS due to malfunctioning technology have been reported [31]. Recently, in the Netherlands, a bus equipped with an electronic gas pedal automatically accelerated due to electromagnetic interference. Suppose, for instance, that in an urban area, rural or motorway speed limits are being automatically transmitted to speed adaptation devices and drivers are relying on the system to regulate their vehicle speed. A malfunctioning system might result in severe accidents with large societal impacts. This could lead to failure of the policy. The adaptive policy must, therefore, include actions to reduce the possibility of such a failure and to take mitigating or corrective actions in case such a failure occurs.

The final step involves implementation. This involves the continuous monitoring of signpost information related to the trigger events. In case of a trigger event, the basic policy might be adjusted. For instance, in case the predefined levels of risky driving behaviour are reached, corrective actions might be undertaken. These could include the exclusion of ‘unsafe’ drivers from those road-types on which unsafe driving behaviour has appeared. Also, in addition to safety-ADAS, the vehicles of the unsafe drivers could be equipped with black-boxes in which real-time vehicle driving data are stored. However, for some trigger events, neither defensive nor corrective actions might be sufficient. In our malfunctioning technology case, if the result was a large accident, the entire policy might become under serious pressure. Or, there might be major changes in stakeholders’ objectives. For instance, travel time and reliability might become more important instead of traffic safety. As such, the original policy should be reconsidered or, if necessary, even abandoned. If so, however, the policymaking process should not have to start all over again. The experiences gained and knowledge gathered in the initial adaptive policymaking process would be available and would accelerate the new policymaking process.

5. ADAPTIVE POLICYMAKING FOR ADAS IMPLEMENTATION II: ROAD TRAFFIC EFFICIENCY

Next to traffic safety, another major objective in (road) transport policies involves the maintenance and improvement of accessibility of important transport nodes. Increasingly, there appears to be a shortage of road capacity to handle traffic demand. This shortage results in a worsening congestion, poor level of service, isolation of regions, environmental pollution, consumption of scarce space, etc. For instance, 10% of the main European motorways are affected by daily traffic jams, implying an external cost of about 0.5% of EU GDP [3]. Several policies have stated, therefore, the need for an improved use of the road infrastructure network (e.g., [3, 19]). Well-known outcomes of interest for policymakers include improvements in vehicle-throughput, travel times, reliability of trip time, congestion probability and average flow speed. The constraints involve public costs, traffic safety, environmental stress, etc. Next to traditional policy measures (new roads, fuel taxes, etc.) and current policies in the field of implementing traffic control technologies (ramp metering, dynamic lane use regulations, route guidance and variable speed limits), future policymaking might consider the implementation of the next generation of ADAS, here called ‘congestion-ADAS.’ These systems, although not as far developed as the category of ‘safety-ADAS,’ could reduce congestion more than traditional and current policies (see also Section 1). Even though congestion-ADAS technologies

will not be sufficiently reliable to fully replace the driver by automatic systems in the near future, they do offer new possibilities for traffic efficiency improvement. Congestion-ADAS are generally expected to be the follow up of safety-ADAS, increasingly automating (parts) of the driver tasks:

- **stop-and-go speed headway control:** an extension of speed headway keeping by which the driver automatically follows his/her predecessor over the full speed range, with the maximum available deceleration, enabling emergency stops and automatic driving in queues;
- **lane keeping control:** the next generation of lane departure avoidance also known as automatic lane holding, by which the driver's vehicle is automatically kept in the centre of the lane;
- **(semi) auto-pilot:** a combination of the above applications by which the driver is enabled to cruise automatically, i.e., feet-off and hands-off cruising. This is also known as the first stage of fully-automated driving.

The next step involves the development of a basic policy for the selected congestion-ADAS. A promising basic policy might be to implement these ADAS technologies for those groups and on those roads that suffer most from congestion. In Figure 3, for example, estimated congested road segments of motorways are presented for the Netherlands in terms of the average vehicle speeds below 60 km/h in 2020 [32]. Groups of interest might include professional road users (truck drivers, business drivers), since these groups value travel time losses and the reliability of travel times substantially higher than other vehicle drivers [33]. As such, these groups are likely to be early adopters of these systems.

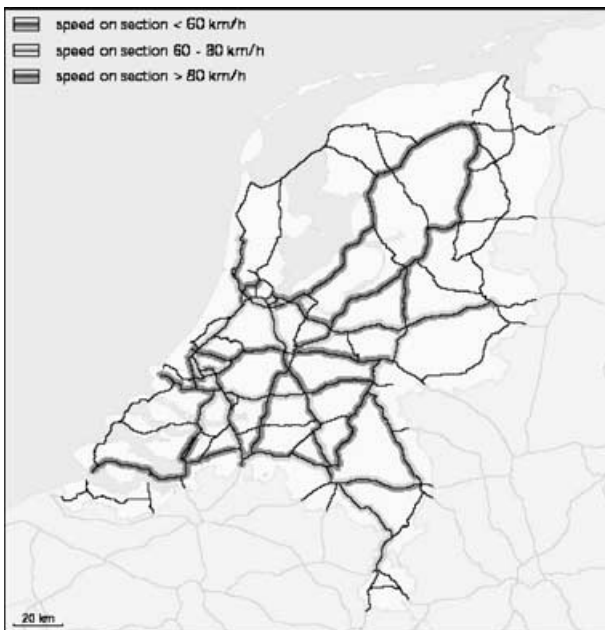


Fig. 3. Speeds on sections of the main Dutch highway network in 2020 without policy implemented.

