



**HAL**  
open science

# Combining Bayesian and AI approaches for Autonomous Driving

Christian Laugier

► **To cite this version:**

Christian Laugier. Combining Bayesian and AI approaches for Autonomous Driving. IROS 2021 - IEEE/RSJ International Conference on Intelligent Robots and Systems - Workshop "Perception and Navigation for Autonomous Robotics in Unstructured and Dynamic Environments", Sep 2021, Prague, Czech Republic. hal-03518232

**HAL Id: hal-03518232**

**<https://inria.hal.science/hal-03518232v1>**

Submitted on 9 Jan 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Combining Bayesian & AI approaches for Autonomous Driving

*Christian LAUGIER, PhD & Dr Es Science*  
*Research Director at Inria & Scientific Advisor for Probayes*  
*Inria Chroma team & IRT Nanoelec – christian.laugier@inria.fr*

## Keynote Speech

*Workshop on “Perception & Navigation for Autonomous Robotics in Unstructured and Dynamic Environments”*  
*IROS 2021, Prague, September 27<sup>th</sup> 2021*



The research work presented in this talk includes contributions from several Chroma team members:

- *Postdocs & Researchers: D. Sierra-Gonzalez, O. Erkent*
- *Research engineers: L. Rummelhard, A. Negre, N. Turro, J.A. David, J. Lussereau, T. Genevois, A. Paigwar*
- *Also some former PhD students & Postdocs*

*=> I warmly thank each of them*



# Brief overview of Technologies & Ongoing challenges for Autonomous Driving

- Due to both Road nuisances (*pollution, traffic jams, accident...*) & Current technological advances, **Technologies & Services for Human Mobility** are evolving rapidly => *Reduce road Nuisances & Costs + Increase Efficiency & Safety*
- Last decade: A Technological breakthrough (*Sensors, GPU, DL...*) & Numerous AV experiments in real traffic conditions



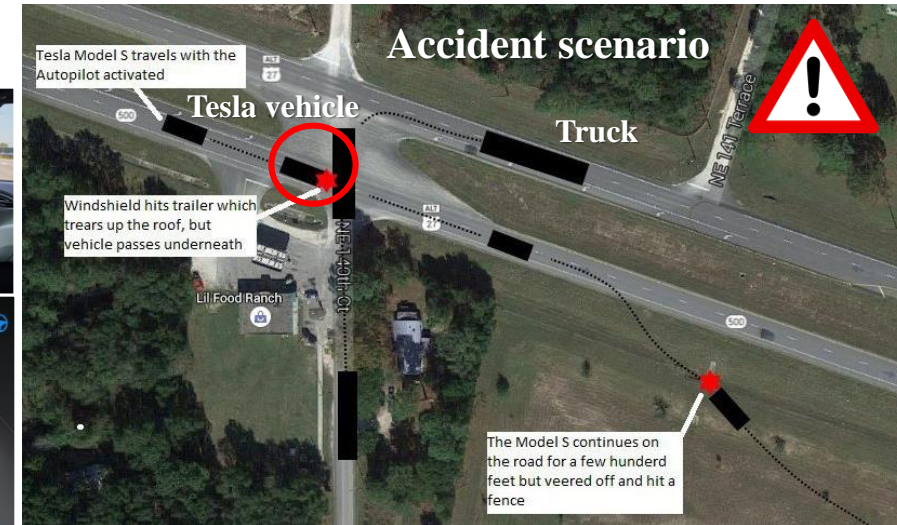
- Millions of miles have been covered in last decade, but **SAFETY** is still not guaranteed ! (*as evidenced by several accidents*)  
=> *Additional R&D work is still mandatory on 2 main research lines:*
  - *Improving “Perception & Decision-making” technologies (in particular for Robustness & Scalability issues)*
  - *Developing “Validation & Certification” approaches for future deployment (in addition to traditional testing approaches)*  
=> *Develop a new Framework including Realistic simulators, Augmented reality capabilities, Integration of Formal methods*  
*This subject is addressed by Inria & IRT Nanoelec (several EU & National projects) ... But not presented in this talk !*



## ❑ Tesla: Driver was killed in a crash with Autopilot L2 active

May 2016

- ✓ A truck turned left and blocked the route of the Tesla vehicle
- ✓ The Autopilot failed to detect the white moving truck, with a brightly lit sky (Camera Mobileye + Radar)
- ✓ The human driver was not vigilant & didn't took over



## ❑ Uber: Pedestrian killed by Self-driving L3 vehicle => First fatal crash involving a pedestrian, see video below

Tempe, Arizona, March 2018

- ✓ Despite the presence of multiple sensors (lidars, cameras ...), the perception system failed to detect the pedestrian & didn't disengaged
- ✓ In addition, the "Safety Driver" reacted too lately (1s before the crash)



# Improving Safety: AVs have to face two main challenges

## 1<sup>st</sup> Challenge : *The need for Robust, Self-diagnosing & Explainable Embedded Perception*



*Video source: AutoPilot Review @ youtube.com*

**Video Scenario (Tesla vehicle with Autopilot active):**

- *The Tesla perception system failed to detect the barriers blocking the left side route.*
- *The human driver has to take over and steer the vehicle away from the blocked route.*



# Improving Safety: AVs have to face two main challenges

## 2<sup>nd</sup> Challenge: *The need for Understandable Driving Decisions* (Sharing the road with human drivers)

Unfortunately, **Human drivers actions** are determined by a complex set of interdependent factors which are very hard to model (e.g. intentions, perception, emotions ...)

