# CAPACITY-ENHANCING AND LOW-GHG EMISSIONS INTELLIGENT TRANSPORT SYSTEMS (ITS) TECHNOLOGIES

**Voula PSARAKI**
Department of Transportation Planning and Engineering, School of Civil Engineering, National Technical University of Athens
vpsaraki@civil.ntua.gr

**Ioanna PAGONI**
Department of Transportation Planning and Engineering, School of Civil Engineering, National Technical University of Athens
ipagoni@central.ntua.gr

**Abstract**
*The focus of the present paper is on the role of Intelligent Transport Systems (ITS) in addressing road capacity issues, and delivering environmental benefits. For this purpose, three ITS technologies are selected: Driver Assistance Systems (DAS); Automated Highway System (AHS) for passenger traffic; and Commercial Vehicle Operations (CVO) for freight traffic, based on the profile of their characteristics and the projected implementation pathways. These are further evaluated as to their potential for improving the road capacity of the TEN-T European network; achieving fuel savings; and reducing $CO_2$ emissions.*

***Keywords***: *Intelligent Transport Systems, Driver Assistance Systems, Automated Highway System, Commercial Vehicle Operations, capacity improvement, $CO_2$ emissions reduction.*
***JEL classification***: R10, R11

## 1. Introduction

Intelligent Transport Systems (ITS) constitute a primary Information and Communication Technology (ICT) that can increase safety, improve operational performance, particularly by reducing congestion, deliver environmental benefits and expand economic and employment growth (Commission of European Communities, European Commission). ITS applications can be grouped into the following categories: Driver Assistance Systems (DAS), Advanced Traveller Information Systems (ATIS), Advanced Transport Management Systems (ATMS), Cooperative Vehicle-Infrastructure Systems (CVIS), which enable the operation of the Automated Highway System (AHS), and Commercial Vehicle Operations (CVO). Within the wide spectrum of ITS systems, three technologies are selected, which are anticipated to emerge in the next decades in Europe and deliver infrastructure capacity and environmental benefits. More specifically are selected DAS and AHS for passenger traffic and CVO for freight traffic. The expected impact of DAS and AHS has been analyzed in a number of studies and reports. The impact of DAS applications on road capacity, traffic conditions and emission reduction is examined in Carslaw et al., Khayyam et al., Minderhoud, Zwaneveld and van Arem, while the implications for safety are studied in Wilmink et al., Baum et al., Abele et al. Capacity calculations under AHS implementations are provided in Carbaugh et al.], Godbole and Lygeros, Hall and Chin, Kanaris et al., and Michael et al. . Fuel efficiency of intelligent vehicles with cooperative communication potential within a vehicle fleet is studied in Manzie et al., Partners of Advanced Transit and Highways. The capabilities of CVO to optimize freight operations and reduce fuel consumption and truck emissions are presented in Crainic et al., Hall and Intihar, The Climate Group. Effects of general ITS on fuel consumption and $CO_2$ emissions are discussed in

The Climate Group, Klunder et al., Reinhardt et al., Ezell, while social acceptability issues are addressed in van Wees and Brookhuis, Petica et al., Haynes and Li.

The present paper contributes to the above literature in two ways. First it conducts an economic analysis of the three ITS technologies, based on the most probable implementation scenario for the time period 2012-2030. The costs associated with these technologies are the primary factor in determining social acceptability. Second, an assessment of capacity improvements, fuel efficiency and reduction of $CO_2$ emission is carried out.

The rest of the paper is organized as follows. Section 2 outlines the main characteristics of DAS, AHS and CVO technologies and their implementation pathways. Cost estimates including retail prices and yearly costs are derived in Section 3. Capacity improvements and reduction of $CO_2$ emission over the TEN-T road network are considered in Section 4. The main conclusions are summarized in Section 5.

## 2. DAS AHS and CVO Characteristics and Implementation Trends

In this section, the main characteristics of the three ITS technologies are presented and their respective implementation pathways in the time horizon 2012-2030 are delineated.

*Driver Assistance Systems (DAS)*

Driver Assistance Systems comprise a range of ICT in-vehicle systems, which support drivers in maintaining a safe speed and distance, driving within a lane and avoid overtaking in critical situations. They inform and warn the driver, provide feedback on driver actions, increase comfort and reduce the workload by actively stabilizing or maneuvering the car.

**Table 1**: DAS applications and status of implementation

| DAS application | Description | EU Market Introduction | Diffusion |
|---|---|---|---|
| Anti Blocking System (ABS) | Prevents the wheels of the vehicle from locking up while braking | 1978 | All new European vehicles |
| Electronic Stability Control (ESC) | Stabilizes the vehicle and prevents skidding | 1999 | All OEMs[(a)], but not in all lines. By 2012-2014 standard equipment |
| Emergency Call (eCall) | Automatically calls emergency services and transmits location data from the scene of an accident | 2003 (for premium cars) | Partially on market: BMW, Lexus. Optional, but may become mandatory |
| Adaptive Cruise Control (ACC) | Maintains a preset distance to the vehicle ahead and adjusts driving speed automatically | 2005 | Optional as comfort function Already available in the market: BMW, Audi, Lexus, Mercedes-Benz |
| Lane Departure Warning (LDW) | Warns the driver when the vehicle begins to move out of its lane (unless a turn signal is on in that direction) on highways | 2005 | Optional equipment sold as safety function. On market: on a number of vehicle models from Citroen to Mercedes-Benz. |
| Lane Change Assistant (LCA) | Continuously monitors the rear blind spots on both sides of the vehicle | 2005 | Partially on market: Audi, Volvo-warning and only small steering force Optional, as comfort function |
| Intelligent Speed Adaptation (ISA) | Constantly monitors vehicle speed and the local speed limit on a road and implements an action when the vehicle is detected to be exceeding the speed limit | 2006[(b)] | Several systems for speed limit advice are available May become mandatory already installed in BMW |
| Collision Avoidance System (CAS) | A sensor, installed at the front end of a vehicle, scans the road ahead for vehicles or obstacles. When an obstacle is detected, the system decides whether collision avoidance action is needed and a manoeuvre is undertaken | After 2015 | Optional as safety function with potential to become mandatory. |

Table notes: [(a)]OEM: Original Equipment Manufacturer
[(b)] As warning function-based on digital maps. After 2015: as an adaptive function.

