Séminaire Modélisation des réseaux de transport

Motion planning and control techniques for driver assistance systems and autonomous vehicles

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Overview

Overview

Introduction

Road vehicles are becoming increasingly automated (VDA, 2015).

> Advanced electric and electronic (E/E) driver assistance systems (ADAS)
> Connected and automated vehicles (autonomous car)

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Motivations

- **Safety** More than 90% of road accidents attributed to driver error (with 31% involving legally intoxicated drivers, and 10% from distracted drivers)
- **Performance** Reduction of driver reaction time (short distance spacing, platooning) and optimal route choice (efficient use of the network)
- **Mobility** For children, old or disable persons with no driving licence; development of share use models and cost reduction of the road transportation
- **Environment** Efficient (smooth) driving and routing (less jam) reducing fuel consumption and pollutant emission

Automation classification

Automation level classification for road vehicles (SAE, 2014)

Automation level ↓

L0 **No automation**	Automated systems have no vehicle control, but may issue warnings	
L1 **Assisted**	Assistance systems (ACC, lane keeping, ...)	Under driver supervision
L2 **Partial automation**	Partial longitudinal and lateral controls for specific situations	Under driver supervision
L3 **Conditional automation**	Longitudinal and lateral controls for specific situations	Without supervision
L4 **High automation**	Full automation for all situations in a defined use case	Without supervision
L5 **Full automation**	Full automation for all situations of a given journey	Without supervision

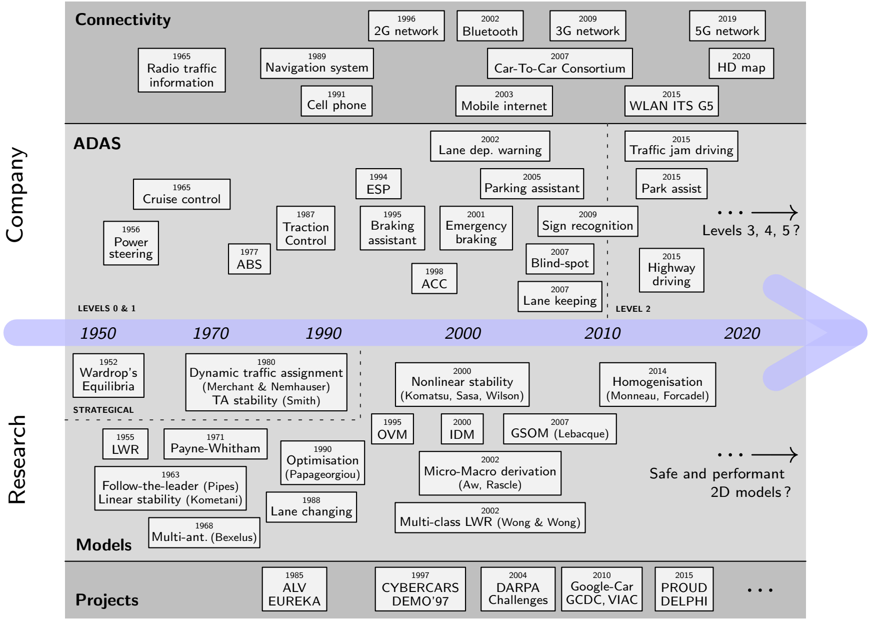
Projections of development

- **Manufacturers :** L3 level by 2020 (Tesla, Google, Nissan, Volvo, BMW, ...)
- **Information services companies**
  - Level 3 by 2020, level 4 by 2025 and level 5 by 2030 (IHS Markit)
  - L3, L4 and L5 Penetration rates of 100, 75 and 25% by 2030 (KPMG)
  - 75% of light-duty vehicle sales automated by 2035 (Navigant)
- **Insurance institutes**
  - All cars may be automated by 2030 (III)
  - Reduction from 30 to 80 % of the accidents (PWC Insurance Monitor)
- **Research** Survey during the Transportation Research Board Workshops on Road Vehicle Automation (around 500 experts, 2014) :

When will automated vehicles take children to school ?

→ More than half expect 2030 at the very earliest; 20% said not until 2040; 10% never expect it.

History



Connectivity
1996 2G network
2002 Bluetooth
2009 3G network
2019 5G network
1965 Radio traffic information
1989 Navigation system
2007 Car-To-Car Consortium
2020 HD map
1991 Cell phone
2003 Mobile internet
2015 WLAN ITS G5
ADAS
2002 Lane dep. warning
2015 Traffic jam driving
1994 ESP
2005 Parking assistant
2015 Park assist
1965 Cruise control
1987 Traction Control
1995 Braking assistant
2001 Emergency braking
2009 Sign recognition
. . . Levels 3, 4, 5 ?
1956 Power steering
1977 ABS
2007 Blind-spot
2015 Highway driving
1998 ACC
2007 Lane keeping
LEVELS 0 & 1
LEVEL 2
Company
1950
1970
1990
2000
2010
2020
1952 Wardrop's Equilibria
1980 Dynamic traffic assignment (Merchant & Nemhauser) TA stability (Smith)
2000 Nonlinear stability (Komatsu, Sasa, Wilson)
2014 Homogenisation (Monneau, Forcadel)
STRATEGICAL
1995 OVM
2000 IDM
2007 GSOM (Lebacque)
1955 LWR
1971 Payne-Whitham
1990 Optimisation (Papageorgiou)
2002 Micro-Macro derivation (Aw, Rascle)
. . . Safe and performant 2D models ?
1963 Follow-the-leader (Pipes) Linear stability (Kometani)
1988 Lane changing
2002 Multi-class LWR (Wong & Wong)
1968 Multi-ant. (Bexelus)
Research
Models
Projects
1985 ALV EUREKA
1997 CYBERCARS DEMO'97
2004 DARPA Challenges
2010 Google-Car GCDC, VIAC
2015 PROUD DELPHI
. . .