More specific estimates of the potential benefits of the different congestion-ADAS are not possible. Currently, an unambiguous and widely accepted definition of congestion, the ways to measure it, and its causes are lacking [34]. As such, statistics on congestion are limited and a coupling between different congestion-ADAS and road types/user groups is not possible. Only some general estimates of benefits of congestion-ADAS can be given, mostly based on traffic flow simulator studies applied for specific road networks of interest:

- **stop-and-go speed headway control:** capacity gains are strongly depending on the specific settings of this system and penetration rates. For instance, for an in-vehicle, autonomous speed headway controlling device at 0.8 s headway, capacity gains of 4% to 25% have been estimated under a 10% respectively 100% penetration rate. Further capacity gains under lower penetration rates are achieved by cooperative speed headway control, for which the subject vehicle and preceding vehicle are both equipped and communicate on acceleration, velocity, and maximum braking rate. This enables closer vehicle following (up to time headways of 0.5 s). It has been estimated that the capacity of a lane could double if all vehicles in this lane are equipped with cooperative speed headway control [35].
- **lane keeping control:** in general, it is expected that this system encourages drivers to decrease their number of intended lane changes, implying less lateral disturbances of traffic flows. This system might also be of use in case of dynamic adjustment of lane width in situations of high traffic density, in order to temporarily generate an extra lane. Improvements of up to 30% in throughput have been found for the extensions of two lanes with normal width to three narrow lanes [36];
- **(semi) auto-pilot:** This 'auto-pilot' could allow equipped vehicles to group themselves in platoons, which would harmonise traffic flows and improve throughput significantly. Estimates on capacity gains vary considerably with interplatoon spacings, intraplatoon spacings, number of vehicles in a platoon, vehicle type(s) within a platoon, road surface conditions, etc. For instance, a study regarding the implementation of two electronically-coupled trucks on motorways showed overall capacity gains between 4% and 9%, depending on the equipment rate [37]. In combination with dedicated lanes, further improvements are possible. Preliminary studies indicate that on fully-automated-driven lanes, compared to manually-driven lanes, a capacity increase of 200% to 300% might be feasible [38] together with substantial reductions in travel time (up to 50%).

Of course, in terms of implementation, these figures are not sufficient to guide policymakers in choosing a promising congestion-ADAS application from a traffic flow improvement point of view. Therefore, both the current data on

congestion and congestion-ADAS impacts need to be improved and matched in a uniform, standardised way. Congestion data should be gathered and analysed on a local level, in order to specify those roads and groups that need, and are willing to pay for, congestion-ADAS facilities. This might support basic policy choices concerning the specific types of congestion-ADAS to implement, for which parts of the road network, and for which types of vehicles and users.

The necessary conditions for the success of this basic policy are more or less similar to those mentioned for the basic policy of the safety-ADAS, but the levels of the conditions for more intervening systems are higher and as such often more difficult to fulfil. The availability of reliable and accurate (communication) technologies, acceptance among (professional) drivers and fleet owners, and clear legislation in the context of liability and third-party insurance are absolutely necessary to enable a basic policy. In addition, congestion-ADAS likely require infrastructure adaptations. For instance, infrastructure instrumentation might reduce the huge performance claims regarding stand-alone, in-vehicle sensors of lane keeping control. Furthermore, in case implementing the (semi-)autopilot on dedicated lanes, entry and exit ramps should be established that allow a check on vehicle conditions.

In the next step, the remaining, adaptive part of the policy is specified in order to handle potential vulnerabilities of the basic policy. For instance, regarding the autopilot, parameter trade-offs between safety, efficiency and comfort might differ among countries, because of the different priorities that different countries place on safety, efficiency and comfort [10]. Note that this is also an important technical problem because of the need to ensure that genuinely hazardous situations are handled, while keeping the frequency of false alarms low enough to ensure customer acceptance and user confidence in the validity of the false alarms that are experienced. An action to mitigate the negative effects of this situation on the success of the policy would be to guide and specify international standardisation on these parameters.

Again, this policy is vulnerable to low acceptance among (professional) drivers and fleet owners, given the relative (high) costs and (possible) limited usability of the systems [10]. Policymakers could hedge against this vulnerability by initially providing some 'demonstration' lanes for automated vehicles only. This will enable users, the public and other decisionmakers to fully experience the benefits of congestion-ADAS, which should stimulate further expansion of dedicated lanes throughout the road network [39]. Furthermore, apart from infrastructure measures, policymakers might also become more active regarding the automotive industry. Public-private, cooperative planning on the communication opportunities between vehicles, future provision of roadway instrumentation, and possible future construction of dedicated lanes will stimulate the automotive sector in equipping their vehicles with the appropriate systems in time.