Table 1 describes each DAS application examined in this paper, along with its market introduction and current status in Europe (Commission of European Communities, Wilmink et al., Abele et al., Department for Transport, Mercedes Benz, BMW, European Commission). Most DAS are currently offered as a 'comfort function' and are optional on luxury passenger cars, while some have the potential to become mandatory standard equipment in European cars in the coming decade. The implementation of DAS results in a first-generation 'intelligent' vehicle, which can operate both in urban and highway environments and provides a driver aid through look-up displays of recommended speeds or routes. The DAS technology is mature and already exists in the European car fleet in the form of driver advisory systems providing guidance, warnings and alerts to drivers (passive form of DAS). At a later stage, active DAS systems, which intervene and automatically control the vehicle, are expected to become available on passenger cars.

*Automated Highway System (AHS)*

AHS combine the use of in-vehicle devices with wireless communications between vehicles and infrastructure. In this way, AHS represents a complete driver replacement system, where driving is computer-controlled. Vehicles can organize themselves into platoons and be linked together in communication networks, which allow the continuous exchange of information about speed, acceleration, braking and obstacles.

To provide a safe and driverless driving, platoon operation is enabled by the use of three different control systems. A longitudinal control system maintains speed and spacing accuracy between the vehicles through the use of radar and radio communication between cars. This system enables short spacing between the cars and thus increases highway capacity, while the maintenance of a constant speed of the platoon leads to a smooth ride. A lateral control system (or steering control system) uses sensors, placed on the infrastructure and the vehicles and aims to keep the vehicle within the dedicated lane. Finally, a fault management system detects and handles failures in the sensors on the vehicles. As a result, in case of a detected failure in a vehicle, the fault management system is activated and puts under control the other cars of the platoon to avoid a crash.

In general, ITS implementation on passenger cars is currently based on in-vehicle technology. It is expected that future ITS applications will be based on a combination of in-vehicle and infrastructure technology, which may slowly evolve to an initial form of AHS. For this purpose, infrastructure providers need to cooperate with vehicle manufacturers and ITS developers to achieve a wider implementation of AHS. However, the potential form of platoons operating in an AHS is not expected to materialize before 2030, as several challenges associated with interoperability, standardization and social acceptability need to be resolved for a wide implementation. The lack of interoperability of ITS, especially for infrastructure-based applications, developed at local or regional levels, prevents the use of ITS across borders or national domains. EU intervention is therefore required to address interoperability and standardization issues. If no new policy is adopted, the above challenges may hamper the wider uptake of ITS.

*Commercial Vehicle Operations (CVO)*

CVO systems incorporate the use of a range of equipment, including roadside equipment, databases, and in-vehicle transponders or other tags. In this paper, Electronic Credentialing, Electronic Screening and Clearance and Fleet Management Systems are considered. In general, CVO applications have already been installed in several European regions, showing a wide variation of implementation. It is expected that some initial penetration of CVO in freight transport sector may be achieved within the next 5 years to meet European demand, while full potential is expected only after 2020. Current initiatives in Europe include e-freight which encompasses the use of ITS in order to minimize paperwork and unproductive processes, lower costs and enhance freight operations (Commission of the European Communities]). The main barriers that could slow CVO deployment include the lack of interoperability, the shortage of technically trained employees within the industry and the lack of a complete digital road map for all major European cities and the Trans-European road network (Hall and Intihar).

Based on the above considerations, the potential evolution of DAS, AHS and CVO will most likely take the form of Figure 1.

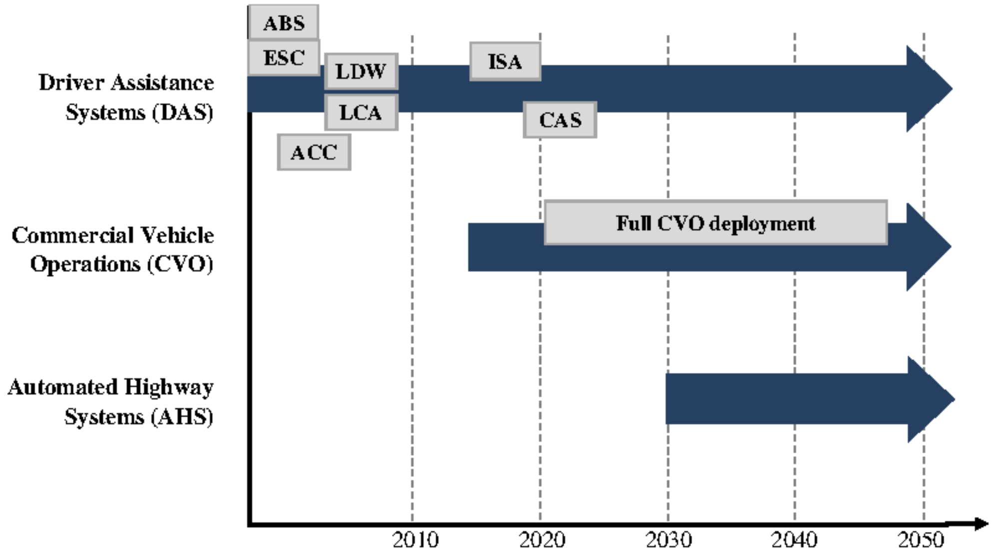


**Figure 1**: Evolution of DAS, AHS and CVO applications over years

## 3. Cost Estimates and User Acceptability

The initial acquisition cost of the three ITS technologies and their yearly costs constitute an important factor in the purchasing decision of consumers. In this section, we assess the retail price of intelligent vehicles along with their yearly costs and compare them with existing vehicles.