Overview

Functional architecture of the motion planning

Automated vehicles are **mission-based** and have a **functional architecture** (Behere und Torngren, 2015; Paden et al., 2016).

Classical components of the autonomous driving :

1. **Perception** Collection, fusion and interpretation of the sensor (radar, camera) and connectivity (V2V, V2I) data

   $\rightarrow$ *Building of a virtual world*

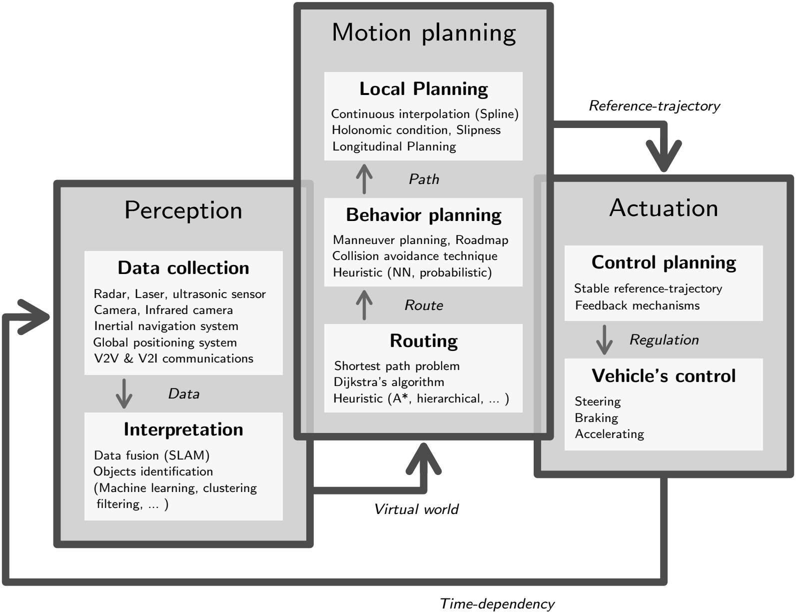
2. **Motion planning** Routing choice and determination of continuous and collision-free reference trajectories

   $\rightarrow$ *Calculation of short and safe feasible paths*

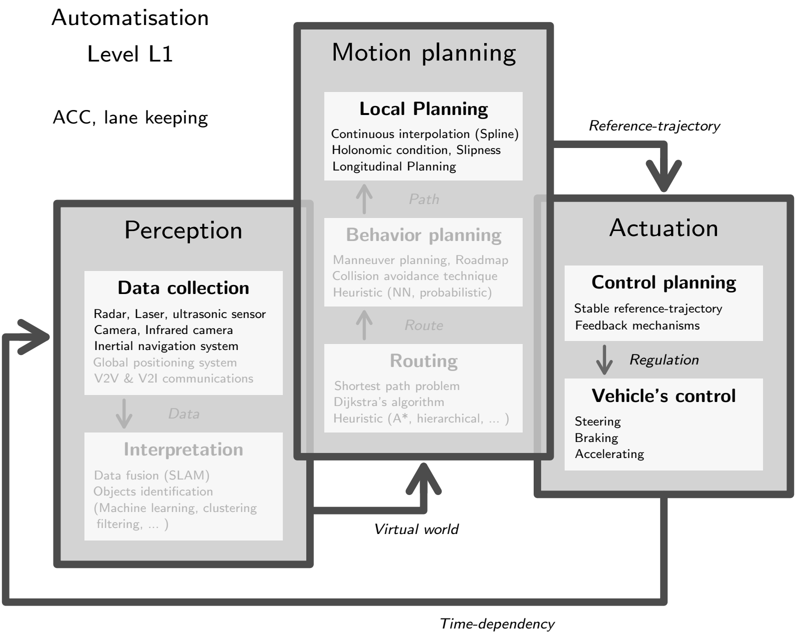
3. **Actuation** Determination of stable commands to the vehicle to follow the reference trajectory