⇒ Predicting **human driver behaviors is inherently uncertain**

⇒ AV have to reason about **“uncertain intentions” of the surrounding vehicles**



The Lexus SUV, fitted with special sensors, struck the public bus on February 14 in Mountain View, California

Video source: *The Telegraph*

**Video scenario involving a Waymo AV & a Human Driven Bus.**

*The accident scenario was recorded by the dashcam of the Bus (bus not visible in the video)*



- *The Waymo AV was blocked by an obstacle and decided to make a left lane change*
- *The bus driver misunderstood the AV intention and didn't yield*
- *The two vehicles collided*



# Perception & Decision-making challenges – *Outline*

Dynamic scene analysis & Navigation Decisions



Embedded Perception & Decision-making for Safe Intentional Navigation



Detecting & Reacting in real-time to Unexpected Events



Typical situation: A pedestrian suddenly comes out from behind a stopped bus

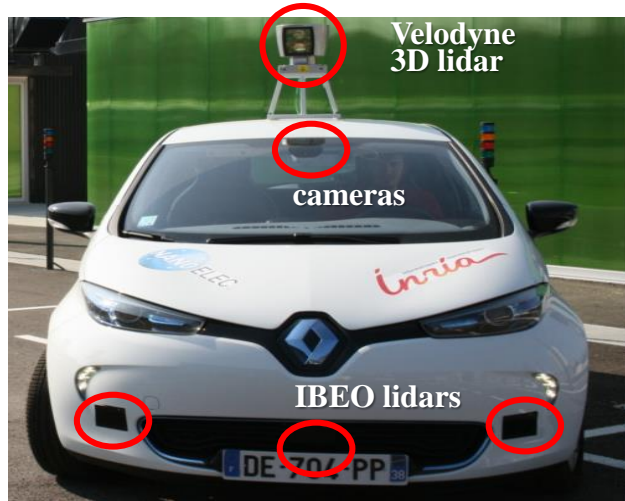
- ⇒ Scene interpretation using Sensing & Prior knowledge
- ⇒ Safe Navigation decisions (using semantics & context)

- ⇒ Detect & Predict imminent collision with “something” (unclassified unexpected event)
- ⇒ Activate appropriate reflexive avoidance strategy

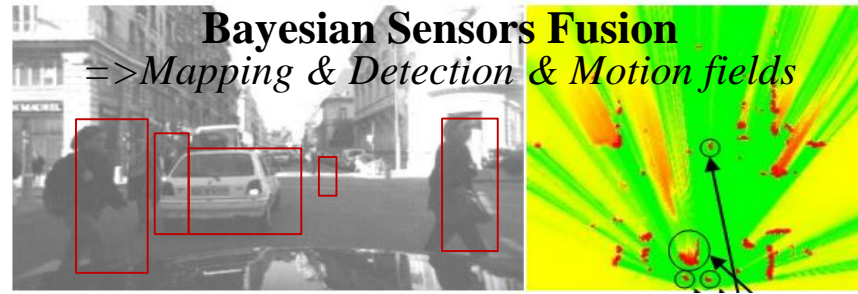
- ❑ **Main constraints:** *Dynamic & Open Environments + Incompleteness & Uncertainty + Sensors limitations & Huge amount of data to process*
- ❑ **Implementation constraints:** *Real-time processing + Software / Hardware integration*
- ❑ **Mixed traffic (Human in the loop):** *A Human-Aware Decision-making process is required*  
=> Taking into account Interactions + Behaviors + Social & Traffic rules
- ❑ **Our Approach:** *Combining Probabilistic & IA approaches*



# 1<sup>st</sup> Paradigm: Embedded Bayesian Perception



**Embedded Multi-Sensors Perception**  
 ⇒ *Continuous monitoring of the surrounding dynamic environment*



**Dynamic scene interpretation & Prediction**  
 (Using Context & Semantics)



## Main Objective

1<sup>st</sup> Leverage dynamic insights to better understand a complex traffic scene !!!

2<sup>nd</sup> Process Noisy data, Uncertainty, Dynamics ... while respecting strong Real-time constraints

## Main Features of our approach

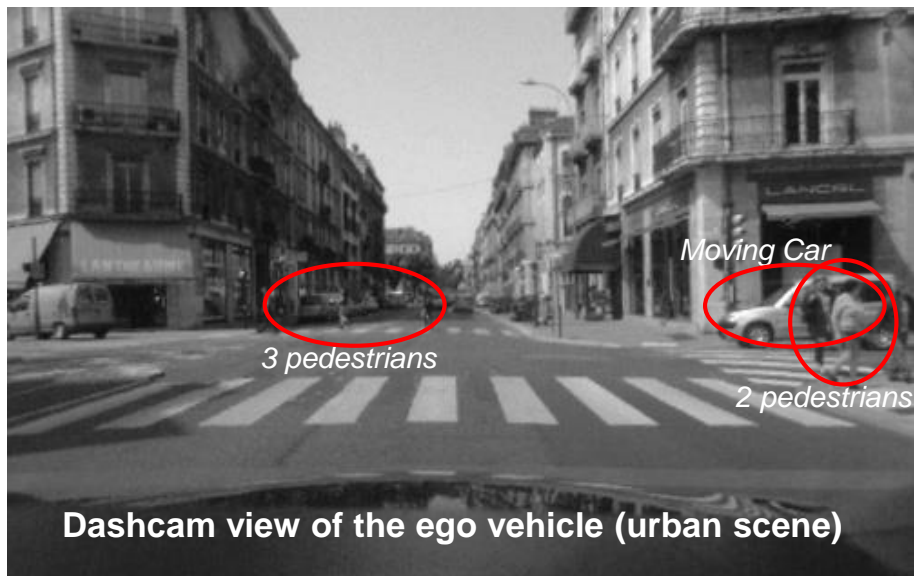
- ✓ Reasoning about **Uncertainty** & a **Time window** ⇒ Reasoning on **Past & Future (predicted) events**
- ✓ Improving robustness using **Bayesian Sensors Fusion**
- ✓ Interpreting the dynamic scene using **Contextual & Semantic information**
- ✓ Implementing the system using **hardware accelerators** (GPU, Multicores, Microcontrollers ...)