**Table 2**: Reference system characteristics

| Characteristics | Reference Passenger Car | Reference Heavy Duty Truck |
|---|---|---|
| Payload | - | 25 tn |
| Fuel type | Petrol | Diesel |
| Fuel Consumption | 6.2 lt/100km | 12.8 lt/1000 tn-km (100% utilization) |
| $CO_2$ Emissions | 145gr/km | 40.4 gr $CO_2$/tn-km |
| Retail Price | 16,500€ | 67,000 € |
| Capital Costs | 660€/year | 2,680 €/year |
| Depreciation | 1,650€/year | 6,700 €/year |
| Operating costs (excluding fuel) | 1,260€/year | 7,005 €/year |
| - Maintenance | 0.049€/km<br>735€/year | 0.039 €/km<br>3,900 €/year |
| - Tires | - | 0.013 €/km<br>1,300 €/year |
| - Parking and tolls | 0.013€/km | 0.008 €/km<br>800 €/year |
| - Insurance | 330€/year | 1,005 €/year |
| Yearly Costs (excluding fuel costs) | 3,570€/year | 16,395 €/year |
| *Average annual distance traveled* | 15,000 km/year | 100,000 km/year |

For comparison purposes, we take the average new European passenger car and the average new European heavy duty truck, operating within the EU-27 road network as a reference baseline. The main characteristics of the reference vehicles are summarized in Table 2 above.

The EU-27 road network is represented by the Trans European (TEN-T) network. The distribution of highway lanes over the network is important for the assessment of AHS platoon operations. It is depicted in Figure 2. Highways with three lanes per direction constitute the majority with a share of 51%. Highways with 3-4 lanes per direction follow, with a share of 15%.

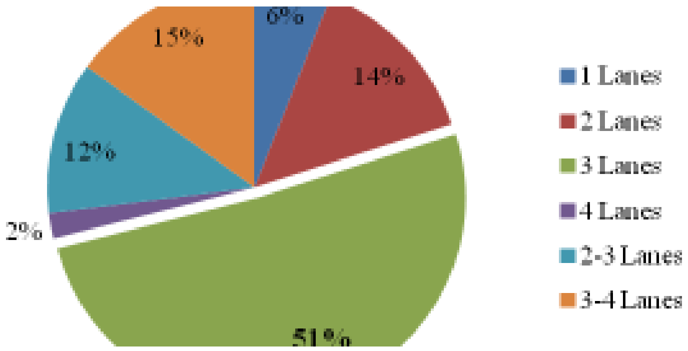


**Figure 2**: Lane distribution over the TEN-T network

The retail price of the reference vehicle is given by the manufacture recommended price, excluding Value Added Tax. Yearly costs are given as the sum of capital costs, depreciation and operating costs (including maintenance, tires, parking and tolls and insurance and excluding fuel costs) and can be expressed by the following equation:

$$\text{Yearly costs} = CC + D + O = r \cdot I + I / n + O \qquad (1)$$

where CC is Capital Costs [€/year], D is Depreciation [€/year], O denotes Operating Costs [€/year], r is discount rate (equal to 4%), I is the initial investment-retail price of the vehicle [€] and n is the vehicle lifetime (equal to 10 years). Insurance costs are assumed to be 2% of the retail price of a passenger car and 1.5% of the retail price of a truck (Psaraki and Pagoni and).

In-vehicle ITS devices are add-ons to the purchase price of a vehicle. The retail price of the intelligent vehicle consists of the retail price of the reference vehicle and the extra unit costs to obtain and integrate the appropriate ITS applications. Cost data for ITS applications were derived from several sources (Wilmink et al. , Baum et al., Research and Innovative Technology Administration) and, then, special effort was made to specify which elements are used by the proposed technologies. The ITS elements that are assumed to be used for DAS, AHS and CVO operations are given in Table 3, along with their unit costs and maintenance costs. Unit costs represent the costs for obtaining ITS components plus the costs for integrating them on the vehicle. An effort has been made to assess components that have already been installed on the vehicles for other purposes (such as DAS) and can be re-used for AHS as well, and components needed only for AHS. The cost estimates for DAS equipment are rough, as DAS systems are typically bundled, while other technologies are rarely installed as a standalone option.

Yearly costs of ITS-equipped vehicles are calculated the same way as for the reference system (based on equation 1). Analysis of individual annualized costs, such as capital, depreciation or operating costs is given in Table 4. Capital and depreciation costs will increase after ITS deployment, as they are directly related to the retail price of intelligent vehicles. Operating costs are also expected to increase. For example, maintenance costs for intelligent vehicles are higher due to the maintenance of the extra ITS elements (see Table 3). For AHS-equipped cars, maintenance costs are expected to increase by

25 €/year. For CVO-equipped trucks, extra costs of about 400 €/year are expected due to the maintenance and repair of the CVO elements. However, it is assumed that other maintenance costs of trucks are about to decrease by 10% in comparison with the reference system, due to their better performance, resulting from fleet management systems. Costs for tires, parking and tolls are assumed to be constant for trucks after CVO installation. Costs for tolls, in the case of AHS, are assumed to be about 10% higher to account for the additional AHS infrastructure investments and maintenance. Insurance costs, which are given as a constant percentage of the retail price of the vehicle (2% for passenger cars and 1.5% for trucks), are expected to increase. Annual insurance costs of AHS compatible vehicles will reduce, because the accident rates will decline as a result of AHS operations, provided liability issues are properly addressed by legislation.

**Table 3**: Unit costs and maintenance costs for DAS AHS and CVO in-vehicle elements

| | **Unit costs [€/vehicle]** | | | **Maintenance Costs [€/vehicle/year]** |
|---|---|---|---|---|
| | Average | Minimum | Maximum | |
| ***DAS ELEMENT*** | | | | - |
| Electronic Stability Control (ESC) | 150 | | | - |
| eCall | 60 | | | - |
| Adaptive Cruise Control (ACC) | 120 | 80 | 160 | - |
| Lane Departure Warning (LDW) | 300 | | | - |
| Lane Change Assistant (LCA) | 225 | 150 | 300 | - |
| Intelligent Speed Adaptation (ISA) | 230 | | | - |
| | | | | |
| ***AHS ELEMENT*** | | | | |
| Communication Equipment | 190 | 130 | 260 | 5 |
| GIS Software | 120 | 100 | 140 | 0 |
| Sensors for Lateral Control | 350 | 290 | 410 | 10 |
| Sensors for Longitudinal Control | 190 | 140 | 240 | 5 |
| Advanced Steering Control | 200 | 180 | 220 | 5 |
| **TOTAL COSTS FOR AHS** | **1,050** | **840** | **1,270** | **25** |
| | | | | |
| ***CVO ELEMENT*** | | | | |
| Electronic Tag | 410 | 300 | 510 | 8 |
| Communication Equipment | 1,090 | 740 | 1,450 | 6 |
| Central Processor and Storage | 190 | 140 | 230 | 4 |
| Differential Global Positioning System (DGPS) | 680 | 300 | 1,070 | 215 |
| Cargo Monitoring Sensors and Gauges | 120 | 80 | 160 | 12 |
| Electronic Cargo Seal Disposable | 10 | 5 | 15 | 0 |
| Autonomous Tracking Unit | 330 | 200 | 465 | 164 |
| ***TOTAL COSTS FOR CVO*** | **2,800** | **1,800** | **3,900** | **400** |

