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CityMobil

Navigation Technologies for Cybercars and Advanced City Vehicles

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1 Executive Summary

This report presents the various technologies available on the market or close to the market, which are available for the navigation of cybercars, automated buses or advanced city vehicles. Navigation, which means the way to automatically guide a vehicle through a trajectory, is a key issue for the deployment of automated vehicles in the urban environment. This deliverable has been elaborated to give some information to the developpers of such systems. It introduces the state of the art of the various techniques now in the market and those which might soon be and tries to match these techniques with the requirements of the various scenarios which have been elaborated in CityMobil SP2. Finally, test procedures for the certification of the automated navigation features of the vehicles are proposed.

Integration of these technologies has gained in maturity, and tomorrow's challenges for navigation technologies is their ability to withstand more operational constraints such as service customisation, traffic management, integration into existing structures, and so that the global architecture eventually reaches fleet-scale for better service and liability.

2 Introduction

In sub-project 3 of CityMobil the technological issues of advanced urban transport systems are addressed. The main objective of this sub-project is to remove technological barriers in order to introduce advanced urban transport systems on a large-scale. Advanced vehicle architectures are developed and the basic subsystems for cybercars and advanced city cars are defined to achieve this objective within the sub-project. A dual-mode platform is developed within SP3 and optimum solutions for human-machine interfaces and information systems are proposed. Furthermore specific obstacle detection systems and navigation techniques, focusing on wireless communication for high throughput are evaluated.

In order to study the described technological issues, working scenarios are developed, which represent different transport areas in modern city life and provide possible solutions for future penetration of innovative transport systems and integration in urban areas under the consideration of the already existing infrastructure. Four scenarios are adressed in Citymobil:

1. Town centre : dual mode vehicles and advanced city cars in a historical town centre
2. E-lanes: high-speed dedicated lanes where vehicles operate in automatic mode
3. Inner city centre: fully automated low-speed vehicles in a pedestrian area
4. Shared traffic: dedicated lanes for automated and classical buses

The scenarios offer a good level of generality and potentiality for the CityMobil sub-project. Functions, such as automatically moving in dedicated lanes, entering and exiting a parking area automatically and joining and leaving a formation of Cybercars, have to be considered within those scenarios.

The selected working scenarios are described in detail to understand the boundary conditions. Considering those scenario descriptions the definition of system requirements are derived for each scenario. The requirements are based on reliable sources such as simulations, experience from previous projects or calculations. Based on the derived requirements, the main technological challenges for the realisation of these scenarios are identified, which allow the subproject to address them in WP3.2 – Human factors, WP 3.3 - Obstacle detection and avoidance and WP3.4 – Cooperative vehicles and navigation. As a result of the deliverable preliminary system definitions are given in form of a description of the vehicles and their components with the necessary additional infrastructure belonging to the system in different scenarios.

This work package deals specifically with the technologies and the requirements for navigation of cybercars, advanced city buses and advanced city vehicles. Its objective is to give to the developers of the systems, recommendations for the introduction of these technologies accordingly with the sites selected.

3 State-of-the-Art in Navigation Technologies

3.1 Sensing

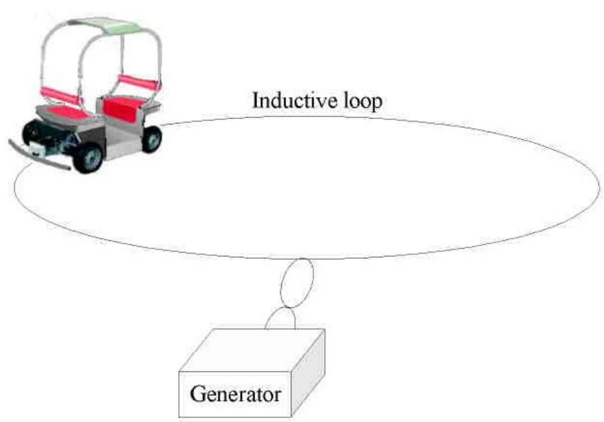
3.1.1 Infrastructure based systems

Wire guidance

Wire guidance is a standard solution in robotics to provide a continuous lateral localisation of an automated vehicle. It has some disadvantages related to the difficulty and cost of installation, as well as the reliability.

The wire is an inductive loop powered by a generator (Figure 1). Inductive track guidance with inductive loops has been proven as a very reliable system. The system is not influenced by dirt, colour, concrete, ice and snow etc. Nevertheless guide wires have to be installed carefully so that the wires do not break and influences caused by metal within the track must be avoided.

Figure 1 The wire guidance system



Three inductive sensors are used to follow the wire. The sensors give a voltage depending on the distance to the wire. Modifying the steering, the vehicle tries to “keep the wire” in the middle of the right and the left sensor.

In good conditions (wire correctly installed, generator with a good adjustment), the lateral control can be made with a very low error. In good conditions (wire correctly installed, generator with a good adjustment), the lateral control can be made with a very low error. For instance, Götting give the following value for guidance precision [22]:

- 100mA with antenna at 50mm height, the given precision about the input information for navigation is of +/- 1mm.
- 300mA with antenna at 500mm height, the given precision about the input information for navigation is of +/- 10mm.

The inconvenient of this technology is that it suffers of perturbation. Any high power electrical source in the surrounding of the installation can disturb the electrical signal in the cable. The sensor embedded on the vehicle can also be disturbed and lead to malfunctioning of the system.

Magnetic markers

The principle is to integrate on the planned trajectory small magnets in the ground (approximately every meter). When detected, those magnets recalibrate the navigation sensors (e.g. odometer) used to predict the relative position. This technology is cheaper on the infrastructure but more costly on the vehicle. It can work at high speed as it was shown in 1997 in the Automated Highway System demonstration in San Diego. Small adjustments in the trajectory are also possible just by software since the trajectories do not have to run exactly through each magnet (the vehicle must sense each magnet just to reposition itself).

Considering the CityMobil application, this technology has an impact on the infrastructure because the road network should be equipped along all the potential paths at least each 1 or 2 meters. This might be improved in the future with better inertial navigation, which would allow for larger spacing. Also, a database of the exact location of each magnet must be compiled which can be costly at the moment when we do not have automatic procedures to do that. Another drawback of the magnets is the possibility for a vehicle to be “lost” in case of a simple failure. If for some reason, the vehicle loses its position, it is difficult to put it back in operation: one must enter by hand its precise location.

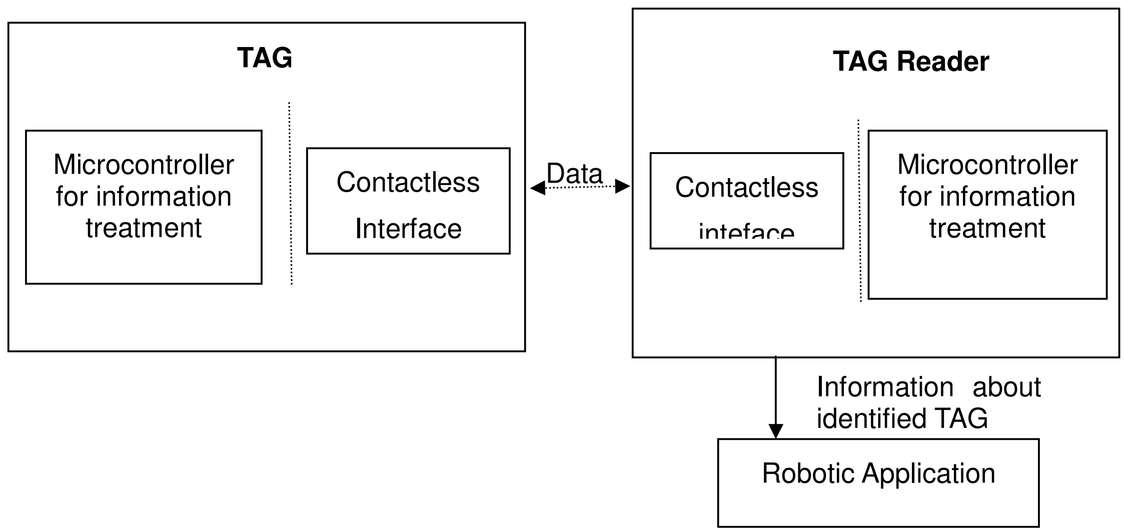
An alternative to magnetic markers is transponder. It uses a similar principle as the magnets, but is more sophisticated. In this case, the road marker are intelligent and can supply not only their position (relative to the vehicle) but also their identity and possibly some network characteristics (cross road configuration, road type, etc..).

With this system the same consideration on the infrastructure as presented above plus the cost of each transponder appears. Also, the current performances are limited by the delay to get a precise localisation, e.g. a few milliseconds. The current vehicle speed is limited to 30 km/h.

RFIDs

The main purpose of the RFID (Radio Frequency Identification) technology is the automated identification of objects with electromagnetic fields. An RFID system has three basic components; transponders (tags), readers (scanners, interrogator) and middleware (application systems) for further processing of the acquired data. There is a large variety of different RFID systems: they can use low, high or ultra high frequencies, tags may emanate only a fixed identifier or can have significant memory and processing capabilities. Transponders can contain effective security protocols or no security features at all. Most of the tags has passive powered by the radio field emitted by the reader but there are also active tags with a separate power supply. The basic components of an RFID system are as follows (Figure 2):

Figure 2 Basic components of an RFID system



Tag

Tags have three basic types:

- Inductively coupled RFID tag - powered by the magnetic field generated by the reader, passive tag.
- Capacitive coupled RFID tags - use a silicon chip, active tag.
- Semi-passive tags - use a battery to run the chip's circuitry, but communicate by drawing power from the reader

The main characteristics of RFID tags are summarized in Table 1.

Table 1 Main characteristics of RFID tags

	Active tag Semi	Passive tag Passive tag	Active tag Semi
Tag Power Source	Internal to tag	Radio wave energy from reader for communication	Energy transferred using RF from reader
Tag Battery	Yes	Battery for chip operation.	No
Availability of power	Continuous	Continuous	Only in field of reader
Required signal strength to tag	Very Low	Low	Very High
Signal strength tag	Very High	Low	Very low
Range	Up to 100 m	In reader range	Up to 3-5 m, usually less
Multi-tag reading	Thousands of tags recognized – up to 160 km/h velocity	Few hundred within reach of the reader	Few hundred within 3m of the reader
Data storage	Up to 1 MB of read/write with sophisticated search	Up to 1 MB	128 kb of read/write
Typical applications	High-value goods, over long range	High-value goods, readable from short range	High volume goods, readable from short range

Interrogator

Interrogators (readers) communicate directly with the smart tags. Depending on the application and technology used, some interrogators not only read, but also remotely write to, the tags. For the majority of low cost tags (tags without batteries), the power to activate the tag microchip is supplied by the reader through the tag antenna when the tag is in the interrogation zone of the reader, as is the timing pulse - these are known as passive tags.

Middleware

Middleware is the interface needed between the interrogator and the existing databases and information management software. It can be a network with interface, which serve as the communication surface for the application.

RFID systems can be grouped according to the

- Way of working to passive, active tags, semi-passive tags,
- Frequency ranges.

Passive tags

RFID tags contain a microchip and a coupling element - an antenna. Tags are activated when they enter the polling zone of the interrogator – otherwise, they stay in passive mode. Chip tags can be both read-only (programmed during manufacture) or, at higher complexity and cost, read-write, or both. Chip tags contain also a memory. The size of the tag depends on the size of the antenna, which increases with range of tag and decreases with frequency. The primary potential benefit of the most promising passive tags is that eventually they could be printed directly on products and packaging for 0.1 cents and replace ten trillion barcodes yearly with something far more versatile and reliable.