   $\rightarrow$ *Steering, braking and acceleration rate controls*

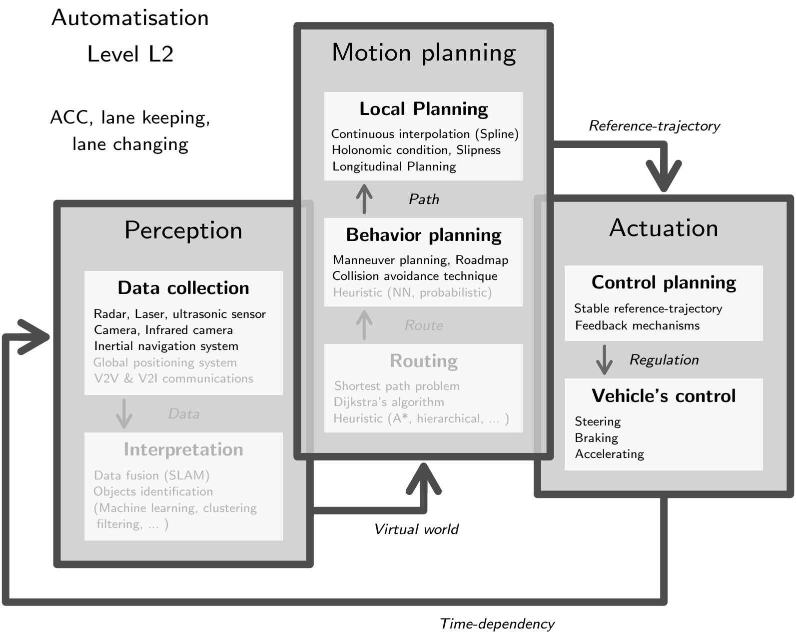
Functional architecture of automated vehicles



Functional architecture of automated vehicles



Functional architecture of automated vehicles

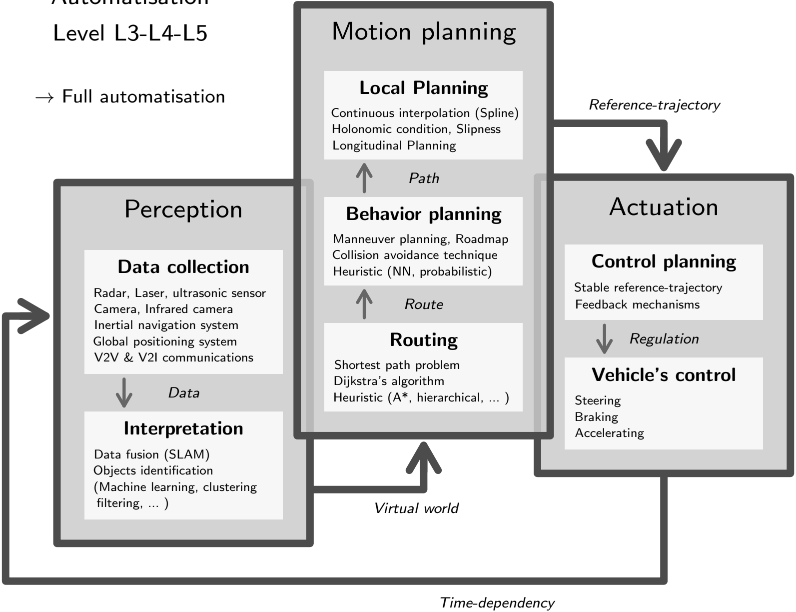


Functional architecture of automated vehicles

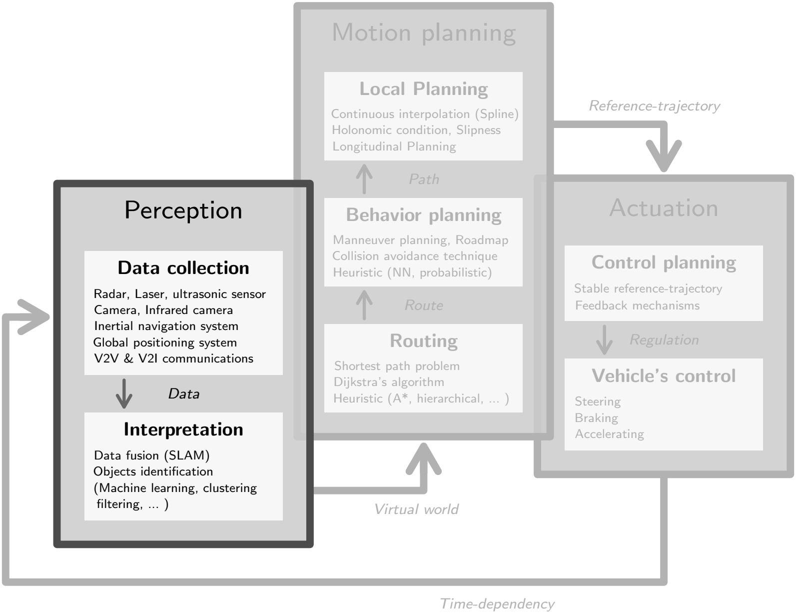
Automatisation

Level L3-L4-L5

→ Full automatisation



Functional architecture of automated vehicles



Sensor and communication technologies

Communication technology

- **Vehicle to vehicle** (V2V) communications (*Car to Car Communication Consortium*)
- **Vehicle to infrastructure** (V2I) communications (information to the driver/vehicle, centralized regulation)

Sensor technology

- **Cameras** coupled to computer vision to monitor traffic signals, road markings or to detect obstacles or turns
- **Radar** (radio wave), **lidar** (laser), **sonar** (sound and ultrasound) to evaluate distance and relative speed with potential obstacles around the vehicle

Exogenous

- **Global Position System** (GPS) to determinate vehicle location
- **Inertial navigation systems** such as accelerometers and gyroscopes to continuously calculate acceleration and rotation

Endogenous

Sensing and perception

Metric knowledge : measuring distances and scenes around the vehicle (sensing)
Small speed : short-range sensing / *Large speed :* long-range in high resolution
(Angular resolution $< 0.1°$ at 130m if speed $>$ 100km/h (Blosseville, 2015))

Conceptual knowledge : identifying lanes, infrastructure, neighbor vehicles, pedestrians or obstacles and their evolution (computer vision – filtering, machine learning, ...)