The resulting cost estimates are presented in Table 4 and Figure 3. Table 4 indicates a moderate increase of the vehicle's retail price (about 6.4% for passenger cars and 4.2% for trucks) after ITS implementation. Operating costs are also increased. However, these additional costs are not much higher than those of a conventional vehicle. Yearly costs (excluding fuel costs) are increased by 6% for AHS cars and 2.7% for CVO-equipped trucks in comparison with conventional vehicles.

Since fuel costs represent high percentages of yearly costs, especially for reference trucks (see Figure 3), the fuel economies offered by the technologies should be taken into account. Fuel consumption data for the reference (see Table 2) and ITS-equipped vehicles (see Table 5) are considered. Annual mileage for conventional and intelligent vehicles is assumed to be the same (given in Table 2). About 35% of the trips of AHS cars are inter-urban and are carried out on highways. An additional 15% corresponds to trips within urban areas over three-lane freeways, which can accommodate AHS-equipped cars. Based on these rough estimates, which vary between countries, we assume that 50% of the annual mileage is potentially done on roads over which AHS will be implemented. Finally, fuel prices in EU-27 during base year were assumed to be: 1.33 €/lt for petrol and 1.25 €/lt for diesel. Table 4 gives a comparison of the yearly costs with and without fuel costs, for reference and ITS-equipped vehicles. The implementation of CVO in trucks results in a reduction of yearly costs (including fuel costs) of 10.6%. The yearly costs (including fuel costs) of AHS cars are only 1.9% higher than the reference cars. We conclude that ITS technologies offer significant savings in fuel consumption in comparison to the average new European car. These savings are estimated to 10% for AHS cars and 16% for CVO trucks.

Besides cost, other factors that influence consumers' decisions to purchase ITS systems include driver safety and comfort, privacy, and liability issues. Each of these factors and behavioural impact are discussed next.

**Table 4**: Cost estimates for AHS and CVO

| | **PASSENGER CARS** | | | **HEAVY DUTY TRUCKS** | | |
|---|---|---|---|---|---|---|
| | **Reference** | **AHS** | $\Delta_{(ref-AHS)}$ | **Reference** | **CVO** | $\Delta_{(ref-CVO)}$ |
| **Retail Price** | **16,500** | **17,550** | **+6.4%** | **67,000** | **69,800** | **+4.2%** |
| Capital costs (€/year) | 660 | 700 | +6.1% | 2,680 | 2,790 | +4.1% |
| Depreciation(€/year) | 1,650 | 1,755 | +6.4% | 6,700 | 6,980 | +4.2% |
| Operating Costs(€/year) | 1,260 | 1,330 | +5.6% | 7,005 | 7,055 | +0.7% |
| - *Maintenance(€/year)* | 735 | 760 | +3.4% | 3,900 | 3,910 | +0.3% |
| - *Tires(€/year)* | - | - | - | 1,300 | 1,300 | 0% |
| - *Parking & Tolls(€/year)* | 195 | 220 | ~+10% | 800 | 800 | 0% |
| - *Insurance(€/year)* | 330 | 350 | +6.1% | 1,005 | 1,045 | +4% |
| **Yearly Costs (€/year) (excluding fuel costs)** | **3,570** | **3,785** | **+6%** | **16,395** | **16,830** | **+2.7%** |
| Fuel Costs (€/year) | 1,240 | 1,115 | -10% | 40,000 | 33,600 | -16% |
| **Yearly Costs (€/year) (including fuel costs)** | **4,810** | **4,900** | **+1.9%** | **56,395** | **50,430** | **-10.6%** |