Semi-passive tag

Active RFID tags have a transmitter and their own power source (typically a battery). The power source is used to run the microchip's circuitry and to broadcast a signal to a reader (the way a cell phone transmits signals to a base station). Passive tags have no battery. Instead, they draw power from the reader, which sends out electromagnetic waves that induce a current in the tag's antenna.

Semi-passive tags use a battery to run the chip's circuitry, but communicate by drawing power from the reader. Active and semi-passive tags are useful for tracking high-value goods that need to be scanned over long ranges, such as railway cars on a track, but they cost more than passive tags, which means they can't be used on low-cost items. (There are companies developing technology that could make active tags far less expensive than they are today.)

The RFID technology cannot be used directly to define the path to follow for a vehicle. Indeed, there is no accuracy on the localization of the RFID tag in the antenna surrounding. However, this system can be used as a topological indicator for the vehicle. Indeed, we could use this RFID tag in order to inform the vehicle that it enters a specific area, like a very slow speed zone.

This type of technology should then not be seen as a tool used for “low level” navigation but as a tool for high level and interpreted navigation at a topological level. RFID tags are disposed in the environment, the antenna is mounted on the vehicle, and when the vehicle enters a given zone then it gets immediately the information and can adapt its behaviour.

3.1.2 GPS based systems

Standard GPS

“Standard GPS“ is a system using a constellation of 24 satellites evenly spaced on 20.200km altitude orbits. It was launched in 1980 by USA DoD. GPS receptors estimate the distance of each visible satellite’s by computing the travelling time of a signal emitted by the satellite. Since, at light speed, a 1ms incertitude leads to 300km shift, the overall timing estimation has to be very precise. Thus, satellites use atomic clocks so that they keep consistent timelines. A GPS receptor, though, uses a cheaper quartz-based clock, which drift is partially corrected through examination of the timestamps of each incoming signals. This correction is performed continually, when a least 4 satellites are simultaneously visible for a small period of time.

Once the receptor is more accurately synchronized with the constellation, estimation of travelling times and associated distances –called pseudo-ranges– is possible. The GPS receptor is necessarily located somewhere within the intersection of all spherical shells whose radiuses are equal to associated receptor/emitter distances and whose centres are located on each satellite.

The overall accuracy is also influenced by various phenomena such as ionospheric refraction, clock drift, multipath propagation, orbital irregularities, leading to an overall accuracy of 15 meters.

The precision of GPS system was – till year 2000 - voluntary degraded by adding a pseudo-random “jitter” in the signal emitted by the satellites. Military applications were granted access to this code, allowing the elimination of this artificial jitter, while civilian applications had their accuracy degraded to 100m.

Differential GPS

DGPS systems use a base station which position is fixed and known. By application of the same algorithms as those of a mobile GPS receptor, the position of the base station is estimated. The difference between estimated position and known position gives an estimation of the error due to DGPS ionospheric refraction and orbital irregularities. This error is broadcasted in the area of the station, and mobile receptors subtract this error from their estimations. Usually, the correction is valid in a 10km area. Wide Area DGPS (WADGPS) provide correction valid in 1000km areas, by decomposing the error among several components: some, which are constant and others that depend on the geometry. With a rough knowledge of their position, mobile receptors are thus able to compute more precise error estimation. DGPS systems can reach a precision up to one meter.

RTK GPS

Real-time Kinematic GPS are top-of-the-range DGPS that emphasize the precision by a more accurate measure of pseudo-ranges. Normal GPS use the timestamp included in the signal emitted by satellites, whereas RTK add correction to that estimation through measurement of carrier phase shift. This implies the use of very performing and costly electronic circuits, as well as high computation power to provide real-time correction.

When all corrections are cumulated, a precision of a few centimetres is reached in good conditions.

3.1.3 Vision based systems

Lane detection

Over the past few years a number of vision-based lane detection systems have been used in a range of automotive applications such as lane-keeping and autonomous vehicle guidance e.g. Autotaxi (Buchanan, 2006). In such systems a monocular greyscale camera is used to monitor the environment in front of the vehicle. An image is acquired and processed according to the simplified flowchart of Figure 3 and as described in more detail in Tucker

(2002). In practice these systems are more complex because of the need for them to be robust to a variety of different lighting and weather conditions and road surfaces.

Figure 3 Lane Detection Processing Flowchart

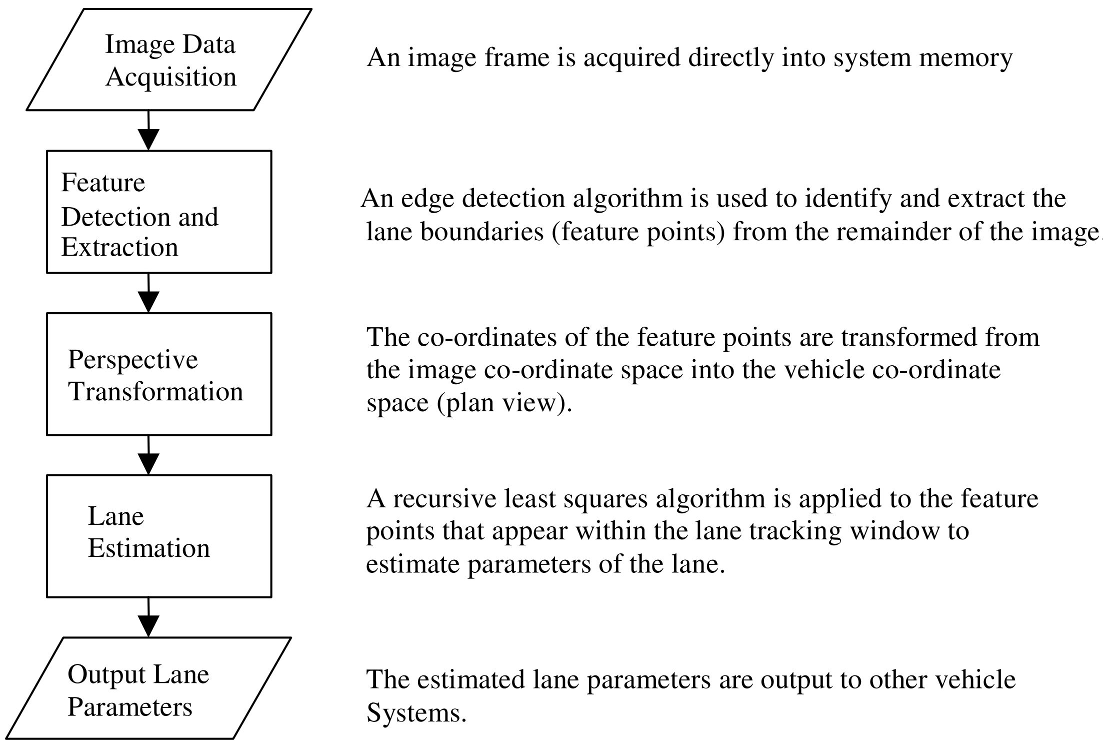


Figure 4 shows captured images overlaid with the detected lanes for a typical highway scenario as well as showing robust performance in severe rain, night operation and also on country roads where fewer lane markings are available (in fact in this last scenario, boundaries and verges define the lane rather than lines).

Figure 4 Lane Detection System Images

Optical markers

Optical markers system consists in using markers coated with a reflective material to reflect light generated near the cameras lens. The cameras sensitivity can be adjusted taking advantage of most cameras' narrow range of sensitivity to light so only the bright markers will be sampled ignoring support type.

The position of the marker is estimated as a position within the two-dimensional image that is captured. The greyscale value of each pixel can be used to provide sub-pixel accuracy.

An object with markers attached at known positions is used to calibrate the cameras so that their positions are estimated and the lens distortion of each camera is measured. Providing two calibrated cameras see a marker, a three-dimensional fix can be obtained.

Professional vendors have sophisticated constraint software to reduce problems from marker swapping since all markers appear identical. Unlike active marker systems and magnetic systems, passive systems do not require wires or electronic equipment. The markers are usually attached directly to the element to detect (vehicle or infrastructure). This type of system can capture large numbers of markers at frame rates as high as 2000fps with high accuracy. The frame rate for a given system is often traded off between resolution and speed.

Optical odometry

Commonly, the localization in outdoor environment is based on the fusion between GPS data and data provided by proprioceptive sensors embedded on the vehicle like odometers and/or Inertial Navigation System (INS). In urban environment, this process is enhanced using a prior knowledge from maps thanks to a map matching algorithm which constraints the trajectory of the vehicle to belong to the road. Nevertheless, the success of such techniques is closely related to the reliability of the GPS data and its availability during the navigation task. Practically, in a dense urban environment (i.e. old city, downtown). These prerequisites hold rarely, due to the presence of vertical structures in the architecture. When reliable GPS data are missing, the localization process is only supported by a dead reckoning method based on the integration of odometry data provided by internal proprioceptive sensors. It is well known that such sensors are subject to an important drift leading to a biased localization.

On the other hand, it is now clearly admitted that, in a near future, every car will be equipped with on-board exteroceptive sensors like vision, lidar or radar for ADAS applications. Such sensors are well adapted to capture the interactions between the vehicle and the local environment in the vehicule-centered frame. Vision sensor is particularly well-adapted to the navigation of an AGV in the complex urban environment: it allows first the extraction of "natural" beacons on the architecture to simultaneously estimate the vehicle ego-motion and produce a "local" map (SLAM) and secondly it allows the tracking of moving object (vehicles, pedestrians, pets) which have their own range of speed and direction (SLAMMOT). The estimate of the vehicle ego motion is then known as optical odometry.

3D servoing

The urban environments are difficult to model: from the single way street to large boulevards, many configurations are possible. Furthermore, the introduction of artificial beacons in a city is not an acceptable universal solution due to the scale problem. The unique common element to all the urban scenes is the road. Due to the urban traffic, the free field of view in front of a vehicle does not exceed some meters but it is rarely less if the safe distance is maintained.

The reconstruction of a city with an embedded vision system is possible according to the static environment, which can be tracked over a video sequence. When a GIS (Geographic Information System) data are available, the vehicle localization tends to a Structure From Motion (SFM) problem because opposite to SLAM methods, the duration of the environment visibility is very short with a travelling vehicle. Otherwise, according to planarity assumptions, a 3D reconstruction of the static environment can be performed as soon as the surfaces are textured enough to segment the different surfaces (road, kerbs, frontages) but although urban furniture like bus stations, poles, red crosses, lamp posts and phone booths. It has therefore been demonstrated that tracking a number of stored images can be a possible solution to the problem of navigation in an urban environment. However, this technique requires the storage of a large number of images for all the possible trajectories.

3.1.4 Sensor Fusion

In the context of navigation sensor fusion is the process that allows using multiple sensors to provide a single enhanced estimation of the vehicle state (position, speed, orientation, etc…). Since multiple sensors fusion relates to integrate multiple observations in order to enhance the current state estimate, it is closely related to the sequential filtering methods where observations from different time instants are fused.

It should be noticed that since this information will be used for decision making, we do not only desire to estimate the vehicle state but also the uncertainty on this estimation.

Today this is a classical problem with standard solutions. The approach universally applied is based on the Bayes theory. The vehicle state is represented as a probability distribution that evolves in time and is modified based on the information provided by the sensors measurements. In this context the problem of sensor fusion is a specific instance of a Sequential Bayesian Filtering problem.

The interest of the Bayesian approach is that it provides a sound mathematical foundation, and allows homogeneously managing heterogeneous sensors. Its main drawback however is that for any but trivial cases the mathematical solutions provided is intractable (too heavy to be computed online). Due to this the practitioners are limited to do more or less realistic approximations.