Common robotic adage: ≪ *Sensing is easy, perception is difficult* ≫

Sensing → **Clustering** → **Identification** → **Tracking**

True negative (ghost objects) vs *false positive* (blindness)

Dynamic sensor/data fusion : SLAM (Simultaneous Localisation and Mapping) with geo-referenced maps (single lanes geometry and topology; Thrun et al. 2005)

Example: Map-aided Evidential Grids for Driving Scene Understanding

Kurdej et al. 2015

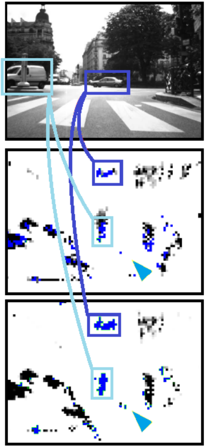
Occupancy grids: Description of the environment in discrete cells

Three evidential occupancy grids:

Prior information (map)
Sensor acquisition
Perception (fuzzy logic)

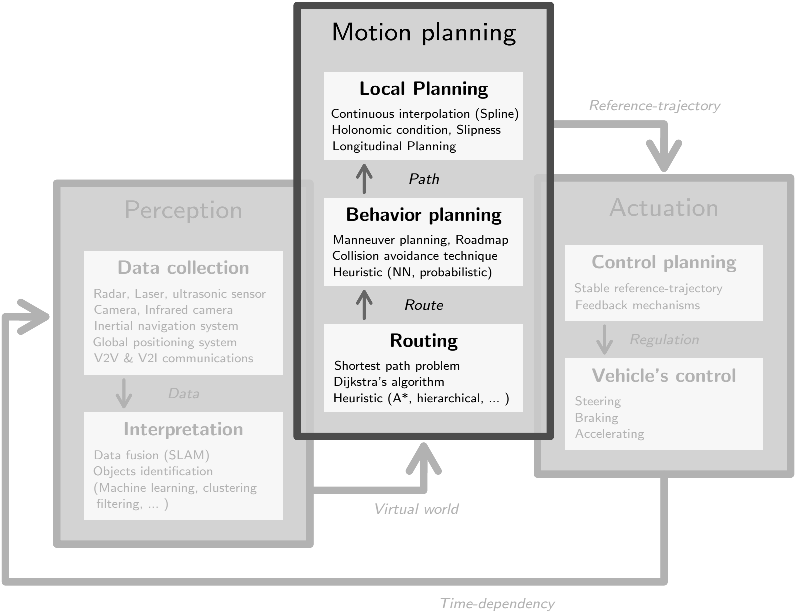
Modelling of the world using a **tessellated representation** of objects such as

- Free navigable space
- Free non-navigable space
- Mapped infrastructure (buildings)
- Unmapped infrastructure
- Stopped objects (obstacles)
- mobile moving objects

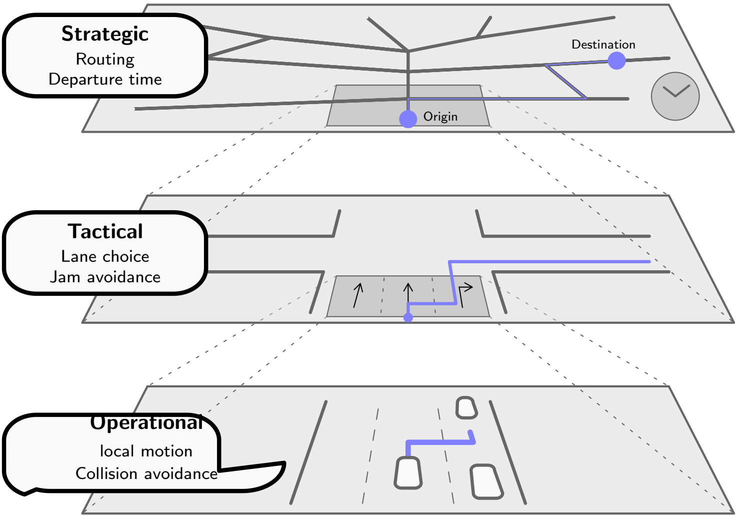


(Moras et al. 2011)

Functional architecture of automated vehicles



Analogy to classical modelling scales in transportation systems



Routing

Shortest path problem in a positive real-valued directed graph

> **Static problem:** polynomial complexity
>
> **Time-dependent formulation:** NP-hard problem (use of heuristics) – Dynamic (numerical) algorithm or reactive algorithm looking for solution at any time

- **Dijstra's algorithm** — Complexity in $O(V^2)$: not practicable in real time
- **A-Star heuristic** — Use of an heuristic cost function guiding the search
- **Decomposition** — Network decomposition in subsets or principal components
- **Preprocessed method** — Preprocessing of balanced partition of the graph
- **Hierarchical method** — Weights according to the hierarchy of road networks
- **Sampling based** — Monte-Carlo techniques for the finding of the shortest path
- **Combination** — Hybrid algorithms combining different methods
- . . . (see Gonzalez et al. 2016 or Bast et al. 2015 for surveys)

Behavior planning

Finding of an efficient and safe (collision-free) path in a dynamical environment with moving obstacles

> **Understanding of the current driving situation** ⇝ Cognitive Vehicle
> **Time-dependent** complex problems