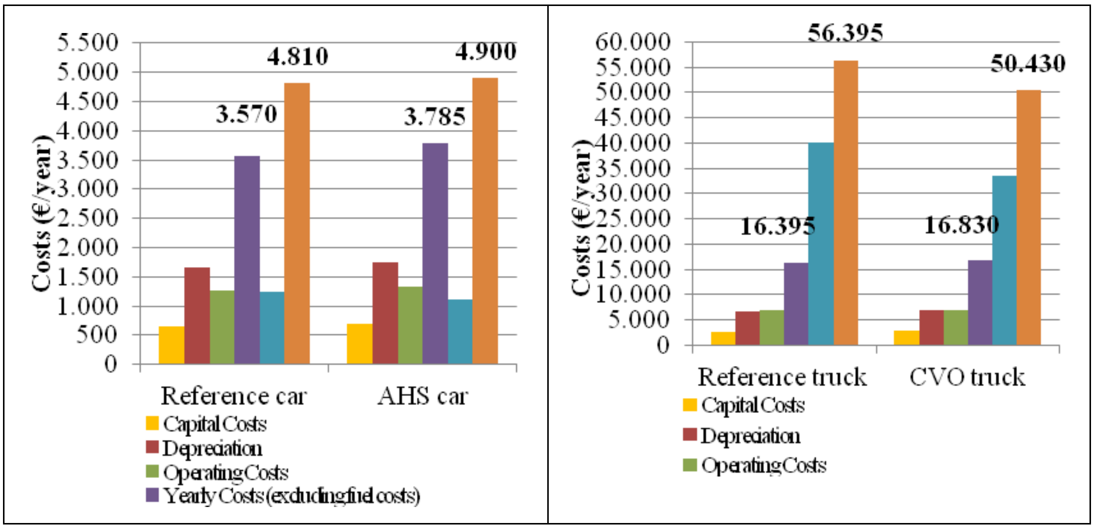


**Figure 3**: Annualized vehicle costs prior and after ITS (AHS or CVO) implementation

*Passenger/Driver safety and comfort*: DAS, AHS and CVO technologies are anticipated to play a significant role in improving road safety. DAS applications such as CAS, ACC, ABS and LDW alert the driver to take action if hazardous conditions are detected or, if no action is taken, they intervene and take over control. ISA and ACC adapt vehicle's acceleration and deceleration and reduce the probability of collisions, often caused by unstable traffic flow, leading drivers to apply high decelerations (Halle). The AHS control systems - longitudinal, lateral and fault management systems - can implement automatic recovery maneuvers to ensure the platoons' safety in the presence of failure, affecting the vehicles and their environment. Furthermore, in case of a failure affecting a vehicle in the platoon, the system is designed to take actions and allow the vehicle to leave its platoon without any hazard (Hamouda et al. ). CVO deployment is also expected to enhance freight transport safety. On the negative side, the use of on-board ITS devices may overload the processing capabilities of drivers and distract them from their primary driving task and create dangerous situations (Hancock and Parasuraman, Golias et al.). Researchers at Ford (Faber) (cited in Haynes and Li) have noted that the average driver does not want to be bothered more than three times in adjusting in-vehicle equipment. In other circumstances, drivers using ITS may have false expectations from their assisting function and adapt unexpected driver behaviour (less alertness and over-expectations), which could eliminate positive safety impacts (van Wees and Brookhuis). At an initial phase of AHS implementation, drivers may feel uncomfortable in a driverless car. The loss of control and the small headways achieved in an AHS may lead to inconvenient driving (Petica et al., de Vos and Hoekstra). There should be an adaptive period after initial implementation, so that drivers get used to the new technologies.

*Privacy*: A number of ITS applications such as eCall, ISA, AHS and CVO implicitly require collection and exchange of traffic data that could raise privacy concerns. These need to be addressed by European regulation.

*Liability*: Liability aspects are mainly attributable to ITS applications (for example ACC, AHS, CAS) that take over control from the driver in critical situations. If the boundaries of responsibilities among vehicle manufacturer, driver, ITS developer or roadway authority are not clearly defined in case of an accident, potential customers may not be willing to pay for the ITS application or service, or vehicle manufacturers may not be willing to sell vehicles with unsolved liability aspects.

Under the assumption that privacy and liability issues are successfully addressed by regulation at the European level, the above analysis and the finding of the experts' survey (Psaraki and Pagoni,) demonstrate that the three ITS technologies hold good promise in terms of user acceptability and should lead to substantial market penetration of ITS applications and services in the next two decades.

## 4. Improvements in Capacity and $CO_2$ Emissions

In this section gains offered by DAS, AHS and CVO in terms of capacity, fuel efficiency and emissions reduction are estimated. Under ideal traffic and geometric conditions, highway capacities can be as high as 2,400 vehicles per hour per lane (veh/h/l). In practice, a 75-80% of the theoretical value should be taken as a realistic figure (Featherstone and Lowson [**Error! Reference source not found.**]), resulting in lower capacities of about 1,800 veh/h/l.

To determine the gains in capacity and emissions, three evolution trends need to be determined: (i) growth of traffic demand, (ii) growth of transport related $CO_2$ emissions, (iii) fuel prices increase.

From 1995 to 2008, passenger kilometers operated by passenger cars went up by 21.4% (approximately 1.5% per year). This was accompanied by a high growth of motorization in Europe, which grew from 380 to 470 cars per 1,000 inhabitants between 1995 and 2008, an annual average of 2 %. The increase of the number of tonne-kilometres transported by road reached 39%. Apart from the bottlenecks in several European corridors, the intense growth of road traffic led to an increase of transportation related $CO_2$ emissions. Based on EU statistics, the amount of $CO_2$ emissions due to road transportation went up by 18% from 1995 to 2007. Finally, fuel price increase is a critical factor for road users, as it adds up to vehicles' operating costs. Despite the variability in automotive diesel oil prices, between 2001 and 2008 prices went up to 48% (European Union [**Error! Reference source not found.**]). Figure 4 presents the evolution of these indicators in EU-27 since 1995.

The European road network expanded to support the trends illustrated in Figure 4. However, it was also recognized that any increase in road capacity, achieved by constructing new highways, provides only temporary relief from traffic congestion, while imposing a high financial and environmental cost. ITS technologies emerged as an alternative for addressing road capacity issues, while at the same time delivering environmental benefits.