The simplest approximation is known as the Kalman Filter, which is the exact solution of the sequential Bayesian filtering problem when the system (vehicle model) is linear and the noise (of the sensors or the model) follows a Gaussian distribution non correlated in time. In general noise is not Gaussian, it is correlated in time and the systems are non linear.

The time correlation issue can be avoided by carefully choosing the sampling rate of the sensors. The noise Gaussian distribution is not true in general however it is usually a good enough approximation.

The non linearity of the systems is usually dealt using the so called Extended Kalman Filter, where the non linear system is linearized around the current state estimate. This solution is known to provide a poor approximation and can diverge easily. A better solution consists on using a Sigma Point Kalman Filter, which will use the non-linear model to propagate the Gaussian estimates. While no convergence guarantee are provided in practice the stability and precision are noticeably enhanced with little additional computation [16].

Another usual approximation for non-linear systems are the particle filters. Here the probability distribution obtained through the sequential Bayesian filtering is approximated using a set of particles (weighted samples of the probability space). This method allows using any model of noise and any level on non-linearity, thus providing support for multimodal distributions. The approximation will be as good as the number of particles, and the computation cost increase proportional to the number of particles [10].

Each algorithm has its own qualities and flaws, greater precision being usually obtained at the expense of more computation power or the quantity of parameters to adjust. The periodicity of state reconstruction is an important issue for the stability of a closed-loop regulation. Thus, a balance between precision and complexity has to be reached during on the field practical experimentation.

Bayesian state-estimators easily deal with sensor failures, heterogeneous sample rates, or a-periodic measurements, since each arrival of a sample allows correction of the latest state prediction and reduction of incertitude, yet correction is optional between two state estimations [4].

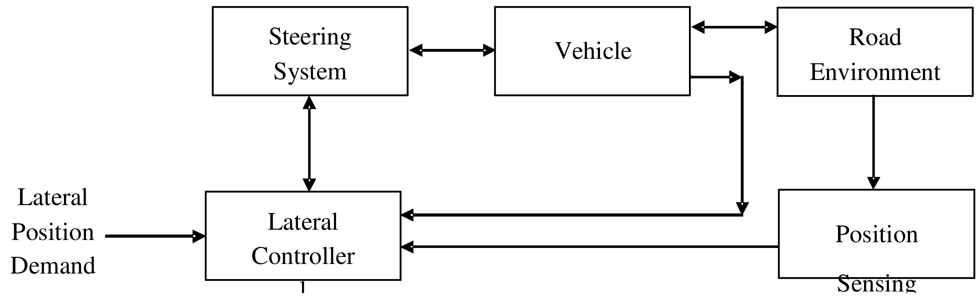
3.2 Control

3.2.1 Lateral control

Single vehicle

The purpose of the lateral control system is to steer a moving vehicle autonomously to satisfy some lateral position demand. A lateral control system is shown in Figure 5. The lateral control algorithm receives environment information, for example, from lane markings, magnetic strips or GPS coordinates and vehicle dynamics measurements (i.e. vehicle speed, yaw rate) and controls the steering system in order to satisfy the demanded lateral position.

Figure 5 Typical lateral control architecture



A key requirement on the lateral control system is that it is fail safe. For example, if a fault caused an incorrect steering angle then the vehicle could change course and possibly create a hazardous situation for the passengers and other surrounding vehicles or pedestrians. Failsafe systems and more recently fault tolerant systems are being implemented in order to address such safety issues.

The lateral control system also needs to have robust performance in the presence of system uncertainties and external disturbances. For example

1. System uncertainties
    a. The lateral dynamics of vehicles are greatly affected by the vehicle longitudinal speed
    b. Tyre cornering stiffness due to difference in road surface, weather conditions and tyre condition (e.g. pressure and wear).
    c. Vehicle mass (and its distribution)
2. External disturbances
    a. Side winds
    b. Road effects such as camber and potholes

A significant amount of research activity has been undertaken to develop lateral control solutions including solutions that are robust to the above system uncertainties and external disturbances. The lateral control solutions that have been developed have used techniques from one of four controller types (TRW Limited, 2001):

Linear Controllers

Linear controllers are mainly based on Proportional Integral Derivative (PID) structure or filters formed by loop shaping techniques. These controllers can be divided into four different sub-categories:

1. Open Loop Controllers. Controllers of this form have limited application due to their inability to cope with disturbances and uncertainty found in the lateral control problem.
2. Constant Gain Controllers. Controllers of this form are used for lane-keeping control with the driver in the loop (as opposed to autonomous vehicles). Such algorithms are based on a feed forward path that uses the road curvature ahead of the vehicle to demand the required trajectory with a feedback path to compensate for disturbances and trajectory tracking errors.
3. Gain Scheduled Controllers. Controllers of this form are an extension of the Constant Gain Controllers whereby different controllers (or gains of the controller) are scheduled with speed. This method enables robust performance to the vehicle lateral dynamics that change with speed.

4. H∞ Controllers. These Controllers are an advanced method that provides robust control solutions to certain disturbances and uncertainty 'models'. However, controllers can be computationally and memory expensive and do not allow easy configuration.

Non-Linear Controllers

Non-linear controllers can be divided into two sub-categories:

1. Optimal Controllers. Controllers of this form are usually based on Linear Quadratic (LQ) and Frequency Shaped Linear Quadratic (FSLQ) models. However, the resulting algorithms can be computationally expensive which can compromise the overall system performance and increase cost.
2. Sliding Mode Controllers (SMC). Controllers of this form can be designed to cope with the non-linear nature of lateral vehicle dynamics.

Fuzzy Rule-Based Controllers

A fuzzy rule-based controller for lateral guidance of a vehicle on an automated highway is described in Hessburg (2001). The controller is designed to achieve "good" tracking of the vehicle to the centre of a lane, while being robust to external disturbances and parameter variations of the vehicle. The fuzzy rule-based controller is flexible and effectively handles a large number of input variables, but there is a large amount of effort required to tune the controller and there is a lack of analytical evaluation that makes certification more difficult.

Connectionist Methods

Connectionist methods, typically using neural networks, combine vehicle position detection and control into one stage. As neural networks are only as good as their training data, reliability of these systems cannot be measured easily and thus they are usually not suitable for safety-critical applications. Four different approaches that have been readily documented are:

1. Neural Network-based Control
2. ALVINN (Autonomous Land Vehicle In a Neural Network)
3. Radial Basis Function
4. ELVIS (Eigenvectors for Land Vehicle Image System)

Independent of the different control strategies applied to the lateral control task the best lateral control results are typically seen by

1. Scheduling gains or controllers with respect to speed to achieve robust performance to lateral dynamic variations with speed
2. Structure controllers with dual-loops control (e.g. position tracker and yaw control loops) to provide robustness to uncertainty
3. Converting the lateral position demand into a yaw rate demand to provide improved stability margins as well as improved passenger comfort.

Increasing the environment 'look-ahead' distance to give improved stability. However, a drawback of increasing the look ahead is that the tracking error becomes larger, especially in tight curves

Platoon

During platoon manoeuvres the following vehicles should follow the preceding vehicles as close as possible, on the same tracks and without collision, even in case of hard accelerations and decelerations and in tight curves.

In this condition lateral control is mandatory to ensure that vehicles will follow exactly the same paths, thus guaranty the absence of collisions and the integrity of the vehicles even in tight and clustered areas.

This lateral control can be made using several techniques. One can use video camera information or laser information or any other sources of information about the relative positioning of the vehicles so that each vehicle follows the same trajectory of the first one (which might be manually driven). However, lateral errors of a few centimetres are possible and will therefore limit the platoon size to a few vehicles. Intervehicle communication is also used to share information between vehicles. This communication improves the stability of the platoon.

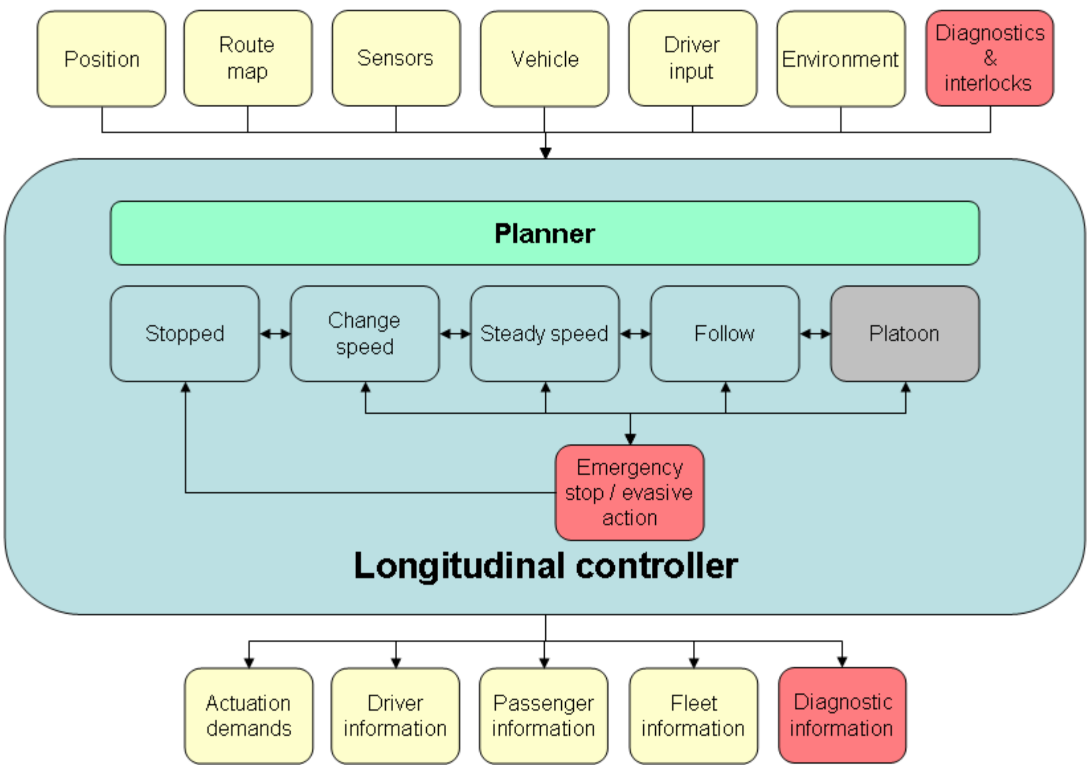
The other alternative is for each vehicle to use the same tracking technique using an infrastructure based solution. In this case, the errors are non cumulative.

3.2.2 Longitudinal control

Single vehicle

The purpose of longitudinal controllers in vehicles is to set and maintain the desired speed of the vehicle (including holding it at stationary). Figure 6 shows a simple functional architecture for an autonomous vehicle's longitudinal controller, showing the main inputs and outputs and sub-functions. (An alternative functional architecture in the context of an intelligent transportation system is given in *National ITS Architecture Version 6.0* (2007) and (SASPENCE).

Figure 6 Simple block diagram of vehicle longitudinal controller



Current research vehicles are being fitted with systems that help build up knowledge of the environment ahead of the vehicle through:

1. Sensors, for example radar, lidar and video, that monitor the scene ahead of the vehicle
2. Maps of the scene, for example, in MAPS&ADAS, maps are considered as a predictive sensor providing look-ahead information for advanced driver assistance systems.

3. Information from other vehicles or infrastructure systems, for example, in WILLWARN, vehicle-to-vehicle and vehicle-to-infrastructure communication is utilized to extend the driver's horizon and intelligently warns the driver of dangerous situations ahead.

From the knowledge of the environment the scene is constructed. In Figure 7 for example, a simple speed limit database that incorporates safe cornering speeds and stop-and-go is constructed. A strategy is then planned for the route that the vehicle is to travel, for example, in Figure 8 the speed profile is planned. A further example is in SASPENCE, where the environment is sensed and the planning layer derives the appropriate velocity and headway for the given driving conditions (and then uses this to issue appropriate audible, visual or haptic warnings to the driver).