# Dynamic Occupancy Grid & Bayesian Filtering

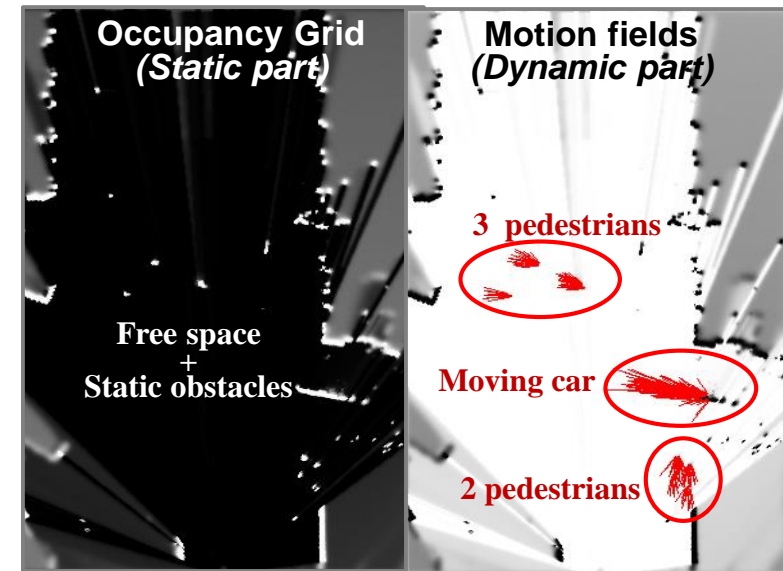
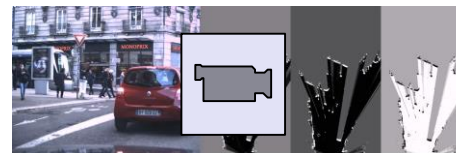
=> Use dynamic information for a better understanding of the observed scene



Sensors data fusion  
+  
Bayesian Filtering  
+  
Extracted Motion Fields



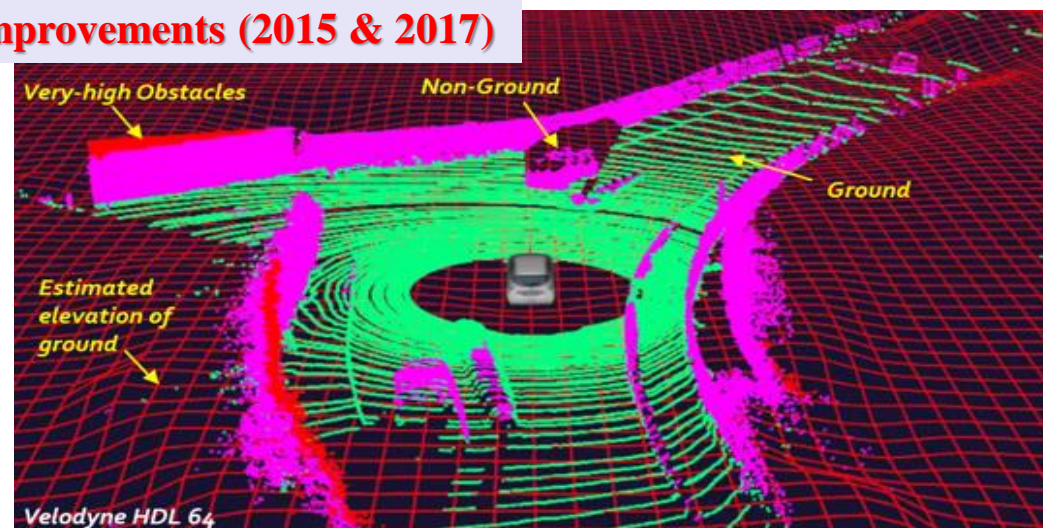
1<sup>st</sup> Embedded & Optimized version  
(HSBOF, patent 2014)



## Patented system Improvements (2015 & 2017)



Moving Objects Classification + Detection & Tracking  
(CMCDOT 2015 & "Dense Occupancy Tracker")