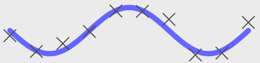
- **Manoeuvre-based** Categorical driving situations: following, lane-keeping, overtaking...
- **Variation methods** Formulation of the problem as an optimisation problem
- **Roadmap** Borrowed from robotic: visibility graph, Voronoi diagram...
- **Potential fields** Gradient problems with attractive (dest.) and repulsive (obstacle) fields
- **Velocity obstacle** Determination of collision-free cones over finite time horizons
- **Heuristic** Neuronal networks, Simulated annealing, ant/swarm optimisation...
- . . . (see Masehian 2016, Tang et al. 2012, Kamil 2015 or Paden et al. 2016 for surveys)

Local planning

Determination of the **reference trajectory**: **smooth trajectory dynamically-feasible** for the vehicle

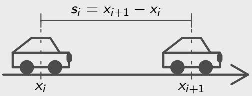
Interpolating curve planners (curvature optimisation)

- Regular interpolation of the reference path
- Clothoid, polynomial, Bézier, spline, ...



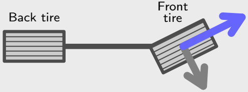
Speed/acceleration planners $\ddot{x}_i = F(s_i, \dot{x}_i, \dot{x}_{i+1}, \ldots)$

- Comfortable and safe following model
- Adaptive cruise control (ACC)

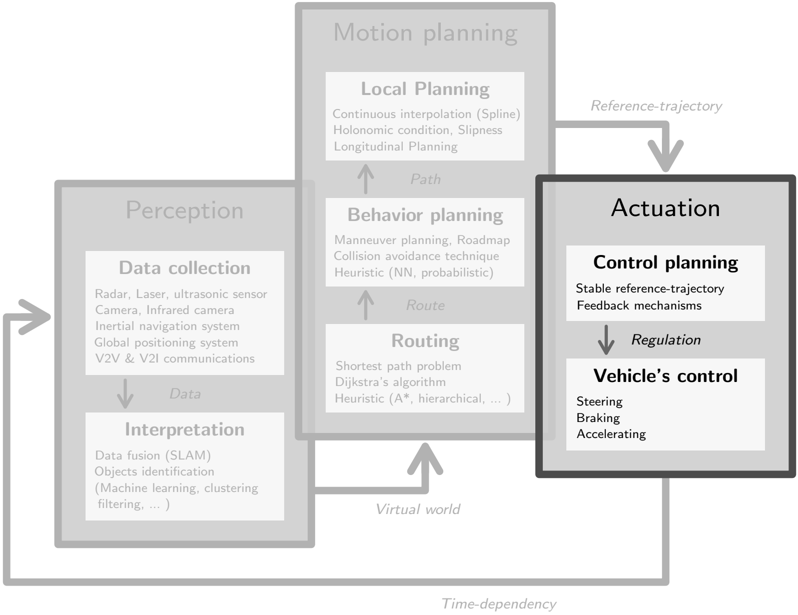


Non-holonomic driving contraints $m\ddot{p}_c = F_f + F_r$

- Kinematic single track constraints
- Inertial and slipness constraints



Functional architecture of automated vehicles



Actuation control

Actuation control in two steps :

1. **Calculation of a command to follow the reference trajectory** $(x_{ref}, v_{ref})(t)$

   → **Feedback mechanisms** fb (e.g. relaxation processes)

$$\ddot{x}(t + T_a) = \mathrm{fb}\big((x, x_{ref}, \dot{x}, v_{ref})(t)\big)$$

with T_a the mechanical application time

2. **Effective mechanical control** of the vehicle

   → **Steering, braking and accelerating controls**

Overview

Stability

Motion planning have to describe **comfortable and safe dynamics**

$\rightarrow$ **Stable and collision-free dynamics**

- **Stability of the route choice** (Smith, 1984)
  - Route choice robust to perturbation / Non-oscillating route choice
  - Motion planning / Routing step

- **Stability of the reference trajectory**
  - Attractive reference trajectory / Exponential stability $\|x(t) - x_{ref}(t)\| \leq Ke^{-\kappa t}$
  - Actuation / Control planning

- **Local and global stability of the homogeneous solution**
  - Congested state – Stability of the homogeneous solutions where all vehicle speed $\dot{x}_i(t) = v$ and spacing $x_{i+1}(t) - x_i(t) = d$ are equal
  - Motion planning / Local planning

Stability of the homogeneous solution

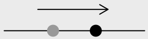
Control of the ACC-systems : description of **stable and collision-free dynamics**[1]

→ **Linear stability theory for dynamical systems**

- **Local stability**

  One vehicle

  - Following behavior behind a vehicle moving at constant speed
  - Stable and collision-free (over-damped convergence)

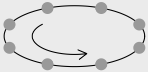


- **String-stability**

  A line of vehicles (ring/infinite lane)

  - Stable homogeneous solutions $(s, v) \in \mathbb{R}_+^2$

$$\left| \begin{array}{ll} x_{i+1}(t) - x_i(t) & \to s \\ \dot{x}_i(t) & \to v \end{array} \right. \quad \text{as} \quad t \to \infty \quad \text{for all } i$$



  - Consideration of local, convective and advective perturbations
  - Control of the system stationary state