Figure 7 Scene interpretation – speed limit 'trajectory'

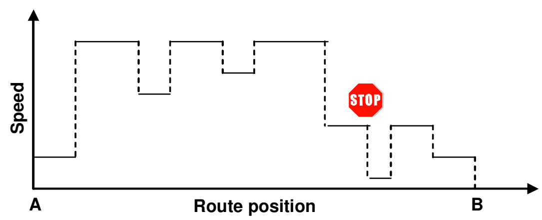
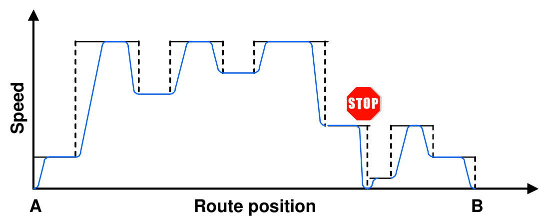


Figure 8 Planned strategy – speed profile



In order to implement the planned strategy the longitudinal controller can be divided in to various sub-functions:

1. **Hold the vehicle at standstill**. Although this may appear a trivial function, it is key to the safety of the system as it represents the 'safe state'. This requirement is common to most types of moving machinery with the interlocking methods and certification requirements in common industrial use.
2. **Changing speed and maintaining a steady speed.** Cruise control systems on road vehicles and electrically propelled vehicles incorporate these functions. Autonomous vehicles also utilise this functionality but with full authority over acceleration and deceleration, for example, to enable a rapid stop. The controller performance of the speed changing function is set to ensure passenger safety and comfort while attempting to follow the planned strategy as closely as possible. Performance is designed to cope with non-linear vehicle response (e.g. engine torque or gear changes) as highlighted in Ganzelmeier and to be robust to widely varying vehicle conditions (e.g. passenger weight).
3. **Following another vehicle**. Vehicles (mostly luxury segment passenger vehicles at present) with adaptive cruise control (ACC) systems can follow target vehicles at a prescribed headway (time between host and target vehicle). Vehicles with ACC systems incorporating 'follow to stop' and 'stop and go' functionality will also soon be available. In addition to the proprietary algorithms used in commercial ACC systems, there are many academic papers in this area, including Sainte-Marie (2004), Girault (1999), Martinez (2005) and Özgüner (1995). A natural extension of this functionality is platooning (see Platoon section). ACC systems, which vehicle manufacturers

market only as driver comfort systems, will require further validation and development to achieve the required safety integrity level for autonomous vehicles.

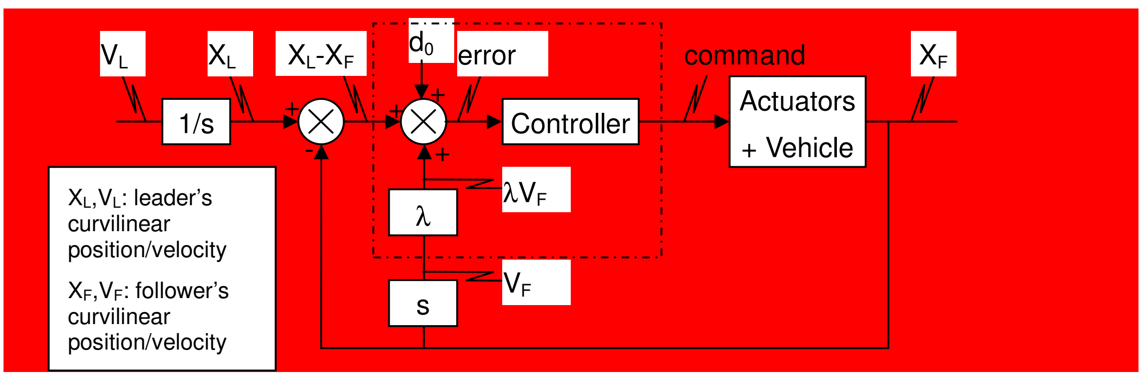
Platoon

When platooning is formulated as a path following problem, lateral and longitudinal control appear as independent problems once the system is linearized. Longitudinal control is usually performed using motor as the command variable to regulate distance between vehicles. Since brakes can deliver limited power in order to dissipate kinetic energy, the minimum secure inter-distance shall be linear as regards to speed: $d = d_0 + \lambda.|v|$, where standard figures for the variables can be $d_0 \approx 2m$, $\lambda \approx 0.5s$ and v is platoon's velocity, for homogeneous vehicles and standard mass/breaking power ratio comparable with those used for usual transport systems.

Inputs used in platooning are usually relative distance, which can be measured by many different devices (laser, stereovision, ultra wave, radar), as well as vehicle speed estimation, which is usually output from Bayesian estimators fusioning various sensors (wheel encoders, IMU, radar). Outputs are motor command.

Vehicle speed can be used to compute reference distance that shall be compared to actual relative distance, and corrected to reduce perturbations introduced by the speed variations of the leading vehicle.

Figure 9 Longitudinal controllers



Many controllers have been studied to stabilize the distance between the two vehicles. Linear controllers usually give satisfactory results in terms of stability.

Nevertheless, non-linear controllers such as LQ controllers can give a better opportunity to express complex constraints on state and command variables. This issue is relevant for platooning applications, since limitation of acceleration, jerk and command is at stakes in order to get a comfortable trip.

Stability of large platoons is to be addressed, since cascading stable systems can lead to instability at platoon scale. One sufficient condition for platoon stability is to have $|| h ||_1 < 1$, where h stands for the system's closed loop transmittance. On the other hand, having $|| h ||_\infty > 1$ is a sufficient condition for instability.

Moreover, inside a platoon, actuator performances can be heterogeneous, due to vehicle diversity. Normalization of vehicle minimum dynamic performances shall be examined, to introduce static requirements. Nevertheless, some hazards may lead a vehicle to stop off matching those requirements. Therefore, monitoring strategies have to be defined, so that the whole platoon dynamically adapts its speed reference. At some point, a defective vehicle shall be asked to leave the platoon. Thus, the necessity of homogeneous minimum vehicle dynamics points the need for communication and cooperative behaviours inside a platoon.

3.2.3 Cooperative formation control

Formation forming is the process of organizing a larger group of individuals into subgroups. In everyday traffic, vehicles organize themselves in clusters with similar behaviour. On highways, for example, vehicles tend to cluster behind slower moving vehicles. In urban areas, clusters of vehicles are induced by traffic light control systems. Apparently, clustering is a natural process for organising groups of individuals.

When vehicles are to be made autonomous and when driver tasks are to be automated to some degree, it is deemed necessary to organize vehicles (and possibly other road users) deliberately and consciously into formations of vehicles. The underlying assumption is that traffic can be organized and controlled more efficiently and safer through increased automation and autonomy of vehicles and traffic control. The CVIS project [6] provides more detailed considerations of cooperative vehicle-infrastructure systems.

The purpose of formation forming is to achieve an organization capable of cooperation, including coordination and collaboration, to improve the efficiency and safety of traffic. Formations here are regarded as deliberately “formed” groups of individuals with common goals, tasks, roles and capabilities. A few examples:

In cooperative following, a formation or platoon consists of a string of vehicles in a single lane that cooperates to improve longitudinal control, especially with respect to stability and safety. The vehicles in the string have some form of cooperative advanced cruise control (CACC), e.g. [15] or platooning. Vehicle-to-vehicle communication is restricted within the platoon to exchange ACC information.

In cooperative merging a formation of vehicles in adjacent lanes cooperate in lane changing and merging. Two types of cooperative merging can be distinguished [11]. In its simplest form, an individual vehicle from one lane requests to merge ahead of an individual in the adjacent lane. Cooperation then is localised to the two vehicles involved. More complex is the merging of adjacent platoons. More complex is the merging of multiple vehicles from one platoon into an adjacent platoon.

In fleet management type applications, such as support for parking and goods delivery, cooperation focuses on the provision of information and guidance. The formation of information seeking vehicles is continuously changing and usually regionally bound.

In [18] autonomous vehicles form ad-hoc cooperation for traversing unsignalized intersections.

The next subsections address several higher level management and control actions relevant for formation forming and that are additional to the lower level longitudinal and lateral vehicle controls of the previous section.

Control architectures

Two basic control architectures are commonly used. The IVHS architecture [19] presents a hierarchical control architecture for our domain, and identifies following control layers:

Network layer for traffic management and routing,

Link layer for traffic control on a network link,

Coordination layer for vehicle coordination and formation control, as discussed here,

Regulation layer for controlling vehicle manoeuvring, and

Physical layer for controlling vehicle systems and devices.

Control tasks are decomposed into subtasks per layer. Control tasks like steering, throttle and brake (sections 3.3.1 and 3.2.2) for example reside in the regulation and physical layers. Coordination with other vehicles for platooning is in the coordination layer.

The complex behaviour for cooperation and formation cannot be appropriately decomposed along these layers only, and another behavioural architecture is introduced (e.g. [8]), and often combined with the control architecture (e.g. [11]). The behavioural architecture allows defining behaviour models for individual subtasks, or alternative tasks, for example for different modes during platooning. A finite state machine then defines when and which behaviour models are used in particular situations and conditions.

Formation control

Vehicle formations are controlled at two levels; the dynamics of a formation as a whole and the dynamics of the individuals within a formation. The latter is specific for the type of formation and cooperation, and will not be considered here any further.

Formations can be configured along various aspects, such as the spatial or control topology, tasks, roles and responsibilities. Specific combinations have been adopted in the past for particular cooperation configurations.

Spatial topologies for intelligent traffic systems are typically determined by the infrastructure (e.g. [12]):

1. Longitudinal strings in a lane, such as platoons or CACC. The strings may be either homogeneous (sequence of similar vehicles) or heterogeneous (different types of vehicles may merging into a string formation).
2. Strings or individual vehicles in adjacent lanes, such as in vehicle and platoon merging respectively.
3. A mesh of vehicles distributed in the local vicinity such as a crossing, or a region of a network.

Both centralized and decentralized control topologies are being used. Centralized topologies are typically found in leader-follower organizations of platoons, and for fleet management type applications in which a roadside service collects and provides information to all other users. Leaderless platooning is a decentralized approach in which all individuals play an equal role and responsibility.

Control topologies have significant consequences on performance and requirements for communication, formation stability and control complexity. String stability of platoons for example is known to be superior for decentralized approaches at the cost of increased communication and control complexity [12][15].

In decentralized control, there is no single individual as master or 'centre' to control the formation behaviour. Instead, individuals act as peers with specific roles and responsibilities, and formation behaviour emerges form their individual behaviours. This diversity results in increased complexity of control, interaction and communication.