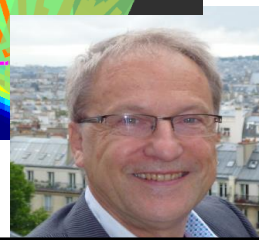
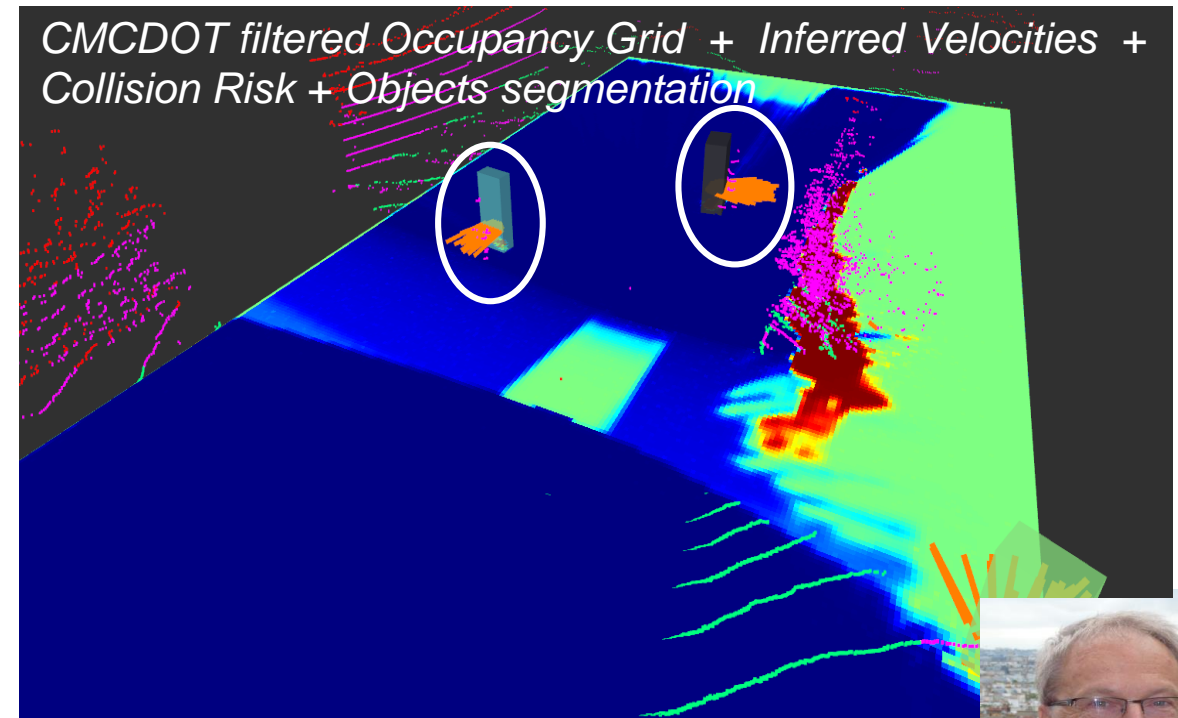
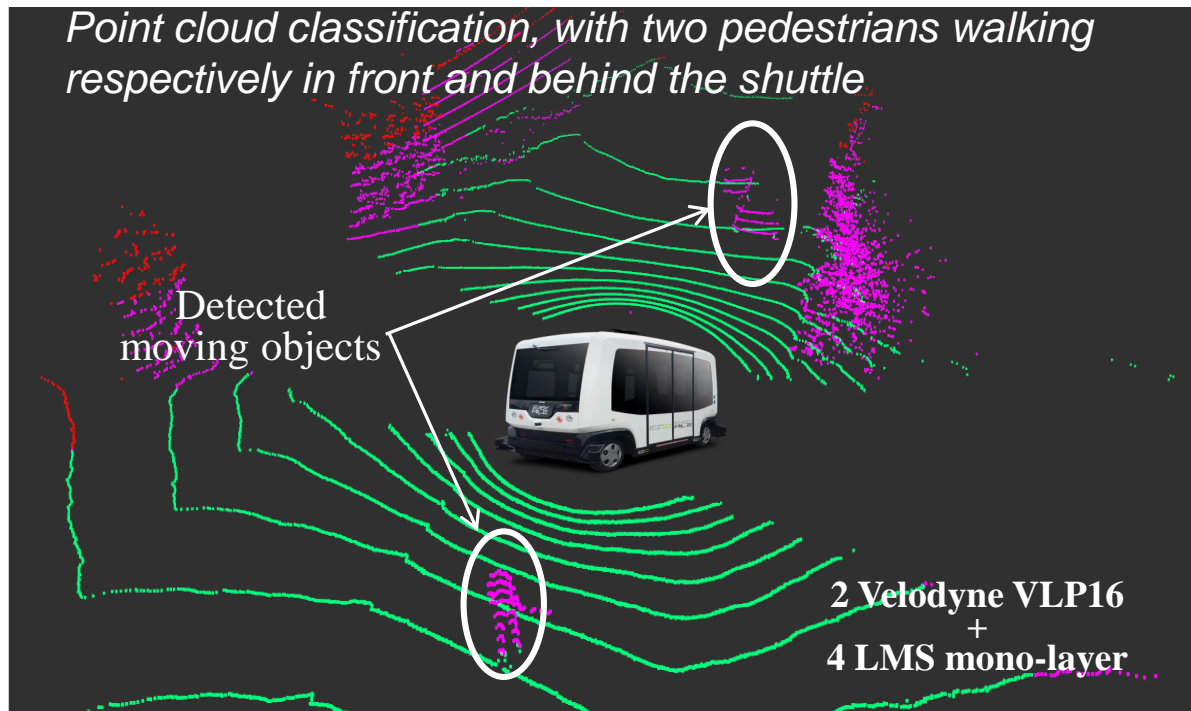
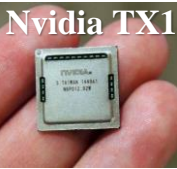


Ground Estimation & Point Cloud Classification  
(patent 2017)