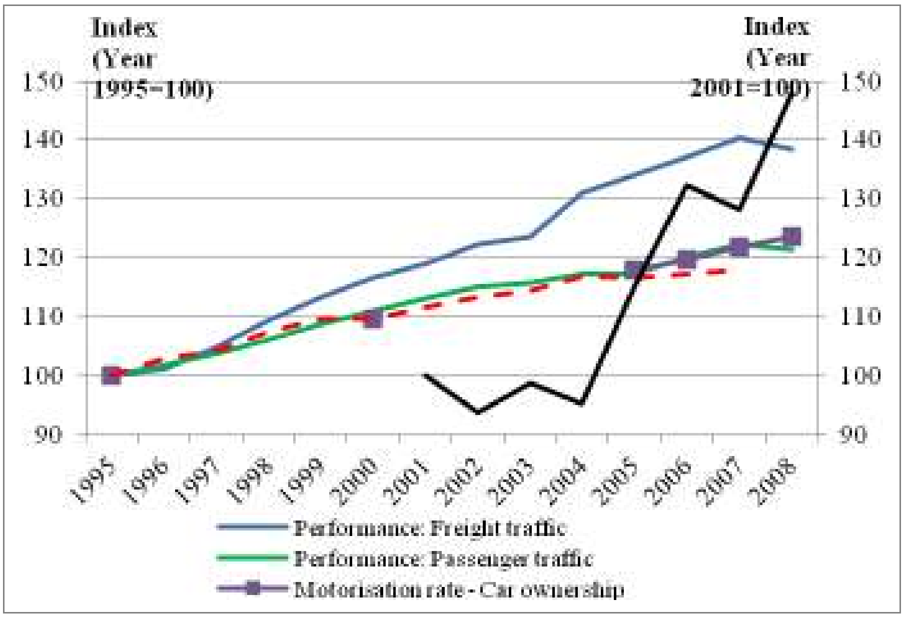


**Figure 4**: Indicators for EU-27 road transportation

Capacity enhancement is achieved mainly through speed and headway adjustment. DAS applications that affect longitudinal control of the vehicles (such as ACC and ISA), have direct effect on road capacity through the decrease of headways and the reduction of accelerations and decelerations. Thus, traffic flow is smoother in comparison with manual traffic. VanderWerf et al. indicate that if 100% of vehicles in a road network are equipped with cooperative ACC, the road may carry twice as many vehicles. ISA keeps the traffic flow more homogenized and thus can increase total throughput by 5% (Vanderschuren). Capacity improvements of about 7-8%, in comparison with manual driving conditions due to the decrease of headway are reported by Zwaneveld and Van Arem, depending greatly on the penetration rate and the headway setting. If we consider that manual driving results in capacities of 1,800-2,400 veh/h/l, driving with DAS would achieve maximum capacities of 1,900-2,600 veh/h/l. Nevertheless, Minderhoud indicates that DAS applications, such as ACC, offer an increase of road capacity only under strict conditions on market penetration and use. Other DAS applications, such as eCall, contribute to capacity enhancement through safety improvements. Usually, road accidents impede the flow of traffic until rescue services have provided first aid to the accident victims and the police have documented the incident. DAS limit accident severity or improve the efficiency of the rescue chain. Thus the accident site is cleared more quickly and congestion is relieved.

Capacity improvement is much higher with AHS applications. Distances between fully automated vehicles are significantly reduced until they reach the minimal safe distance. This results in more vehicles in a given lane. For example, a study of PATH research program (Partners of Advanced Transit and Highways) describes an eight-car platoon with fixed separation distance of 6.5 meters at all speeds up to full highway speed. Other studies (Michael et al., Tsao et al.) report even shorter intra-platoon spacing, significantly depending on the relative velocity. Higher speeds require larger headway and thus lead to small capacity increase. In addition, AHS stabilizes traffic flow and provides the vehicles with conditions of constant cruise speed. Thus, traffic equilibrium can be reached avoiding stop-and-go operations and inefficiencies caused by inattentiveness, merging, weaving, and lane changing (Halle). Studies that have simulated automated highway capacity have resulted in capacities up to 8,000 veh/h/l. This high capacity corresponds to 16-vehicles platoon, with a vehicle length of 5m and intra-platoon spacings of 0.1 seconds (Featherstone). We suggest that this theoretical value is reduced by 20-25% to account for the entry and exit of vehicles to and from the dedicated AHS lane. Then we obtain capacity values of 6,400 veh/h/l.

The level of capacity improvement strongly depends on the platoon size, the intra-platoon (between vehicles) and inter-platoon separations, the vehicle mix, the length of the trip operated in the platoons and the frequency with which vehicles enter and exit platoons. Platoon size may vary from 5 to 20 vehicles per platoon. The size of the platoon is constrained by the need to achieve communication between the platoon leader and all its followers in the platoon (Tsao et al.). With regard to vehicle mix, introducing even small percentages of trucks or buses to the flow of passenger cars can significantly reduce the achievable capacity because of the poorer performance of heavier vehicles. For example, mixing of different classes of vehicles reduces capacity by about 11% in the case of mixing 2.5% buses and 2.5% trucks with passenger vehicles, and by about 23% for 5% buses and 5% trucks (Kanaris et al.). Finally, the length of the trip operated in AHS is significant for determining capacity improvement, with short trip lengths and frequent entries and exits limiting capacity gains. Our calculations consider that AHS is implemented in 50%-60% of the high priority corridors of European highways, where drivers intend to travel long distance trips and one lane is dedicated for AHS operations.

Fuel efficiency is improved by the potential of DAS applications to reduce vehicles' accelerations and decelerations and smooth traffic flow. The positive effects of ISA on the environment are due to the reduction and homogenization of driving speeds. Likewise, ACC maintain constant speed and make 'speed-ups' and abrupt braking unnecessary. For other DAS such as eCall, LDW, LCA, reduction of $CO_2$ emissions comes as a side effect of safety improvements and congestion reduction. Accidents are reduced and queue formation is avoided, reducing the amount of congestion and emissions generated (Klunder et al., The Department of Transport). ISA deployment can achieve a 2-5% reduction of $CO_2$ emissions (Carsten and Fowkes, Goodwin et al., Regan et al.). For ACC, 0.5-10% $CO_2$ emissions reduction is reported (Klunder et al., Mercedes Benz, Halle, Liang and Peng). Other DAS applications such as ABS, show no clear potential on fuel consumption and $CO_2$ emissions. For this reason, the lower bound on fuel consumption and reduction of $CO_2$ emission by DAS is set to zero in Table 5.

Apart from the ability of the longitudinal control of the AHS to reduce the severity of accelerations and decelerations and create smoother traffic flow, fuel burnt reduction may come as a result of the unique platoon configuration. Short spacing between platoon vehicles, produce a significant reduction in aerodynamic drag for all of the vehicles, both leader and followers. An estimate of 15-25% reduction in fuel consumption and $CO_2$ emissions is possible with the implementation of

AHS (Partners for Advanced Transit and Highways, Browand and Michaelian). The reduction of delays and elimination of stops achieved by CVO may contribute to an average 16% reduction in fuel burnt and transport emissions (The Climate Group, Reinhardt et al.).

Table 5 summarizes the capacity and environmental benefits provided by the DAS, AHS and CVO deployment. The minimum and maximum values support different modeling assumptions. The overall gains strongly depend on the penetration levels of these technologies.