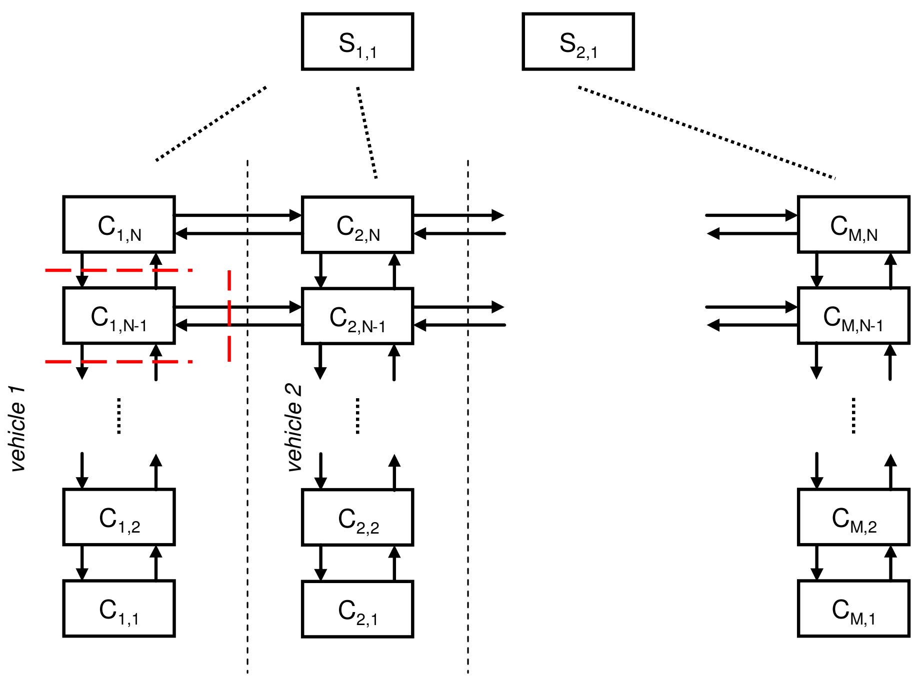
Formations are static when the configuration is predefined. A static configuration is frequently adopted in demonstration projects simply due to the limited number of available cooperating vehicles. For static configurations the stability of the configuration can be determined beforehand and built into the configuration and controllers. For dynamically changing configurations on the other hand, criteria and control for maintaining stability and safety of the formation should be incorporated as a capability of the control systems and architecture (see for example [15]). Dynamic formations also require additional tasks and responsibilities for managing the configuration, such as tasks for joining, leaving, merging and splitting formations.

Interaction protocols

Intelligent transportation systems in general and applications targeted by the CityMobil project in particular can be considered as distributed problem solvers. Various parties (e.g. vehicles, road side units, traffic management entities, etc.) are involved in the problem solving process and each has only a limited "knowledge" about the environment and about the others. The environment of vehicle formation control is evolving in time, various incidents may disturb the system thus continuous adaptation is a precondition of the efficient operation.

As briefly summarized in the previous sections the control system of automated vehicles decomposed in different ways (e.g. functional hierarchy, interacting responsibilities, behaviour based schemes) [4] [17] [1]. In cooperative schemes there is interaction between the players participating in the coordination on different levels. For a hierarchically decomposition control architecture Figure 9 shows a typical interaction scheme (the interactions with the supervisory (e.g. link) levels are not detailed). It should be emphasized that the models used at a higher level is not an abstraction of the lower level models. Rather the models used in the different layers are matched with the particular functions assigned to those layers [17]. At certain layers continuous models are used, others can be represented as discrete event systems (DES) or finite state machines (FSM) [19].

Figure 10 Hierarchically decomposed control



The "inter-player" coordination is typically implemented at the higher layers of the hierarchy, which can be represented as discrete models. The coordination activities involve leader election, negotiation, auctioning, delegation, etc. These and other typical interaction schemes are thoroughly researched fields in distributed artificial intelligence and multi-agent systems. A selection of interaction protocols were developed and standardized and thus are readily available for use in intelligent transportation systems [9].

Transportation systems "live" in the real world and beside the interactions considered so far they also interact with the physical environment. In this context the correctness of the operation, the behaviour under unexpected circumstances and under (partial) failure conditions are of primary concern. It is especially challenging analyzing the behaviour emerging from the interactions among the highly autonomous entities of the automated transportation system. Simulation based techniques are widely used (i.e. for analyzing "what if" scenarios) but this way exhaustive coverage can only be achieved in relatively simple cases (i.e. clearly decomposable systems, very limited interactions). Driven by the need of formal validation of interaction schemes the DES and FSM based modelling of the protocols and the interfaces of the higher-level functionalities received significant attention. Methods were already developed for validating inter-layer and inter-entity interaction protocols both under nominal conditions and at the presence of particular failure modes [14] [20].

World Modelling

Independently of the decomposition scheme applied the functional elements of control system operate (e.g. calculate control command, reason, make decision, etc.) in response to the state of the surrounding world. In order to derive any actions the controllers should have an understanding of the embedding environment. Consequently the modelling, representation and maintaining an up-to-date world image is of crucial importance in order to achieve sensible/intelligent behaviour on system level. For lower level functionalities (or simple, reflex behaviours) the "world" is small and simple (e.g. the hosting vehicle itself). For higher-level functionalities the "world" becomes more complex, highly dynamic, only partially known and uncertain.

Sensory inputs, digital maps and communication serve as primary inputs for the world model building and update. In cooperative distributed control schemes maintaining coherence of the world representation at the various entities pose new challenges [1]. In order to widen coverage and/or decrease uncertainty in the model it may be necessary to "fuse" the different world models.

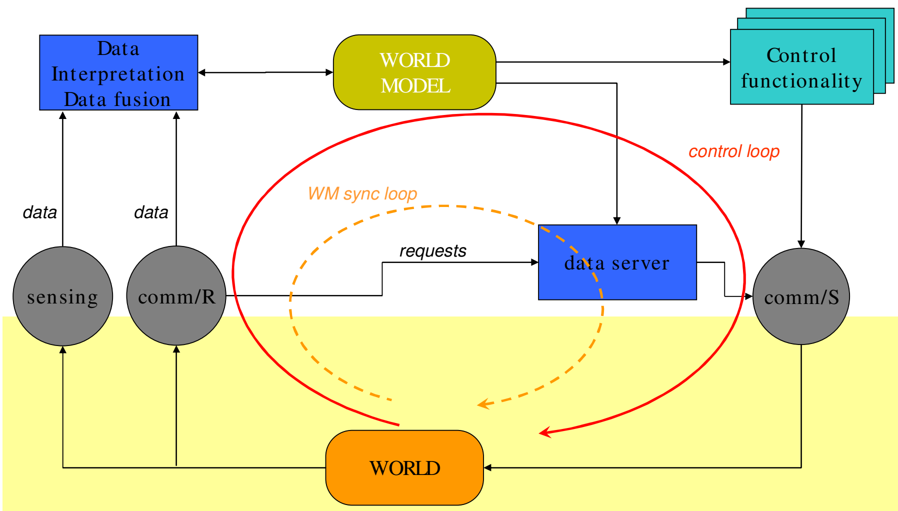
Building and maintaining a sufficiently and accurate representation of the world is a challenging task itself for higher level control functionalities and triggered significant research efforts. Under the SAFESPOT EU research program a comprehensive requirement analysis and overview of the possible world modelling approaches were carried out [6] [7]. Below we summarize the main findings.

The world model (WM) should therefore provide a formal representation of the relevant surrounding world in order to support proper, efficient and safe behaviour. To assure dependable operations some (control) functions would disable themselves if confronting unknown situations and/or high observation uncertainties. Consequently the WM is considered as one of the primary input sources for the control systems and other on-board applications. It is inefficient and potentially unsafe to maintain partial world representations by the individual control functionalities (e.g. CACC, merge assistant, LDW, etc.) or perhaps directly feed in sensory inputs to them. Instead a shared WM should be created and maintained on entity basis and all control functionalities of that entity access this shared model.

Figure 11 shows the interaction between WM and other control related components. From the control functionalities point of view the WM is the model of the world as known by the vehicle. It contains objects characterized by attributes, uncertainties and object relations (e.g. information about the front vehicle, closest neighbour, reachable road-side station, street-crossing landmark, etc.). All incoming data sources (sensors, communication, data from other

WMs) go through the data interpretation and fusion module, which is responsible for maintaining the coherence in the WM (i.e. a single real world object is represented only once in WM, calculate object attribute uncertainties based on multiple observations, etc.). The data server carries out the data exchange with other WMs on demand basis. A very advantageous feature of the scheme described is that the control functionalities become independent of the concrete implementation of the sensory and communication subsystems. The control is derived based on the content of the WM (i.e. the best possible "image" of the relevant surroundings). The controllers should be able to handle uncertainties and should exhibit "self awareness", i.e. they are not allowed to act if the uncertainties are too high or cannot interpret (understand) the configuration in the world.

Figure 11 World model data flow



3.3 Actuation

Actuation means production of forces through energy transformation. This transformation shall be as efficient as possible with little waste (pollution) production, high output and controllability. The general trend in actuation technologies is to use electromechanical technologies, assisted by electronic controllers. The latter provide very flexible behaviours through the use of software, whereas traditional technologies can support but a few functionalities.

3.3.1 Steering Systems

Steering mechanicals are now largely assisted by electrics and electronics. The first device introduced in automotive steering applications was electric power steering (EPS), which provides both comfort and vehicle controllability through increased steering couple. Fail-safe, reliable and affordable architectures were defined. Both market and certification authorities have welcomed this innovation.

Steer-by-wire technology replaces classical steering column by two ECUs linked by a multiplexed bus, one being in charge of sensing driver's steering reference, while the other controls the electric power unit. If driver's command is simply amplified as with EPS systems, the added value of steer-by-wire systems is increased controllability, whereas certification authorities yet have to be convinced of a potential increased security, since risks of safety regression exist.

Automotive constructors and members of the X-by-Wire Consortium now push forward redundant material architectures, using redounded and deterministic multiplexed communications, such as FlexRay or TTP (time triggered protocol), and point out the increasing maturity of automotive development cycle. Advanced city cars and cybercars applications use lateral control, which can either rely on EPS or Steer-by-Wire technology, the latter providing numerical control flexibility.

3.3.2 Brake systems

ABS (Anti-lock Braking System) can activate and release each brake up to 50 times per second. This fine control enables each tire to get optimal longitudinal and satisfactory lateral frictions, so that braking distance is minimized while manoeuvrability stays acceptable.

Current automotive applications gather wheel speed information at disposal; identify wheels that have slower-than-average rotations speeds as skidding wheels and briefly interrupt associated braking so that non-slippery rotation is resumed.

ESP (Electronic Stability Program) systems put optimal yaw (spin) control at stakes, introducing correlation between steering angle, individual wheel speed and engine power to optimize trajectory control in bends, avoiding under steering (plowing) and over steering (fishtailing) by fine tuning of individual wheel rotation speed. The increase in vehicle controllability overwhelms human capability, since it can be done only with numerical technologies, such as internal state representation and estimation.

X-By-Wire technology offer the possibility to unify optimal braking and stability control into one global control problem, where longitudinal and lateral control are treated at the same time, with greater commandability, since braking can be controlled at pedal and wheel level, while steering can be controlled at steering column and wheel level.

Regenerative brake systems offer the possibility to revert kinetic energy into electric energy, instead of thermal dissipation. If hybrid propulsion is available, this electric energy can be eventually reverted for later propulsion needs, with greater overall energetic efficiency. They also provide an alternative for rotation speed control, with greater dynamics.

3.3.3 Propulsion systems

Being AUTS mostly applied to urban mobility, polluting emissions are a fundamental aspect to be evaluated for propulsion systems, especially for inner city scenarios. In this section, emissions and energy consumptions data will be evaluated, concerning vehicles equipped with traditional internal combustion engines, hybrid and electric drivetrains. All the data about pollutant agents and energy consumption are provided by recent EUCAR (European Council for Automotive R&D) studies.

Internal combustion engines (ICE)

Traditional internal combustion engines (ICE), even after the improvements due to future European regulations (EURO 5), don't allow further significant enhancement for the future.