[1] see for instance Darbha et al. 2009; Kikuchi et al. 2003; Zhou et al. 2005; Paden et al. 2016

Homogenisation

Homogenisation: *Monotone* convergence of the system to the homogeneous solution (Monneau & Forcadel, 2014)

→ Control of the **transient and stationary states** of the system

→ **Bounds of minimal speed and spacing**

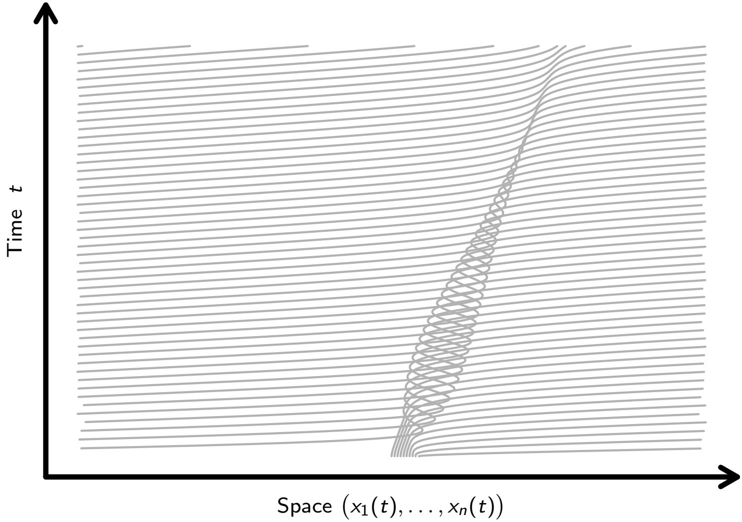
Principle : constraints on the model's parameters

- Invariance principle for spacing variables
- Comparison principle on the invariant sets
- Convergence of the system to homogeneous solution by up- and down-bounds

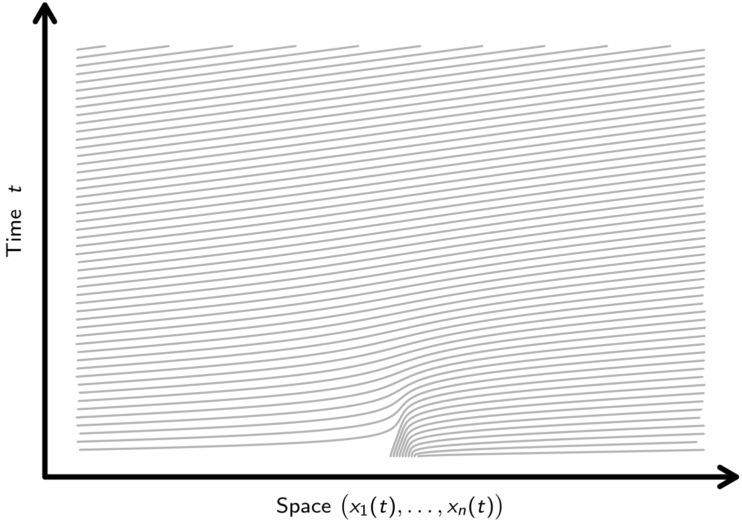
Example: Optimal velocity model (OVM) $\ddot{x}_i(t) = \frac{1}{\tau}\big(V(s_i(t)) - \dot{x}_i(t)\big)$

$$\begin{array}{|ll} \text{Global stability :} & \tau V'(s) < 1/2 \\ \text{Homogenisation :} & \tau V'(s) < 1/4 \end{array}$$