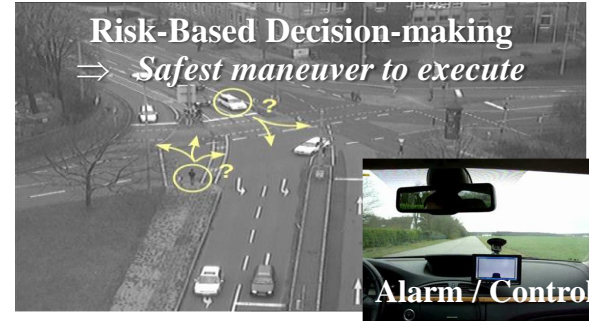
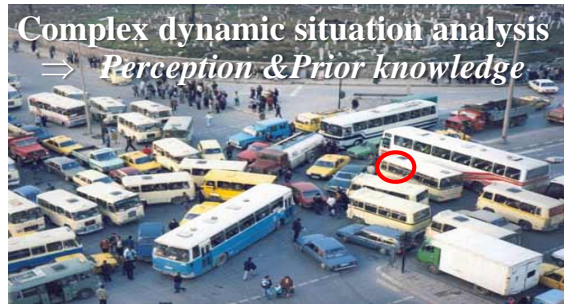


- **POC 2019: Complete system implemented on Nvidia TX1**, and easily connected to the shuttle system network *in a few days* (using ROS)
- **Shuttle sensors data** has been fused and processed in **real-time**, with a successful Detection & Characterization of the **Moving & Static Obstacles**
- **Full integration on a commercial product** still under development with an industrial company (confidential)



# 2<sup>nd</sup> Paradigm: Collision Risk Assessment & Avoidance Strategies

=> Avoiding Pending & Future Collisions



Situation analysis + Prediction & Collision Risk Assessment + Safest Driving Decision

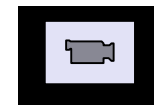
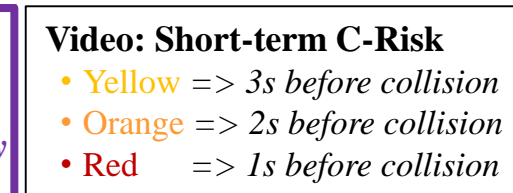
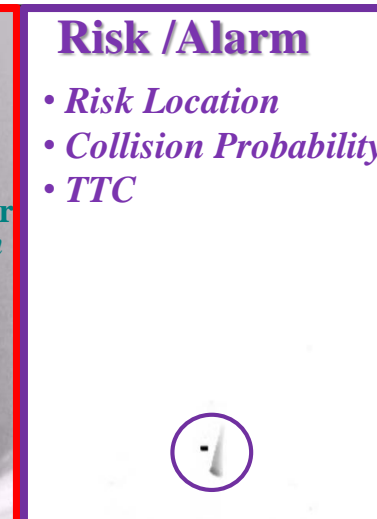
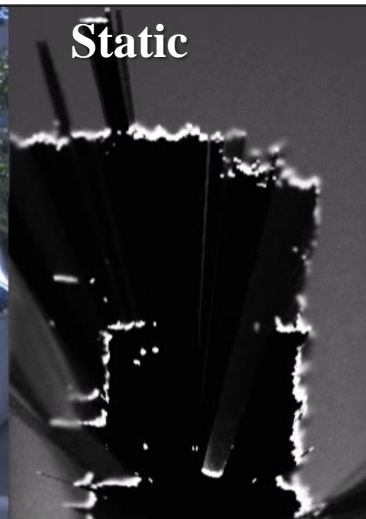
## Main Features of our approach:

- ✓ **Predict** dynamic environment changes on a given “time horizon  $t+\delta$ ” (*using both History & Motion models*)
- ✓ **Estimate** the **Probabilistic Collision Risk** at horizon  $t+\delta$  ( $\delta = a\ few\ seconds\ ahead$ ). *Two types of Collision-Risk (C-Risk) have to be considered, depending on both the time horizon & the semantic information available*
- ✓ “**Short-term C-Risk**” characteristics: *The Collision Risk is estimated at the **Grid-level**, the Moving obstacles are not classified, the time-horizon  $\delta = 3-5s$ , and the Prediction step is based on a “conservative motion hypothesis”*
- ✓ “**Mid-term C-Risk**” characteristics: *The Collision Risk is estimated at the **Object level**, the Involved entities are classified, and the Prediction step requires to reason about “Behavior models & Semantic information”*
- ✓ **Driving Decisions** are taken on the basis of the Predicted behaviors of all the observed surrounding traffic participants (cars, cycles, pedestrians...), the **Social & Traffic rules**, and the expected traffic participants Interactions

## Experimental results (Urban streets & Test track)

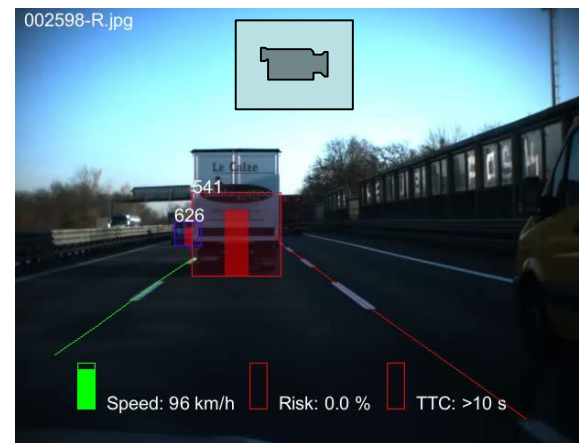
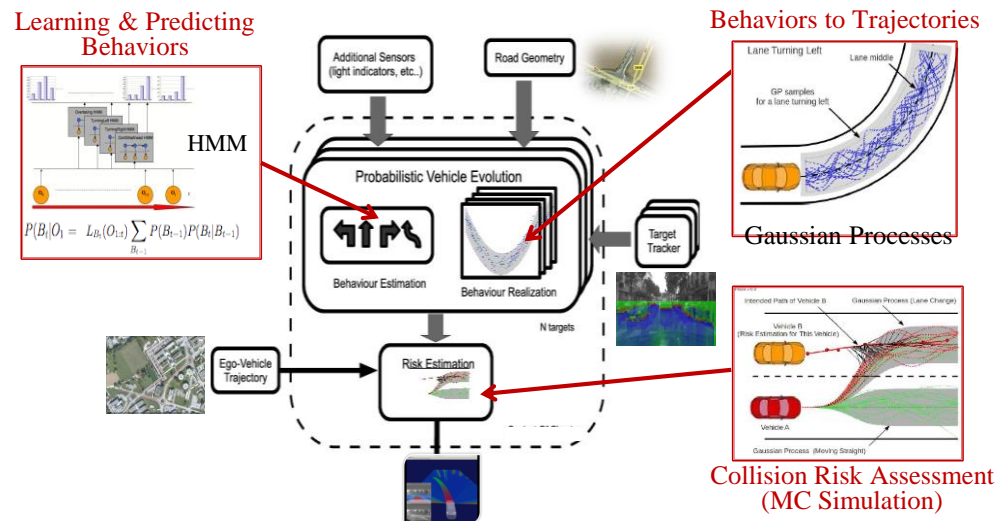