EUCAR studies show that by the year 2010 the "*well-to-wheel*" (comprehensive of the whole energetic transformations involved) equivalent emissions of CO_2 for an average-performance vehicle in the standard NEDC cycle can be predicted as follows:

Table 2 "Well-to-wheel" equivalent emissions of CO_2 for ICE

Type	CO2 [g/km] (year 2010)	CO2 [g/km] (year 2007)
Diesel	160	170
Gasoline	170	195
Methane	150	180

Concerning the *local* pollutant emissions, the following table outlines the data until the time horizon of 2010:

Table 3 Local emissions constrains for ICE

	2005 (EURO 4)				2010 (EURO 5)			
Type	CO [g/km]	HC [g/km]	NOx [g/km]	PM [g/km]	CO [g/km]	HC [g/km]	NOx [g/km]	PM [g/km]
Diesel	0.50	-	0.25	0.025	0.50		0.20	0.005
Gasoline	1.00	0.10	0.08	-	1.00	0.075	0.06	-
Methane	1.00	0.10	0.08	-	1.00	0.075	0.06	-

Standard energy consumption “well-to-wheel” are shown in the table below:

Table 4 “Well-to-wheel” energy consumptions for ICE

Type	2002 [Wh/km]	2010 [Wh/km]
Diesel	610	570
Gasoline	710	590
Methane	810	670

Hybrid drivetrain

A hybrid drivetrain vehicle is based on the cooperation between an endothermic engine and an electric motor. This kind of vehicles can be classified according to structural configuration or degree of hybridisation.

The structural classification identifies three different configurations: series, parallel and series-parallel.

In **series hybrid** configuration, the traction is only provided by electric motor. The thermal unit has the task of powering an electric generator, which, in turn, powers a battery and the electric motor. The ICE operates constantly at maximum efficiency conditions and minimum emissions; the electric motor provides an average power, which is completed by the energy stored in the battery for peak operating conditions, if requested. Battery also supports the traction for short distance working without endothermic engine.

This configuration is the most efficient in terms of polluting emissions, especially at low speeds.

In the **parallel hybrid** structure, motive power can be provided by ICE or by electric motor, alternatively or at the same time. The battery is recharged by an internal electric generator, and has a higher voltage than traditional 12V car batteries. This solution is the most commonly used at present for stock car production, even if it requires a more complex transmission system.

A combination of **serial-parallel** configurations can be obtained, by decoupling the power supplied by the ICE from the power demanded by the driver. In this way, different combinations of electric and mechanical motive power can be exploited according to the requested torque.

Another categorization can be done, depending on the balance in providing motive power.

A **full hybrid** system works with the drivetrain provided only by electric source, only by engine or by both sources. This is the most complex, but also the most flexible and clean hybridisation method, and allows the widest operational range for both drivetrain sources.

A mild hybrid vehicle exploits the electric drivetrain only when the car is coasting, braking, or stopped, to allow a clean and quick restart.

In **mild hybrid** systems the electric unit is smaller than in full hybrid systems, which can run autonomously in only-electric mode for tens of kilometres. In both cases the battery is recharged only exploiting the ICE power.

If the power provided by the electric unit is relevant, the system needs a battery pack even larger than in full hybrid systems. Since recharging such large batteries using the ICE power would lead to inefficiencies, in this case the plug-in hybrid solution is preferred.

Vehicles equipped with a plug-in hybrid system operate as full hybrid, with in addition the ability to recharge the battery from the electric power grid.

Such systems have all the benefits of full hybrids, plus an extended electric-only autonomy and a more efficient endothermic unit, which is only in part involved in the battery recharging.

Hence, these vehicles could be used in electric-only mode for everyday urban commuting, while for longer trips the extended range and efficiency of endothermic unit is exploited.

Electric grid recharge gives also environmental benefits, but no specific recharging infrastructures are easily available at present.

All sorts of hybrid system can be equipped with an endothermic unit powered by gasoline, diesel or methane.

EUCAR data about emissions and consumptions are shown in the following tables:

Table 5 "Well-to-wheel" equivalent emissions of CO2 for hybrid systems

Types	CO2 [g/km] (year 2010)
Diesel hybrid (mild)	130
Gasoline hybrid (mild)	140
Methane hybrid (mild)	120
Plug-in hybrid	70-90

Table 6 Local emissions constrains for hybrid systems

	Year 2010 (EURO 5)			
Type	CO [g/km]	HC [g/km]	NOx [g/km]	PM [g/km]
Diesel hybrid	0.50	-	0.20	0.005
Gasoline hybrid	1.00	0.075	0.06	-
Methane hybrid	1.00	0.075	0.06	-
Diesel plug-in	0.25	-	0.10	0.0025
Gasoline plug-in	0.25	-	0.03	-
Methane plug-in	0.25	-	0.03	-

Table 7 "Well-to-wheel" energy consumptions for hybrid systems

Type	Wh/km (year 2010)
Diesel hybrid	470
Gasoline hybrid	530
Methane hybrid	500
Diesel plug-in	390
Gasoline plug-in	420
Methane plug-in	405

Electric drivetrain

These systems use electric motor and electronic controller to drive the vehicle. Motor is usually powered by the chemical energy stored in rechargeable battery pack. Besides the electric grid energy, a small-sized generator may be present, to achieve a range extension in case of extra-demand. Recent technology progress in the field of rechargeable batteries, especially Ni/Cd, Li/ion and Na/NiCl batteries, should allow new developments for this kind of vehicle.

Electric motor can be also fed by energy produced by fuel cells, which produces electric energy consuming a fuel (commonly hydrogen), which is used as a reactant in an electrochemical conversion process; hydrogen can be stored in a pressured tank and refilled once consumed, but safety issues must be carefully considered for the storage system.

The remarkable benefit of such systems is that they have no local pollutant emission and are in substance independent from fossil fuels.

Two different layouts can be adopted for electric drivetrain systems: single-motor and multi-motor. In the latter case motors are smaller and located in correspondence of each driving wheel, without the need of driveshaft and differential.

A particular system, named regenerative braking, is usually adopted for additional battery recharge (also in hybrid systems). It consists in converting some of the kinetic energy in electrical energy during braking, and recovering it in the battery or in specific capacitors.

EUCAR studies provide the following emission and consumption data for electric battery vehicles:

Table 8 “Well-to-wheel” equivalent emissions of CO2 for electric cars

Type	CO2 [g/km] (year 2007)	CO2 [g/km] (year 2010)
Battery	90 (Ni/Cd battery)	50 (Na/NiCl battery; Lithium -ion)

Table 9 “Well-to-wheel” energy consumptions for electric cars

Type	Wh/km (year 2007)	Wh/km (year 2010)
Battery	450 (Ni/Cd battery)	310 (Na/NiCl battery; Lithium -ion)

4 Requirements for control technologies according to scenarios

In the following section the control requirements for the various scenarios elaborated in the deliverable D3.1 are discussed. The first scenario deals with partly automated dual mode vehicles/advanced city cars in a historical town centre, the second with a combination of both fully automated cybercars and partly automated dual mode vehicles/advanced city cars (mixed traffic) on dedicated lanes and the third scenario with cybercars in inner city centre. The last scenario describes automated BRT (Bus rapid transport) systems on dedicated lanes, which are shared with dual mode vehicles and cybercars.

4.1 Town centre

This scenario deals with a historical city centre inside the city structure, which is not well connected to surrounding districts, consists of a network of small roads and limiting vehicle access and parking places. The environment is therefore rather complex. The advanced city vehicles will be parked around the zone and allowed to drive in a dedicated network of roads. The dual mode vehicles provide assisted driving, especially in difficult or narrow passages, in order to follow a fixed trajectory (e.g. in a right angle curve) or to stop at precisely defined places.

Obstacle detection for increased safety of the other road users, especially pedestrians and cyclists is a key element of those vehicles. The capability of use in platoon, where the first vehicle is manually driven and a second one is linked automatically, for instance in order to pick up a vehicle or bring it to users is considered in this scenario.

4.1.1 Navigation system

The complexity of scenario topology requires an accurate and reliable navigation system.

Critical aspects to be considered are:

- Tracking vehicle position with respect to the infrastructure;
- Accuracy in following the planned trajectory, especially in presence of narrow passages and tight curves
- Manoeuvring capability (e.g. self-parking, U-turns…).

For these purposes, an accurate position and path detection system must be provided, together with a reliable vehicle control system for automatic path following.

4.1.2 Position detection system

The architectural peculiarities of the city centre (high and tight buildings) could make GPS (or other satellite-based technology) not reliable for accurate measurements; dynamic on-board sensors (i.e. odometers, steering and yaw sensors) are not accurate enough (e.g. due to not uniform road surfaces or signal processing errors) for the purpose, hence a local-infrastructures based system should be adopted.

The navigation system must provide accurate measurements for:

- Absolute position within the whole scenario;
- Longitudinal position along the planned path;
- Lateral position with respect to lane or path;
- Heading angle with respect to the lane or path.

Absolute positioning is mainly used for platoon monitoring and management, then an acceptable accuracy is 1 metre; instead, for path-relative position detection a more accurate system must be provided, possibly with interaction between on-board sensors and dedicated infrastructures. The detection system must be able to operate with the vehicle in motion, with a velocity range of 0 to 30 Km/h, in order to follow the vehicle also during start/stop manoeuvres.

Concerning the position detection with respect to lane or path, the system must provide reliable measurements up to 25 m forward the vehicle. The precision required is proportional to the distance from the vehicle d, according to the following relationships:

Maximum lateral uncertainty $\leq 0.05 + 0.005 \times d$ metres;

Maximum longitudinal uncertainty $\leq 0.05 + 0.005 \times d$ metres;

For heading angle estimation, the accuracy requested is < <1°.

All the position data must be refreshed with a frequency of at least 15 Hz.

Reliability issues

Position detection system must be able to operate also in critical conditions such as poor lighting, sun or lamp dazzling, snow, rain and fog.

If a navigation sensor is placed on-board (e.g. radar, digital camera), then measurement deviations due to vehicle dynamics (especially pitch phenomena) must be reduced as much as possible.

4.1.3 Vehicle dynamic control system

Data collected by path detection are used as input to the dynamic control system, which is in charge of driving the vehicle along the assigned path, without any user intervention.

Key features are then accuracy in path following task, and reliability of control strategies: hence, advanced drive-by-wire technologies must be applied to traditional steering, braking and traction systems. Also control smoothness must be achieved, in order to obtain a comfortable trip perception.

The lateral control sub-system drives the steering wheel angle, while the longitudinal control sub-system allows the vehicle to keep the right speed according to route characteristics.

Lateral control

To control the lateral motion of the vehicle, a steering-by-wire system must be provided. A torque must be applied to the steering wheel, according to the information provided by the path detection system.

The refresh rate for the steering torque must be at least 50 Hz, and the requested precision for the path following task must be 5 cm or less.

Longitudinal control

For automatic brake control, a deceleration request must be provided to the brake-by-wire system.

The longitudinal control has an important role in platooning control and obstacle avoidance, having the purpose of keeping the safe distance between vehicles and of stopping the vehicle in case of a dangerous obstacle detected.

Thus, also for longitudinal control is requested a refresh rate of 50 Hz and an accuracy in speed control of 0.3 m/s (≈ 1 Km/h).

Finally, automatic braking system must also implements parking brake functionality, hence the brake-by-wire control system must be available and working also when the vehicle is switched-off and current is not supplied.

4.1.4 Requirements summary

The following table summarizes key features required for position detection and path following in this scenario.