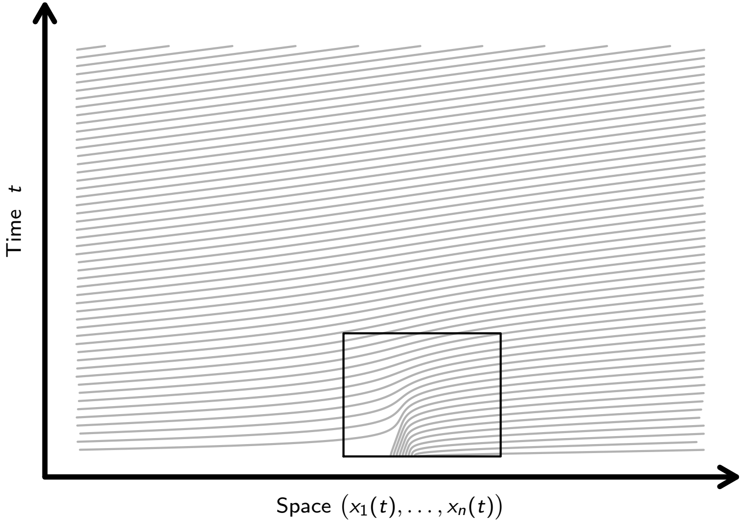
Stability



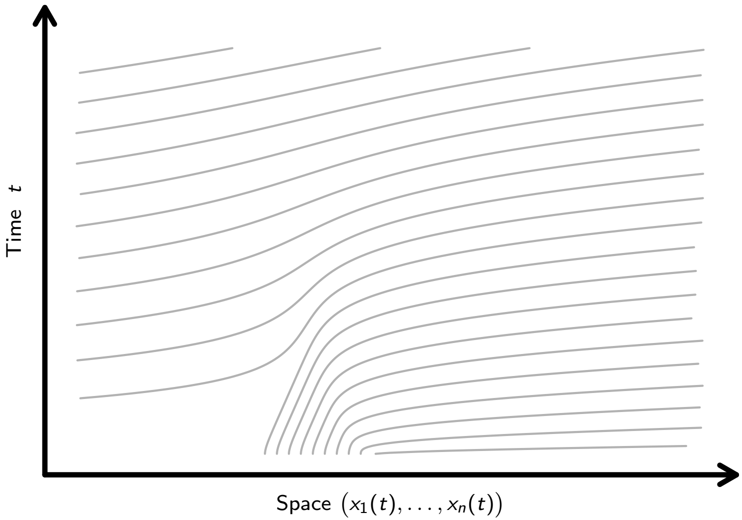
Stability + Homogenisation



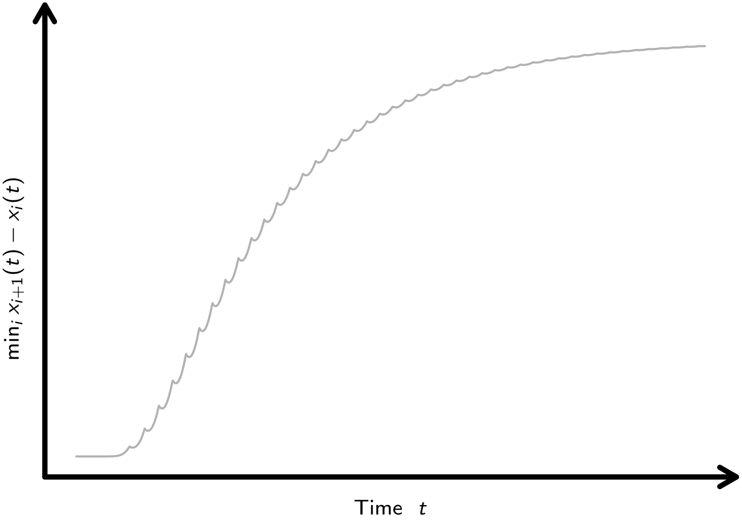
Stability + Homogenisation



Stability + Homogenisation



Stability + Homogenisation



Safety for automated vehicles

The **safety** is a central aspect of connected and automated vehicles

Essential argument

- **for** the development of automated vehicle (more than 90 % of the accident due to human errors; Singh, 2014),
- and **against** : safety of autonomous vehicles still need to be proven

Biggest risk sources for autonomous vehicles : **collisions** (Lefèvre et al., 2014)

Potential high severity of the damage in case of collision (injure, fatality)

→ Depends on the speed and type of collision

Very low exposure

Limit of the empirical evaluation

Even if many accidents in road traffic occur, the **probability for a accident with injures or fatalities per unit of distance is very low**.

→ Example USA :
- Injure-rate is around 40 per 100M kilometres
- Fatality-rate is around 0.7 per 100M kilometres

Example (Kalra and Paddock, 2015): we have to observe without accident 100 autonomous vehicles driving 24h a day and 365 days a year during

4 mouths (injure) or **19 years** (Fatality)
12M km 658M km

to statistically prove that injure- and fatality-rate of the autonomous vehicles is smaller that the rate of conventional vehicles.

Connected and automated vehicles are **technologies in development**
→ **Empirical evaluation of the safety not suitable**

Functional safety from the ISO 26262 standard

Standardisation (Schlummer, 2014) : IEC 61508 (generic norm), ISO 26262 (automotive area) or companies and associations' directives, ...

ISO 26262-3 und 26262-4 : Functional safety for the concept and development phases of E/E systems in road cars

→ **Completeness and consistence problem**

For all items and all driving situations :

P1: Hazards analyse & Risk assessment	→	**P2:** Functional safety concepts	→	**P3:** Technical safety concepts

- **Exhaustive listing** of all driving situations and associated potential hazards (AMDEC, dependability, situation classification)
- Risk assessment : **ASIL risk classification scheme** as function of *Severity*, *Exposure*, *Controllability*

Classification of the driving situations

Discrete (categorical) descriptions of the driving situations according to (Warg et al., 2014; Jang et al., 2015; VDA, 2015b) :

- **Vehicle** speed, direction, state, mode, manoeuvre, ...
- **Road** road type, surface type, curving, slope, ...
- **Neighborhood** infrastructure, vehicles, pedestrians, obstacles, ...
- **Environment** weather, luminosity, temperature, ...

Driving situations, environment and potential hazards are **numerous and varied** : they can only exhaustively be described in **specific simple conditions**.

→ Example – Driving in **highways** : *following, lane keeping, lane changing*

Driving situations in **urban** or **peri-urban** are **more complex**.

Safety concepts

Functional safety concept: *Collision avoidance systems*

→ *Controllability* part of the ASIL risk classification

Technical safety concepts

- **Emergency protocols**
  - System failure: failure detection, emergency breaking
  - Unexpected event: emergency avoidance procedure (*reactive control*, Binfet-Kull et al. 1998).
- **Driving situation analysis**
  - Setting of safe conditions for all manoeuvres (mathematical criteria based on distances, speeds...)
- **Redundancy**
  - Sensing : Sensor/camera/GPS/carte fusion (SLAM)
  - Motion planning : use of several planners
  - Actuation : for instance steering through stereo-breaking

Functional safety for autonomous vehicles : limit

Main difference with autonomous vehicles (Warg et al., 2014):

- *Conventional vehicle :* **the driver is responsible** for the vehicle control.
- *Autonomous vehicle :* **the automated driving system is responsible**.