**Table 5**: Capacity and environmental benefits of ITS

| | Capacity (veh/h/l) | | | Fuel consumption & $CO_2$ Emissions Reduction [(a)] | | |
|---|---|---|---|---|---|---|
| | Average | Minimum | Maximum | Average | Minimum | Maximum |
| **DAS** | 2,000 | 1,900 | 2,600 | 5% | 0% | 10% |
| **AHS** | 4,300 | 4,300 | 6,400 | 20% | 15% | 25% |
| **CVO** | | No direct effects | | 16% | 6% | 26% |

[(a)] *These percentages apply to both fuel consumption and $CO_2$ emissions reduction. There is a direct and proportional relationship between fuel consumption and $CO_2$ emissions. An improvement in terms of fuel efficiency would be immediately translated into a reduction of $CO_2$ emissions and vice versa (when related to road traffic and fossil fuel) (Reinhardt).*

## 5. Conclusions

In this paper DAS, AHS and CVO have been considered. Retail prices and yearly costs were estimated and factors influencing user acceptability were discussed. Capacity gains over the TEN-T road network, fuel savings and reduction in $CO_2$ emissions were presented. Cost estimates indicate a 6.4% increase of the vehicle's retail price for passenger cars and 4.2% for trucks. Yearly costs of intelligent vehicles excluding fuel costs rise by 6% in the case of AHS cars and 2.7% in the case of CVO-equipped trucks. The inclusion of fuel costs reduces yearly costs by 10.6% in comparison to conventional trucks. In the long term, AHS is the most promising technology, offering an average of 20% reduction in $CO_2$ emissions. Highway capacity on AHS lanes is estimated to be 6,400 veh/h/l, when the reference capacity is 1,800 veh/h/l.

The advantages offered by ITS require wide adoption rates. High penetration mandates resolution of interoperability, privacy and liability issues with appropriate legislative initiatives at the European level.

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**References**

1. Commission of the European Communities (2008), *Action Plan for the deployment of Intelligent Transport Systems in Europe and the Proposal for a directive of the European Parliament and of the Council laying down the framework for the deployment of Intelligent Transport Systems in the field of road transport and their interfaces with other transport modes-Impact assessment*, SEC(2008) 3083, Brussels, Commission of the European Communities.
2. European Commission (2011), *White Paper: Roadmap to a Single European Transport Area - towards a competitive and resource efficient transport system*, COM(2011) 144 final, Brussels, European Commission.
3. Carslaw, D., Goodman, P., Lai, F. and Carsten, O. (2010), Comprehensive Analysis of the Carbon Impacts of Vehicle Intelligent Speed Control", *Atmospheric Environment, 44* (23), pp. 2674-2680.
4. Khayyam, H., Nahavandi, S. and Davis, S. (2012), Adaptive Cruise Control look-ahead System for Energy Management of Vehicles, *Expert Systems with Applications, 39* (3), pp. 3874-3885.

5. Minderhoud, M.M. (1999), *Supported driving: Impacts on motorway traffic flow,* PhD Thesis, Delft University of Technology, The Netherlands.
6. Zwaneveld, P.J. and Van Arem, B. (1997), *Traffic effects of Automated Vehicle Guidance systems: A literature survey*, The Netherlands, TNO Inro.
7. Wilmink, I., Janssen, W., Jonkers, E., Malone, K., van Noort, M., Klunder, G., Rämä, P., Sihvola, N., Kulmala, R., Schirokoff, A., Lind, G., Benz, T., Peters, H. and Schönebeck, S. (2008), Impact Assessment of Intelligent Vehicle Safety Systems, Deliverable D4, eImpact Project.
8. Baum, H., Geibler, T., Schneider, J., Westerkamp, U., Schulz, W., Esser, K., Kurte, J., Alkim, T., Hamernikova, V., Gelova, E. and Vitale, C. (2008), Stakeholder analyses for Intelligent Vehicle Safety Systems, Deliverable D8, eImpact Project.
9. Abele, J., Kerlen, C. and Krueger, S. (2005), Exploratory Study on the Potential Socio-economic Impact of the Introduction of Intelligent Safety Systems in Road Vehicles, SEISS Final Report.
10. Carbaugh, J., Godbole, D. and Sengupta, R. (1998), Safety and Capacity Analysis of Automated and Manual Highway Systems, *Transportation Research Part C, 6* (1-2), pp. 69-99.
11. Godbole, D. and Lygeros, J. (2000), Safety and Throughput analysis of Automated Highway Systems, California PATH Research Report UCB-ITS-PRR-2000-1, Berkeley, University of California.
12. Hall, R. and Chin, C. (2005), Vehicle Sorting for Platoon Formation: Impacts on Highway Entry and Throughput, *Transportation Research Part C, 13*(5-6), pp. 405-420.
13. Kanaris, A., Ioannou, P. and Ho, F. (1996), Spacing and Capacity Evaluations for different AHS concepts, California PATH Research Report UCB-ITS-PRR-96-30, Berkeley, University of California.
14. Michael, J.B., Godbole, D., Lygeros, J. and Sengupta, R. (1998), Capacity Analysis of Traffic Flow over a Single-lane Automated Highway System, *Journal of Intelligent Transportation Systems, 4*(1-2), pp. 49-80.
15. Manzie, C., Watson, H. and Halgamuge, S. (2007), Fuel Economy Improvements for Urban Driving: Hybrid vs. Intelligent Vehicles, *Transportation Research Part C, 15* (1), pp. 1-16.
16. Partners for Advanced Transit and Highways, *Vehicle platooning and automated highways*", Berkeley, University of California.
17. Crainic, T.G., Gendreau, M. and Potvin, J.Y. (2009), Intelligent Freight-Transportation Systems: Assessment and the Contribution of Operations Research, *Transportation Research Part C, 17*(6), pp. 541-557.
18. Hall, R. and Intihar, C. (1997), Commercial Vehicle Operations: Government Interfaces and Intelligent Transportation Systems, California PATH Research ReportUCB-ITS-PRR-97-12, Berkeley, University of California.
19. The Climate Group (2008), '*SMART 2020: Enabling the Low Carbon Economy in the Information Age'*, Retrieved November 1, 2011 from: <http://www.smart2020.org/_assets/ files/02_Smart2020Report.pdf>
20. Klunder, G.A., Malone, K., Mak, J., Wilmink, I.R., Schirokoff, A., Sihvola, N., Holmén, C., Berger, A., de Lange, R., Roeterdink, W. and Kosmatopoulos, E. (2009), Impact of Information and Communication Technologies on Energy Efficiency in Road Transport, Final Report, Delft, The Netherlands,.
21. Reinhardt, W., Hadrovic, A., Grabec, I., Botman, W., Klanner, W., Tomassini, M., Oehman, P., Follin, P., Kjellgren, F. and Sansone, F., Roadmap on ICT for energy efficiency and recommendations for sustainable networking, Deliverable D4.4, Intelligent Cars Thematic Network Project.
22. Ezell, S. (2010), *Explaining International IT Application Leadership: Intelligent Transportation Systems*, The Information Technology & Innovation Foundation.
23. Van Wees, K. and Brookhuis, K. (2005), Product Liability for ADAS: Legal and Human Factors Perspectives, *European Journal of Transport and Infrastructure Research, 5*(4), pp. 357-372.