Table 10 Requirements summary for town centre scenario

Vehicle speed range	0 – 30 Km/h
Position detection refresh rate	15 Hz
Absolute vehicle position detection accuracy	1 m
Path detection range	*d* = 25 m
Path-relative lateral vehicle position detection accuracy	≤ 0.05 + 0.005 x *d* metres
Path-relative longitudinal vehicle position detection accuracy	≤ 0.05 + 0.005 x *d* metres
Heading angle accuracy	< <1°
Lateral control refresh rate	50 Hz
Path following accuracy	< 5 cm
Longitudinal control refresh rate	50 Hz
Speed control accuracy	< 0.3 m/s
Efficiency in critical condition (snow, rain, fog, poor lighting, dazzling)	
Pitch deviation compensation	
Manoeuvring capability (self-parking, U-turns…)	
Parking brake operating with vehicle switched-off	

4.2 Principal urban roads with an equipped lane (called „e-lane“)

This scenario deals with a migration step towards autonomous driving by utilising a so-called "e-lane". Hereby defined roads signposts indicate the possibility of driving autonomously on an e-lane. This e-lane is exclusively reserved for higher automated traffic. With a dual mode vehicle, which is specially equipped and certified, the e-lane can be used. Once the vehicle is on the e-lane the guidance of the vehicle is conducted autonomously.

The driver can focus on other activities (e.g. read newspaper, office work etc.). The driver can intervene and take over the responsibility and leave the e-lane, whenever he wants to.

The vehicles drive up to a velocity of 120 km/h on protected lanes, so that there is no interaction with pedestrians, cyclists etc.

The navigation of an automated vehicle in an e-lane concerns both the longitudinal and the lateral position and control of the vehicle. The difficulty lies in doing this at fairly high speed with total safety, even in the case of malfunctions of other vehicles.

Since the e-lanes will be rather straight, the lateral position and the control should be quite simple to put in place. The requirements call for a lateral error with respect to the nominal trajectory of up to 10-20 cm. The major constraint on the lateral position is the comfort of the control which should not induce uncomfortable lateral accelerations in terms of amplitude and frequencies and this at various speeds, up to the 120km/h. Unfortunately, no specific measures are set in books so, we must conduct experiments at various speeds to determine what is acceptable besides a jerk of 1m/s3.

The longitudinal control must insure there is no collision between successive vehicles, even in the case of an emergency braking of one of the vehicles. A trade-off has to be found between safe distances and the throughput. Here again, longitudinal accelerations should be kept at a comfortable level with jerks bellow 1m/s3.

Given all these constraints and the particular geometry of the e-lanes, it can be safely suggested that the best techniques for lateral control should be infrastructure based with magnetic, RFID or visual markers with additional sensors from inertial systems for controlling the lateral accelerations. For longitudinal control, existing sensors for ACC and Stop&Go such as radars or lidars should do the job for time gaps down to one second. However, it should b recommended that short delay communications should be put in place to exchange accelerations between the vehicles and insure a better longitudinal control.

4.3 Inner city centre

In the “inner City” scenario a limited fleet of automated vehicles drive fully autonomously in the city centre at low speed. The user can enter the vehicles at defined access points and then has the possibilities to choose the destination on pre-defined tracks. The Cybercars have to interact with pedestrian and cyclists on one side and with other Cybercars and low speed vehicles (cleaning machines etc.) on the other side. For user pick-up and maintenance parking places are reserved. A fleet management system optimises the displacement of the vehicles in real time.

Dynamics / manoeuvrability requirements

- Cybercars’ speed shall be limited to 5km/h in pace running areas in order to minimise lethal collision risks
- Cybercars’ speed shall be limited to 15km/h in small streets so that their speeds stay homogeneous with those of bicycles
- Cybercars and platoons shall be able to operate backwards so that they can get out of a narrow blocked street
- In pace running areas, Cybercars shall progressively slow down to 2km/h when obstacles are detected within a 5m range, with a 0.5 $m.s^{-2}$ maximum deceleration so that inevitable collision zones shrink while a comfortable deceleration is exerted and 2km/h speed is eventually reached the need for triggering an emergency braking is inevitable
- In pace running areas, Cybercars shall activate emergency braking when obstacles are detected within a 1m range, with a $2.5 m.s^{-2}$ maximum deceleration so that collision is avoided or occurs with a minimal kinetic energy
- In small streets, Cybercars shall progressively slow down to 5km/h when obstacles are detected within a 30m range, with a 0.5 $m.s^{-2}$ maximum deceleration so that

inevitable collision zones shrink while a comfortable deceleration is exerted and 5km/h speed is eventually reached when the obstacle stands at 5m

- Sidewalk docking manoeuvres shall have 10cm precision to minimise stumbling risks

Pedestrian/passenger interaction requirements

- Forward manoeuvres shall be signalled by a visual output
- Backward manoeuvres shall be signalled by visual and auditory outputs
- Lateral manoeuvres shall be signalled by blinkers
- Visual signals outputs indicating forward and/or backwards manoeuvres shall be seen from the front and back quadrants within 30 m.
- Visual signals outputs indicating left (respectively right) manoeuvres shall be seen from front, back and left (respectively right) quadrants within 30 m.
- Auditory signals output by cybercars shall be heard all around the vehicle within 15m.
- Front and rear bumpers shall trigger an emergency braking if they are hit
- If the inner on-off switch of a cybercar is hit by a passenger, emergency braking is triggered
- Passengers and remote operators shall be able to communicate

The navigation system must provide reliable and accurate measurements for:

- Absolute position within the whole scenario
- Longitudinal position along the planned path
- Lateral position with respect to lane or path
- Heading angle with respect to the lane or path

Centralized control-related requirements

- Cybercars shall transmit their position estimation every minute to the centralized control for optimal traffic estimation.
- Cybercars providing service shall transmit their estimated time of arrival (ETA) every minute to the centralized control for an efficient resource (vehicle) re-allocation.
- Centralized control shall integrate a static model to optimize placement of free vehicles according to time and day so that predictable steps in demand are anticipated.
- Centralized control shall dynamically adapt placement of free vehicles according to local deviation from the static model so that perturbations in demand are taken into account.
- Centralized control shall adapt its placement strategies in response to a local demand increase/decrease step within 5 minutes so that a sudden local burst in trip demand is satisfied before clients' exasperation.
- Cybercars stuck for more than one minute shall send an alarm to a centralized control centre + snapshot / streaming / communication for a sensible diagnosis of the blocking situation.

- Centralized control shall download street segments/areas operating interdiction with a frequency of five minutes so that they do not engage blocked streets.
- Centralized control shall immediately be informed of emergency calls and braking triggered by passengers or external bumpers.
- Centralized control operator shall be able to revert cybercars back to operational state after an emergency braking that was triggered by an external bumper or a passenger on-off switch, so that a sensible diagnosis precedes vehicle's trip resuming.

4.4 Shared traffic space with automated busses and dual mode vehicles

The fourth scenario consists of dedicated lanes for automated busses and dual mode vehicles/Cybercars. It is based on infrastructure, which is already available in some European cities today. A well-organised, automated public transport system alone can help to improve the increasing traffic congestions in European cities. The combination of automated busses and other types of automated vehicles provides an even more efficient saturation of valuable space for traffic on one side and intensifies the deployment of advanced innovative transport systems on the other side, because only minor modifications of the already existing infrastructure are needed.

In this scenario a cooperative control system in form of the traffic management system can improve the handling of traffic. Mixed automated vehicles share one driving lane, whereas dual mode vehicles can leave the dedicated lanes at any exit. The dual mode vehicles and Cybercars are integrated into existing infrastructure.

In this scenario the key points are communication, supervision, obstacle detection, information between vehicles and with a control centre.

The vehicle concerned by this scenario should be able to exchange information about their behaviour or state:

- Dual mode vehicle entering/leaving the dedicated lane
- Position of automated buses, cybercars, dual mode vehicles on the track
- Speed and direction of displacement of each vehicles

The vehicles must also exchange information about their environment:

- Information about traffic situation
- Detection of obstacles on the track
- State of the circulation on the dedicated lane (like a vehicle stopped on the track or reduced speed due to congestion)
- Emergency stop of a vehicle (cybercars should inform immediately all vehicles being in the surrounding about its failure). This information must be delivered without any delay.

The information about vehicle manoeuvre must be also visual. This type of information is very important for dual mode vehicle as they can switch from a non-autonomous context to an autonomous context. The requirements are then more or less the same as the information given by cybercars to pedestrian in the inner city scenario:

- Forward manoeuvres shall be signalled by a visual output
- Backward manoeuvres shall be signalled by visual and auditory outputs

- Lateral manoeuvres shall be signalled by blinkers
- Visual signals outputs indicating forward and/or backwards manoeuvres shall be seen from the front and back quadrants within 30 m.
- Visual signals outputs indicating left (respectively right) manoeuvres shall be seen from front, back and left (respectively right) quadrants within 30 m.
- Auditory signals output by cybercars shall be heard all around the vehicle within 15 m.
- If the inner on-off switch of a cybercar is hit by a passenger, emergency braking is triggered

Vehicles must inform the control centre about:

- Dual mode vehicle entering or leaving the dedicated lane
- Type, Position, Behaviour (destination, state) of each vehicle circulating on the dedicated lane
- Problem encountered by vehicle (failure, obstacle detected)

Concerning automated buses and cybercars their requirements in term of centralized control are the same than for cybercars in inner city scenario:

- Cybercars shall transmit their position estimation every minute to the centralized control
- Cybercars providing service shall transmit their estimated time of arrival (ETA) every minute to the centralized control
- Centralized control shall integrate a static model to optimize placement of free vehicles according to time and day
- Centralized control shall dynamically adapt placement of free vehicles according to local deviation from the static model.
- Centralized control shall adapt its placement strategies in response to a local demand increase/decrease step within 5 minutes
- Cybercars stuck for more than one minute shall send an alarm to a centralized control centre + snapshot / streaming / communication
- Centralized control shall download street segments/areas operating interdiction with a frequency of five minutes
- Centralized control shall immediately informed of emergency calls and braking triggered by passengers or external bumpers

Centralized control operator shall be able to revert cybercars back to operational state after an emergency braking that was trigger by an external bumper or an passenger on-off switch.

5 Navigation control tests for certification

In the following section a test setup is described, which can be used in the certification process of cybercars and dual mode vehicles. The test setup in this section is aimed at evaluating the navigation function of a vehicle. Within CityMobil D3.3.1 and D3.4.2, test protocols for the functions of respectively obstacle detection and communication are described in a similar manner. Section 5.1 contains a short summary of the different steps needed to reach certification of a cybercar system. After this a proposal of a test procedure is shown and explained in more detail in section 5.2. Section 5.3 contains links between the test procedure and the different defined CityMobil scenarios.

5.1 Certification procedures

In sub-project 2 of CityMobil future scenarios are addressed. As part of this subproject, WP 2.5 –Legal and administrative issues has made a brief survey of existing legislation, legal traditions and cultural differences in Europe. Deliverable 2.5.3 [5] contains the existing standards and guidelines that could be relevant for the future certification of cybercars. The information in that deliverable is primarily based on the work documented in D6.1 [14] and D6.2 [18] of the EU project Cybercars. A short summary:

Traditional vehicles that use public roads have to meet a large number of requirements laid down in standards and regulations. The sheer number of standards limits the car developers in their innovations. But the standards also give the developers guidance on how to create safe and reliable vehicles. When they develop new vehicles the manufacturers know the limits within which they have to stay in order to have their vehicle certified for use on public roads.

In contrast to the extensive set of certification standards for traditional vehicles, there are hardly any rules for vehicles that use private grounds or for vehicles that do not fit into the categories of the European Directive 70/156/EEC. This means on one hand that manufacturers have a large amount of freedom in designing their systems, which creates room for innovative solutions. On the other hand, however, manufacturers and operators run great liability risks in case something goes wrong with their systems. Operators and authorities will be reluctant to introduce innovative systems if there is no objective judgment possible on the safety of such systems. An objective judgment is only possible if it can be proven that a system meets generally accepted standards.

Traditional road vehicles are meant for use on public roads. These public roads represent a system to which a very strict set of rules, that we call traffic regulations applies. When a car is certified the environment in which it is to operate is not explicitly considered. That is not necessary because it is an implicit part of the vehicle design that the vehicle will operate in: the very rigid environment of our public road system. This however is different for Cybernetic Transport Systems.