## Collision prediction in a crash scenario (in test track)



=> Increased time horizon & complexity + Reasoning on Behaviors & Interactions

## □ Trajectory prediction & C-Risk assessment => Patent 2010 (Inria, Toyota, Probayes)



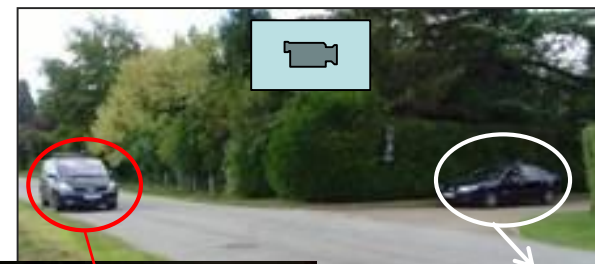
Courtesy Probayes

Cooperation still on-going (R&D contracts + PhDs)

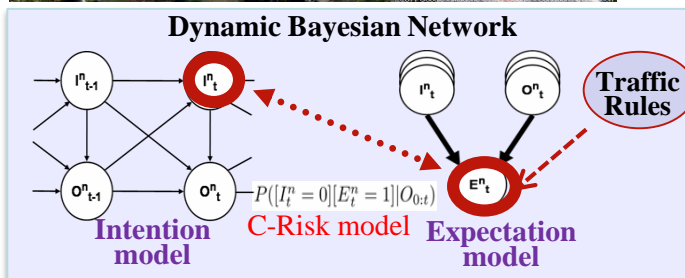
## □ Intention & Expectation (Mixed Traffic & Interactions) => Patents 2012 (Inria - Renault) & 2013 (Inria - Berkeley)



Human-like reasoning



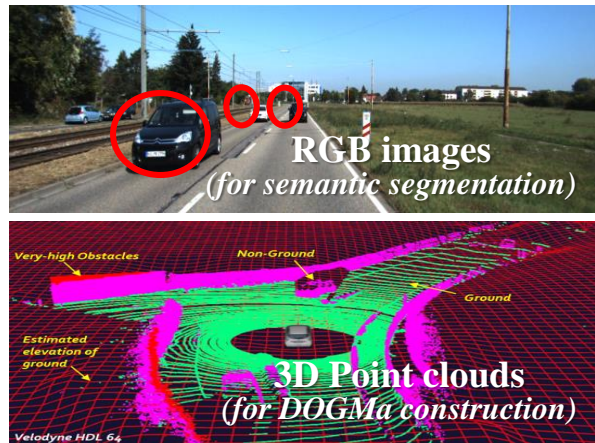
Cooperation still on-going (R&D contracts + PhDs)



# 3<sup>rd</sup> Paradigm: Models improvements using Machine Learning

=> Exploit the complementarities of Bayesian Perception & DL based Computer Vision approaches  
 (Richer semantics, Better understanding of 3D dynamic scenes, Mandatory for Decision-making step)

## □ Perception level: *Fusing DOGMa & Semantically segmented RGB images*



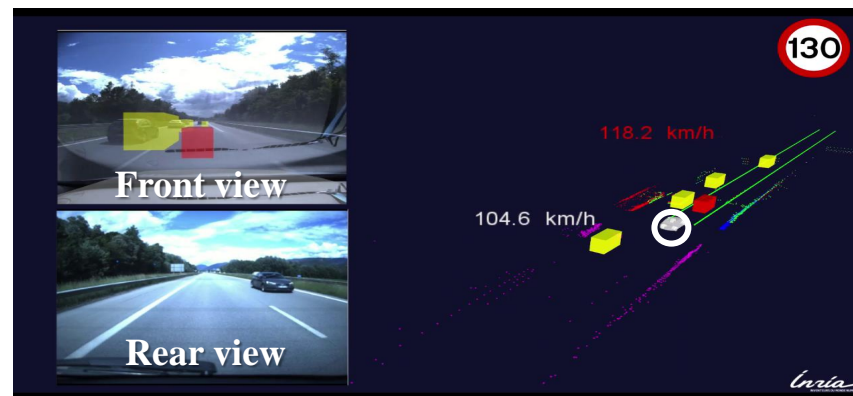
- Unknown
- Building
- Sky
- Road
- Vegetation
- Sidewalk
- Car
- Pedestrian
- Cyclist
- Signage
- Fence
- Free
- Static
- Dynamic