A more uncertain vulnerability involves the impact congestion-ADAS might have on driving behaviour. For instance, the (semi-) autopilot might reduce the driver workload, leading to the loss of driving skills [10]. During the first few minutes after changing from the auto-pilot to manual driving, an increase in driver workload could be a problem. Furthermore, system failures could require the driver to intervene, and, since the driver might be less alert, this could cause improper reactions. Extensive use of the autopilot could further have major impacts on driving skills. If all driving tasks are automated, drivers will become deskilled, so if the system performance is less than 100%, drivers will not be adequately skilled to take over. Hence, the driving behaviour of drivers with the auto-pilot should be monitored closely, especially in reaction to system malfunctions and transition periods from automatic to manual driving and vice versa. Policymakers could mandate the automatic recording of vehicle dynamics and driving behaviour with 'black boxes' and require full and detailed accident analysis in the case of ADAS equipped vehicles. Appropriate triggers should be defined that would implement corrective policy actions when certain pre-defined levels of underload or overload of driving tasks are reached or to take policy actions if accidents increase.

It is not hard to imagine that one of the most uncertain vulnerabilities of congestion-ADAS is a serious technological failure of (one of) the system components. Although these systems are likely to reduce the probability of a small accident (i.e., a rear-end collision between two vehicles or a single vehicle roadway departure), these systems may result in a small probability of large accidents (like in air traffic). To what extent traditional accidents will be mitigated can be estimated, but it is not possible to predict how many accidents will arise from new mechanisms caused by failures in system components or logic since they are not known [10]. For instance, the potentially, high capacity improvements of cooperative speed headway control and the (semi-) autopilot are achieved under close following headways. These improvements often assume perfect communications in terms of no missing messages and instantaneous availability of required information [40]. Delays of messages or temporary communication interruptions are likely to increase collision risks. Within a convoy of electronically coupled vehicles this might result in a multiple collision. Such an event would seriously affect the societal opinion of these systems and undermine the basic policy. An adaptive policy should include actions to reduce the possibility of such a failure as well as mitigating actions in case such a failure occurs.

After an agreement has been reached on the basic policy, the final step involves implementation of this policy. The adaptive policymaking process is pursued until a trigger event is reached. Suppose for instance that predefined levels of risky driving behaviour are reached during transitions from automatic to manual driving. A corrective action might

be to build in driver-monitoring systems that warn the driver or even control the vehicle in case of driver inattention, fatigue, etc. during transitions. Such systems are already in development [41]. Another trigger relates to the increasing feelings of inequity among the general public in the use of the congestion-ADAS. If, for instance, the basic policy involves the implementation of a (semi-) autopilot for trucks only on a dedicated lane, the general public might criticise the limited benefits of (partially) tax-paid investments [42]. Defensive actions might include defending the policy in public forums and highlighting the traffic improvements of congestion-ADAS both for users and non-users in relation to agreed-upon policy objectives. Even the most serious trigger-event – a large accident due to malfunctioning technology – might be handled by corrective and/or defensive actions. The policy might be corrected by, for example, adding supplementary investments in technologies that prevent future technological failures. Defensive actions include the institutionalisation of additional safeguards.

6. CONCLUSIONS

This paper has focused on the complexities and uncertainties surrounding the implementation of ADAS technology from the perspective of public policymaking. On the one hand, several studies and pilot projects have shown that ADAS technologies have great potential to contribute to general transport policy goals. On the other hand, public policy and decisionmaking is confronted with the existence of large uncertainties related to the future of ADAS development and implementation and the response of drivers to such systems.

A generic, integrated view of policymaking has been presented that views it as a way of making choices regarding a system (e.g., the transport system) in order to obtain desired outcomes. But, there exist large uncertainties about the outcomes of ADAS policy decisions and about the valuation of the outcomes by stakeholders involved in or affected by ADAS policy decisions. The challenge for enlightened policymaking is to develop innovative approaches to handle these uncertainties.

The paper proposed an approach involving a flexible or adaptive policy that allows adaptations in time as knowledge about ADAS proceeds and critical events for ADAS implementation take place. In particular, policymakers are encouraged to first develop a normative view and then guide the implementation and adaptation process based on gathering information that allows the resolution of the uncertainties over time.

The adaptive policy approach was illustrated for two of the main transport policy objectives: an improvement of road traffic safety and a reduction of traffic congestion. We showed how policymakers can cope with uncertainties in ADAS implementation and how these policies might be adjusted as new information becomes available on ADAS

performance in reality. This illustration showed that, compared to traditional policymaking, the adaptive approach is highly promising in terms of handling the range of uncertainties related to ADAS implementation for traffic safety and efficiency.

Future challenges in this field involve a further specification and testing of the adaptive approach focused on developing systematic approaches to fully identifying the vulnerabilities; the level of (un)certainly of these vulnerabilities and the trigger events and their values. One way of testing of the adaptive approach might be to use scenario and simulation gaming to compare the adaptive policymaking approach to more traditional policymaking approaches.

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