To reach certification for a cybercar system in a certain environment ideally the following is needed:

- A comprehensive safety assessment of the vehicle in its surrounding. CityMobil deliverable D 2.5.3 contains the theory of both the risk reduction methodology and safety assessment analysis. It is not sufficient to certify the vehicle and vehicle related systems because of the interaction of the vehicles with the environment. The risk reduction methodology is a first step aiming at reducing the safety risks associated with the environment. After that a safety assessment analysis aims at reducing the safety risks associated with the system as a whole.
- A set of standards, which the cybercar system or subsystem or certain functions of the system should meet.

The three main functions that drivers carry out are observing; analysing/deciding and transferring the decision to the vehicle systems. In a cybercar the sensors, the obstacle detection system, the vehicle controller and the different actuators take over these functions. For traditional vehicles standards on component level exist. For these 'new' components such standards do not exist. In the following sections an attempt is therefore made to define a test protocol to evaluate the navigation control function of a cybercar or dual mode vehicle. Such a test could become part of a future navigation control standard.

5.2 Navigation control test procedure for certification

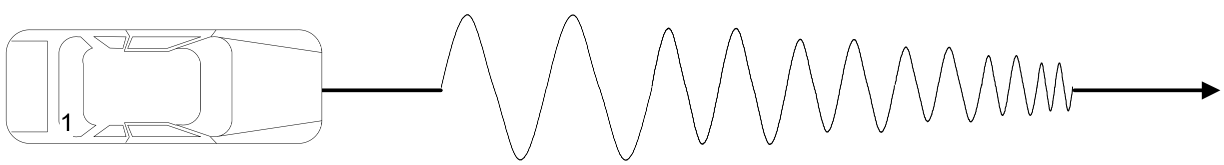
CityMobil deliverable D3.1.1 contains a description of the four different scenarios considered in the project CityMobil. Next to the description some requirements for navigation control are stated. In chapter 4 of the current deliverable more detailed requirements are given. All these requirements are taken into account during the definition of the measurement protocol below. Specific experience is gained with the 2nd generation Parkshuttle from Frog navigation systems.

5.2.1 Lateral control

The procedure described below is based on the so-called frequency response test used by car manufacturers in different ways during the development of a new vehicle. This test is used to assess the transient and steady state turning performance of a vehicle in the linear (normal) driving domain. The linear range includes all turning manoeuvres where lateral acceleration levels are relatively low (max 0.35 g). Changes in turning performance with speed are an important indicator of vehicle characteristics. An example of an implementation of a frequency response test is to drive a vehicle at a constant velocity (e.g. 120 km/h) and to give a sine wave input of constant amplitude and varying frequency to the steering system.

To evaluate the lateral navigation control of a cybercar or dual mode vehicle a modified frequency response test is conducted. In contradiction to the standard conducted frequency response test, the manoeuvre that the vehicle has to make is prescribed and not the steering wheel input. The vehicle that has to be evaluated has to drive a predefined trajectory with a constant velocity. This trajectory consists of several sine waves. The frequency of the waves varies from 0.1 – 1 Hz in steps of 0.1 Hz. The amplitude of the waves is chosen such that the lateral acceleration is 0.35g for all frequency steps.

Figure 12 Predefined test trajectory



The criterion at which the lateral navigation control is judged is the ability to follow the predefined track.

The following procedural steps should be taken:

If the navigation control of the vehicle is infrastructure based or vision based, the track possible has to be prepared for the navigation test. E.g. magnetic markers or white lines might be needed. Two track surfaces are needed; one track with an asphalt-like surface and one track on a paved road.

After the preparation the vehicle needs to be informed to drive the predefined path. The working of the lateral navigation control installed in the vehicle will be checked by measuring the lateral difference between the followed path and the predefined path. The central point between the front wheels will be the measurement point. The lateral difference should not be larger than 10 cm.

Perform the tests under the following conditions:

1.1 The vehicle should drive over the defined test track at the maximum speed at which it is allowed to operate in its operational environment. No extra mass should be added to the vehicle. The surface of the track should be asphalt-like.

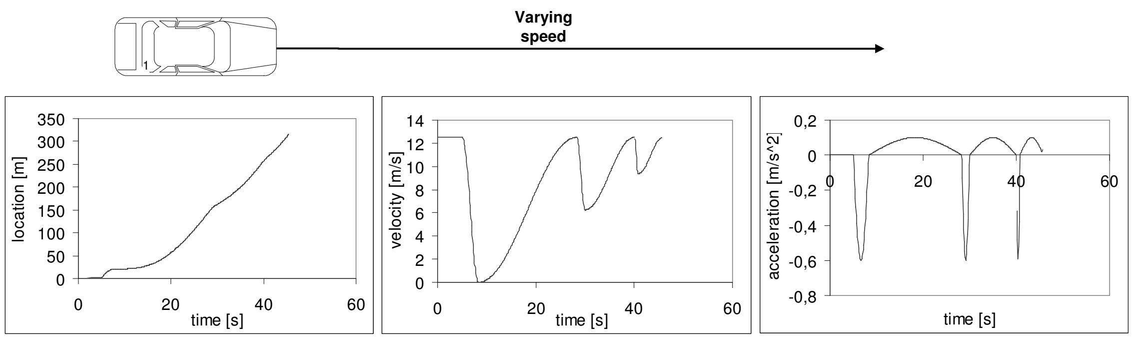
1.2 Add the maximal allowed mass to the vehicle and repeat 1.1.

- Repeat 1.1-1.2 at half the maximal speed of the vehicle.
- Repeat 1.1-1.2 at a track on a paved road.

5.2.2 Longitudinal control

To evaluate the longitudinal control of a cybercar or dual mode vehicle the vehicle has to follow a predefined straight path with a varying velocity profile. The track and velocity profile are shown in the next figure. The velocity profile contains several sine wave shapes. These sine waves are chosen such that the vehicle accelerates with a maximal acceleration value of 0.1g and decelerates with a max deceleration value of 0.6g. In the first sine wave the velocity of the vehicle varies between the initial velocity and 0, in the next sine waves the velocity amplitude reduces with a factor 0.5. This results in velocity changes at higher frequencies.

Figure 13 Predefined test trajectory



The criterion at which the longitudinal navigation control is judged is the ability to follow the predefined track. The location of the vehicle at a specific point in time should not deviate more than 50 cm from the predefined location.

The following procedural steps should be taken:

If the navigation control of the vehicle is infrastructure based or vision based, the track possible has to be prepared for the navigation test. E.g. magnetic markers or white lines might be needed. Two track surfaces are needed; one track with an asphalt-like surface and one track on a paved road.

After the preparation the vehicle needs to be informed to drive the predefined path. The working of the longitudinal navigation control installed in the vehicle will be checked by measuring the difference between the followed path and the predefined path. The central point between the front wheels will be the measurement point. The difference should not be larger than 50 cm.

Perform the tests under the following conditions:

1.1 The vehicle should drive over the defined test track with an initial speed equal to the maximum speed at which it is allowed to operate in its operational environment. No extra mass should be added to the vehicle. The surface of the track should be asphalt-like.

1.2 Add the maximal allowed mass to the vehicle and repeat 1.1.

- Repeat 1.1-1.2 at half the maximal speed of the vehicle.
- Repeat 1.1-1.2 at a track on a paved road.

5.3 Navigation control test for the different scenarios

The following table contains the four CityMobil scenarios as described in chapter 4. For each scenario the most important characteristics are shown. On base of these characteristics the navigation control tests that are most suited to evaluate the navigation performance are marked and when needed, additional remarks are made.

Figure 14 Test protocols for CityMobil scenarios

	1. lateral control	2. longitudinal control
Town centre Dual mode vehicles Longitudinal guidance Lateral guidance Platooning of cars	X	X
Principal road with an equipped e-lane Dual mode vehicles Longitudinal guidance (ACC like) Lateral guidance (LKAS like) No platooning	X	
Inner city centre Cybercars Longitudinal guidance Lateral guidance Platooning of cars	X	X
Shared traffic space cybercars dual mode vehicles automated high tech buses Longitudinal guidance Lateral guidance No platooning	X	X

For the scenario principal road with an equipped e-lane, the level of assistance is limited; the assistance is similar to ACC and LKAS. It is therefore not possible to prescribe a certain velocity profile to the vehicle. The longitudinal control procedure is therefore not applicable.

Since the lateral control is based on existing serial-production system of LKAS type the lateral control might not pass the lateral control test.

For the scenario shared traffic space, the frequencies used in the lateral test might be too high for large vehicles like busses.

In the town centre and inner city centre scenarios platooning is foreseen. For both the lateral and longitudinal test, a reference first-in-line vehicle is needed that will drive the prescribed paths. The vehicle under test will follow this reference vehicle. For the longitudinal control test, a different criterion is needed to evaluate the performance. This extra criterion will incorporate some kind of reaction time.

5.4 Remarks test procedure

In the section above an attempt is made to define a test protocol for the function of navigation control, which could be a base for a future standard. The following is noted:

1. Since a general test protocol is defined, there is no direct link to the CityMobil scenarios, which as described in earlier sections. As seen in section 5.3 most vehicles in the different scenarios can be evaluated.
2. The test procedure only contains a very limited number of possible test configurations, e.g. a limited number velocities, masses, road surfaces.. The effect of side winds, road effects such as camber and potholes, surrounding objects etc are not taken into account. It is clear that this test protocol does not take into account all the specific disadvantages of certain navigation technologies. Like the influence of the surroundings on GPS-based navigation technologies. Since a certification test protocol is described which could be become used in the standardized certification process of a cybercar vehicle it is not feasible to include a large range of measurements under different environments. These tests should be part of the development of the navigation control systems. The risk and the effect of possible mal functioning of the navigation of a particular cybercar under certain (environmental) conditions has to be evaluated in an extended safety assessment of the vehicle in its surrounding.
3. The description of the test procedure is not fully determined. I.e. not all dimensions and locations are explicitly mentioned. This would go in to too many details, more than needed at the moment of writing.
4. The specific values for locations, dimensions and velocities are mainly based on experience, but might be subject to change when more test experience is gained.
5. Again it must be noted that to reach certification of an entire automatic guided vehicle system, the certification test of e.g. the function of navigation control is only part of the process. A comprehensive safety assessment of the vehicle in its surrounding is required. The safety analysis should give indications of the risk of malfunctioning of the navigation control function in non-standard situations.

6 Conclusion

Navigation technologies provide a wide range of sensors and actuators that fit the needs of the four deployment scenarios addressed in CityMobil. Many prototypes integrate them in full control autonomous control architectures, yet certifications procedures are to be defined in order to demonstrate the liable navigation capability of advanced city cars.

GPS technologies -now trivialised- and dense measurement technologies such as vision, radar and laser systems, coupled with increasing computational power have entered the cockpit of advanced city cars and fill the gap between successive infrastructure-based markers, the latter providing highly liable information sources for navigation.

Automotive actuators are now heavily assisted with electronics and electro-mechanics, for greater functionalities and performances -greater output and fewer emissions- although at the cost of complexity, pointing the need for advanced control architectures that use all information available on board or even from other vehicles.

These control architectures are evolving towards more complex schemes that can sensibly handle many navigation primitives, eventually reaching fleet-scale control strategy.

Certification procedures for advanced city cars need to be defined from general recommendations or derived from existing specific norms. This requires technology expertise as well as experimentation on the field to provide valuable input for iterative maturation of these procedures.

Tomorrow’s challenges for navigation technologies is their ability to withstand more operational constraints such as service customisation, traffic management, integration into existing structures, and so that the global architecture eventually reaches fleet-scale for better service and liability.

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