→ **Exhaustive listing of all driving situations and hazards** with autonomous vehicle at the levels L3, L4 or L5 is **not possible**.[2]

≪ *The higher complexity and the partly implicit definition of the tasks* [of autonomous vehicles] *for the E/E systems will make it harder to argue completeness and correctness of the safety requirements in each phase of the ISO 26262 life-cycle.* ≫ (Bergenhem et al., 2015).

≪ *Vehicle-level testing won't be enough to ensure safety. It has long been known that it is infeasible to test systems thoroughly enough to ensure ultra-dependable system operation.* [...] *Thus, alternate methods of validation are required, potentially including approaches such as simulation or formal proofs* ≫ (Koopman und Wagner, 2016).

[2] Warg et al., 2014; Bergenhem et al., 2015; Johansson, 2016; Koopman und Wagner, 2016.

Dynamic safety analysis

Development of **specific tools for the safety** aiming to take into account the **varied dynamical aspect** of the driving

- Working group *safety of the intended function (SoTIF)* in the revision of the ISO 26262 standard

Examples :

→ **Dynamic evaluation of the safety** with temporal indicators as **Time-to-Collision**, **Time-to-React** or **Time-Gap** (Tamke et al., 2011; Berthelot et al., 2012)

→ Dynamic detection of **unusual events** or **conflictual manoeuvres** (Lefèvre, 2014)

→ **Mathematical analyse** of the collision possibilities; Development of **robust collision-free models and avoidance techniques** (Zhou und Peng, 2005)

→ **Real-time trajectories predictions** by **simulations** (Eidehall und Petersson, 2008; Ammoud et al., 2009; Chen und Chen, 2010; P. Olivares et al., 2016)

Overview

Conclusion

Advanced driver assistance systems are growing up equipments proposed by manufacturers or automotive suppliers

- Improvement of the **safety** and the **driving comfort**
- Levels L1 and L2 of automation

Progressive transition to connected and autonomous vehicles (Blosseville, 2015)

- **Autonomous Vehicles** Level L3 of automation (autonomous highway driving)
  - High intelligence of the embedded systems (perception, map)
- **Connected vehicles** Autonomy + Connectivity — Level L4
  - Formalisation of the driving in different contexts (highway, peri-urban, urban)
  - Deployment of V2X communications
- **Integrated vehicles** Connected + Cooperation with the infrastructure — Level L5
  - High performances on networks (optimal affectation)
  - Safety solution at high speed and in complex 2D contexts (mixed urban traffic)

Challenges

Full driving automation depends on the **advances of intelligent transportation systems**, **sensor** and **connectivity technologies**, and **computational capacity** (Blosseville, 2015)

- Motion in **complex 2D urban environments** with **mixed traffic**
  - Driving situation **very varied** / Driving behavior **few structured** (Saad, 1987)
  - Complicated algorithms for the perception and the motion (machine learning, neural networks, ...) for which the **reliability is hard to estimate**.
  - *Long time* anticipation
- Autonomous vehicles to **avoid crashes due to human errors**. Yet most of the time, human driving is free of accident.

  $\rightarrow$ Challenge for automated cars: **replicate the crash-free performance** of human drivers. New type of crashes may emerge (ITF, OECD).
- Full autonomous vehicles (level L5) on **personal rapid transit systems**
  - Own infrastructure and driving rules
  - Increase of the mobility

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Empirical evaluation of the accident-rate

- p is the probability of accident for autonomous vehicles.
- p_0 is the probability of accident in real traffic.

D is the collision-free traveled distance; it has a geometric distribution with parameter p. Therefore $P(D \leq n) = 1 - (1-p)^n$.

We test

$$H_0 = \{p \geq p_0\}.$$

For a given traveled time n, we reject H_0 if $R_n = \{D > n\}$.

The probability of a false-positive is then

$$P_{H_0}(R_n) = 1 - P_{H_0}(D \leq n) \leq 1 - P_{p=p_0}(D \leq n) = (1-p_0)^n = \alpha.$$

We have $p < p_0$ with confidence-level $1 - \alpha$ if

$$n \geq \frac{\ln(\alpha)}{\ln(1-p_0)}.$$

Example of driving situation classification (H. Jang et al., 2015)

Factor	Sub-factor	Element	State
Vehicle	Driving Speed		Very Slow, Slow, Normal and Fast
	External Attachment		Without/with external attachment
	Operational Mode		Driving, Parking, Fuelling, Repairing
	Maneuver	Engine	On, Off
		Velocity	Accelerating, Constant, Decelerating
		Direction	Lane Keeping, Lane Changing, Turning
		Movement	Stop, Forward, Backward
Road	Linearity		Straight, Curved
	Slope		Plain, Sloped
	Layout		Invisible (blocked) , Visible (unblocked)
	Coarseness		Paved, Unpaved, Troublesome
	Nearby Elements	Obstacle	Clean, Obstacle
		Traffic	Smooth flow, Congestion
		Pedestrians	No, A Few, Many
Environment	Surface		Clear, Water (by rain etc), Snow/Ice
	Visibility		Dark, Bright, Foggy
	Temperature		Low, Medium, High
	Momentum		Windy, Calm