**DOGMa:** *Dynamic Occupancy Grid Map*  
**BEV:** *Bird's Eye View*

## □ Prediction & Decision-making level: *Learn driving skills for Autonomous Driving*

*Step 1: Modeling Driver Behavior using Inverse Reinforcement Learning (IRL)*

*Step 2: Predict motions of surrounding vehicles & Make Driving Decisions for Ego Vehicle*





**Ozgur Erkent**

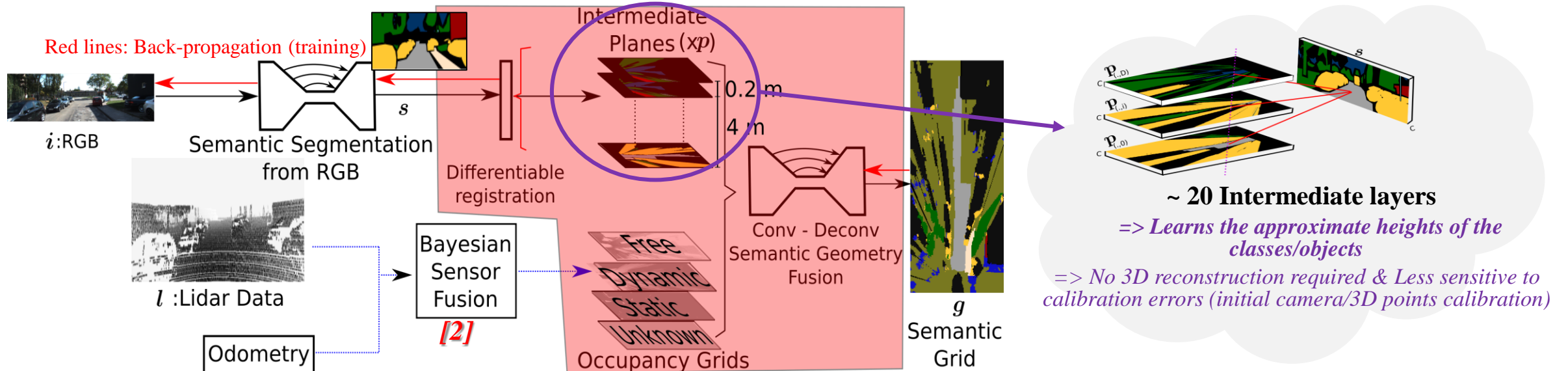
Starting Research Position at Inria Chroma team (2017-21).  
External Collaborator at Inria & Assistant Professor at Ankara Univ (since July 2021)

**Objective:** Add *Semantic information* (cars, pedestrians, roads, buildings...) in each cell of the Dynamic Occupancy Grid Map, by exploiting *additional RGB inputs*

**Approach:** A new “Hybrid Sensor Fusion approach” combining **DOGMa & Semantically Segmented RGB images (using DL)**

**DOGMa:** Dynamic Occupancy Grid Map

## Semantic Grid Neural Network [1] [3] [Patent Inria & Toyota 2019]



**Implementation / Testing:** Segnet Cuda/GPU + Kitti dataset

[1] *Semantic grid estimation with a Hybrid Bayesian and Deep Neural Network approach*, O. Erkent et al., IEEE IROS 2018

[2] *Conditional Monte Carlo Dense Occupancy Tracker*, Rummelhard et al., ITSC 2015

[3] *Segnet: A deep convolutional encoder-decoder architecture for image segmentation*, Badrinarayanan et al., IEEE PAMI 39(12) 2017