24. Petica, S., Vicens, V., Bekiaris, E., Portouli, V., Papakonstantinou, C., Peters, B., Artaud, P., Brookhuis, K., De Waard, D., Nathanail, T., Ploix, D., Coda, A. and Damiani, S. (1996), Driver Needs and Public Acceptance of Emergency Control Aids, Report of SAVE Project.
25. Haynes, K. and Li, M. (2004), Analytical Alternatives in Intelligent Transportation System (ITS) Evaluation, *Research in Transportation Economics, 8*, pp. 127-149.
26. The Department for Transport (2004), *Development Study for Cooperative Vehicle Highway Systems (CVHS)*, Surrey, UK.
27. Mercedes Benz (2011), *Mercedes Benz Tech Center: Assistance systems*. Retrieved March 10, from: <http://www3.mercedes-benz.com/mbcom_v4/ gr/techcenter2009/ en.html#/assistance/ overview>
28. BMW (2011), *BMW Connected Drive: Driver Assistance.* Retrieved March 15, from: http://www.bmw.com/com/en/insights/technology/connecteddrive/2010/safety/drive_assistance/index.html
29. European Commission (2008), Improving the Safety and Environmental Performance of Vehicles", IP/08/786, Brussels.
30. Psaraki, V. and Pagoni, I. (2011), Transport Infrastructure Capacity Assessment: Road Passenger Transport. Deliverable D6.1, TOSCA project.
31. Psaraki, V. and Pagoni, I. (2011), Transport infrastructure capacity assessment: Road Freight Transport. Deliverable D6.2, TOSCA project.
32. Research and Innovative Technology Administration (2010), *ITS Unit Costs Database (in 2009 dollars) as of 30 October 2010: Equipment list adjusted 2009*. Retrieved December 10, from: < http://www.itscosts.its.dot.gov/ its/benecost.nsf/ Images/ Reports/$File/ CostElements%202010-10-30.pdf>
33. Halle, S. (2005), *Automated Highway Systems: Platoons of vehicles viewed as a multiagent system*, Master's Thesis, Université Laval, Québec.
34. Hamouda, O., Kaâniche, M. and Kanoun, K. (2009), Safety Modeling and Evaluation of Automated Highway Systems, 39th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN-09), Lisbon, Portugal, pp.73-82.
35. Hancock, P.A. and Parasuraman, R. (1992), Human Factors and Safety in the Design of Intelligent Vehicle-Highway Systems (IVHS), *Journal of Safety Research, 23* (4), pp.181-198.
36. Golias, J., Yannis, G. and Antoniou, K. (2002), Classification of Driver-assistance Systems according to their Impact on Road Safety and Traffic Efficiency, *Transport reviews, 22*(2), pp. 179-196.
37. Faber, G. (1991), *IVHS Human Factor Issues*, Paper presented at the 2nd International Conference on Applications of Advanced Technologies in Transportation Engineering, Minneapolis, MN, August 18-21.
38. De Vos, A.P. and Hoekstra, W. (1997), *Behavioural Aspects of Automatic Vehicle Guidance (AVG): Leaving the Automated Lane*, Soesterberg, The Netherlands, TNO Human Factors Research Institute.
39. Featherstone, C. and Lowson, M. (2004), *Viability and Benefits of Platooning in Automated Transport Systems*, Deliverable of CyberCars Project.
40. European Union (2010), *EU Energy and Transport in Figures: Statistical Pocketbook 2010*, Luxembourg, Publications' Office of the European Union.
41. VanderWerf, J., Shladover, S.E., Miller, M.A. and Kourjanskaia, N. (2002), *Evaluation of the Effects of Adaptive Cruise Control on Highway Traffic Flow Capacity and Implications for Development of Future Automated Systems*, Proceedings of the 81th Annual Meeting of Transportation Research Board, Washington D.C., January 13-17.

42. Vanderschuren, M. (2003), *The Benefits of Intelligent Transport Systems: Modelling the Effects of Different ITS Systems*, Proceedings of the 22nd Southern African Transport Conference (SATC2003), Pretoria, South Africa, July 14-16.
43. Tsao, J., Hall, R. and Hongola, B. (1994), *Capacity of Automated Highway Systems: Effect of Platooning and Barriers*, California PATH Research Report UCB-ITS-PRR-93-26, Berkeley, University of California.
44. Carsten, O. and Fowkes, M. (2000), *External Vehicle Speed Control: Executive Summary of Project Results*, Leeds, UK, University of Leeds.
45. Goodwin, F., Achterberg, F. and Beckmann, J. (2006), *Intelligent Speed Assistance-Myths and reality: ETSC position on ISA,* Brussels, European Transport Safety Council.
46. Regan, M., Triggs, T.J., Young, K.L., Tomasevic, N., Mitsopoulos, E., Stephan, K. and Tingvall, C. (2006), *On-road evaluation of Intelligent Speed Adaptation, Following Distance Warning and Seatbelt Reminder Systems: Final Results of the TAC SafeCar Project*, Australia, Monash University Accident Research Centre.
47. Liang, C.Y. and Peng, H. (2000), String Stability Analysis of Adaptive Cruise Controlled Vehicles, *JSME International Journal Series C,43*(3), pp. 671-677.
48. Browand, F. and Michaelian, M. (2000), Platoon Travel Saves Fuel… How much?, *Intellimotion, 9*(2), pp. 1-5, 11.