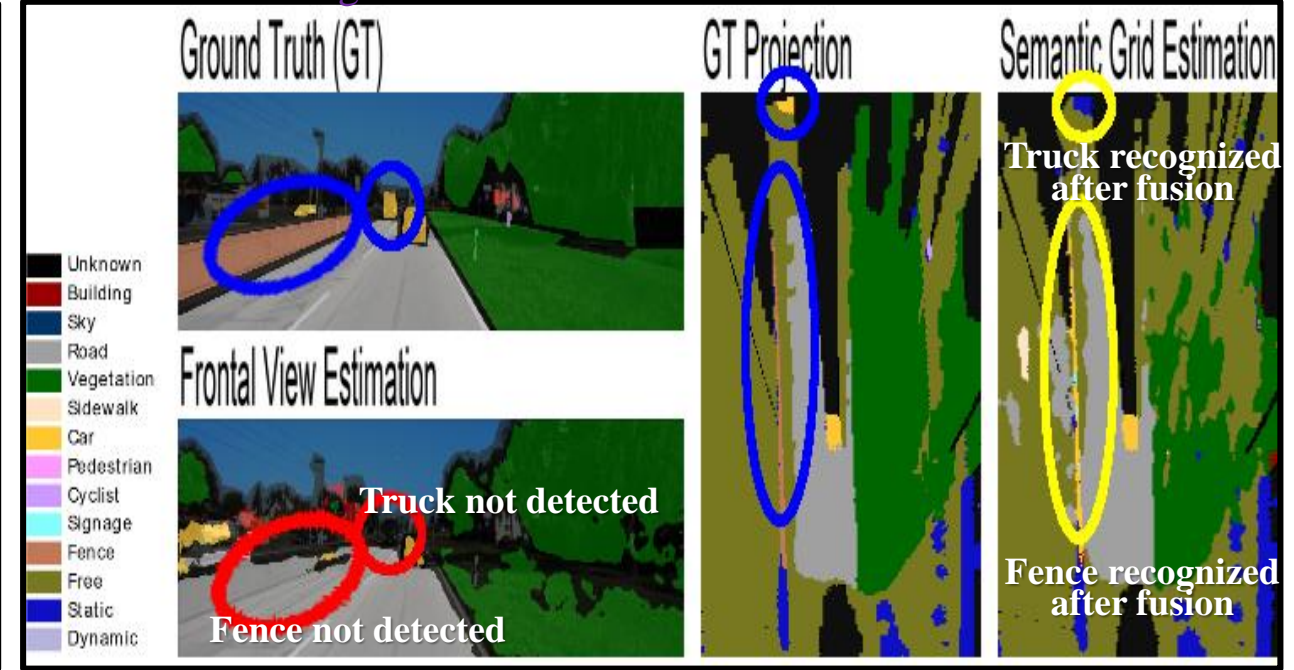
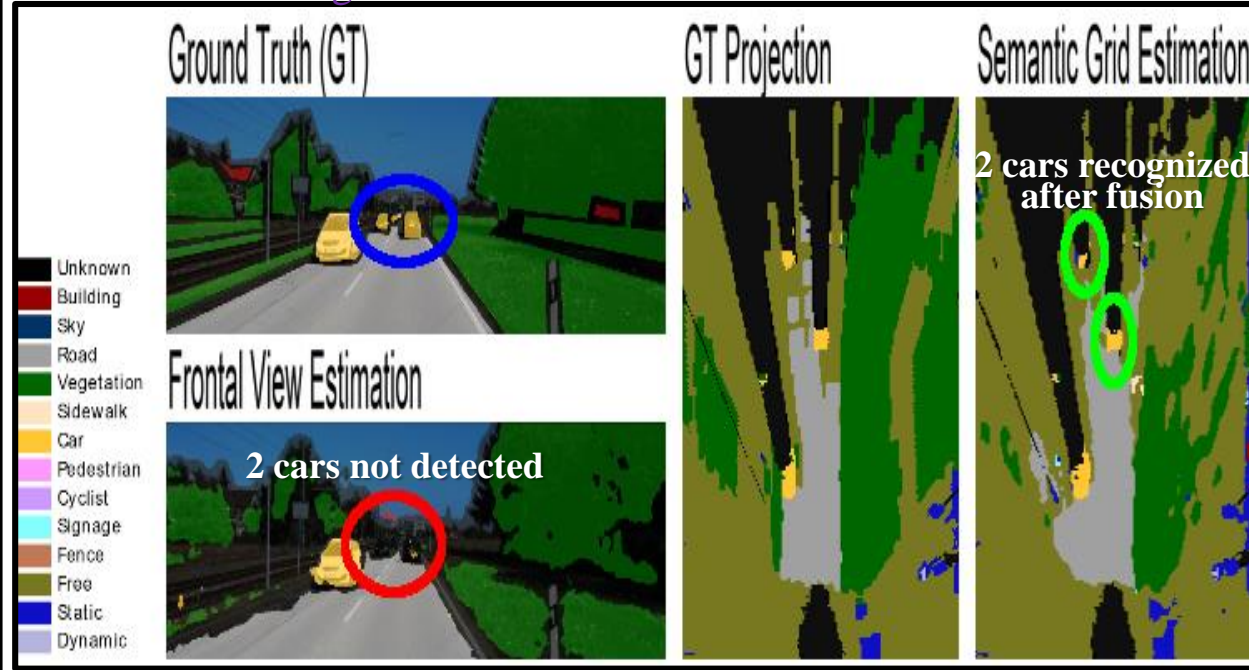


Traditional Semantic Segmentation

Hybrid Sensor Fusion

Traditional Semantic Segmentation

Hybrid Sensor Fusion



=> **2 cars not detected** in frontal view estimation... but **recognized as an obstacle in Semantic Grid** (with the help of DOGMa)

=> **Truck & Fence not detected** in frontal view estimation... but **recognized as an obstacle in Semantic Grid** (with the help of DOGMa)

[1] Semantic grid estimation with a Hybrid Bayesian and Deep Neural Network approach, O. Erkent et al., IEEE IROS 2018





# Perception Level (2): 3D Object Detection using Lidar & RGB camera (Frustum PointPillars)



Anshul Paigwar  
Research Engineer, Inria



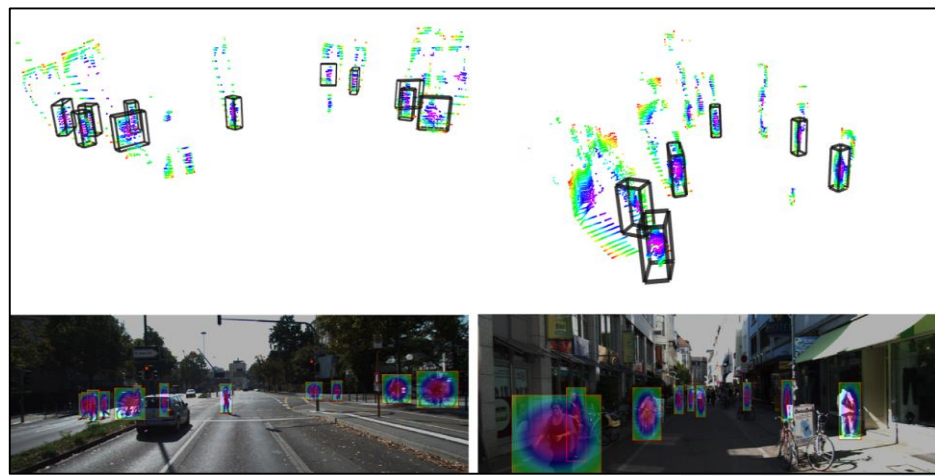
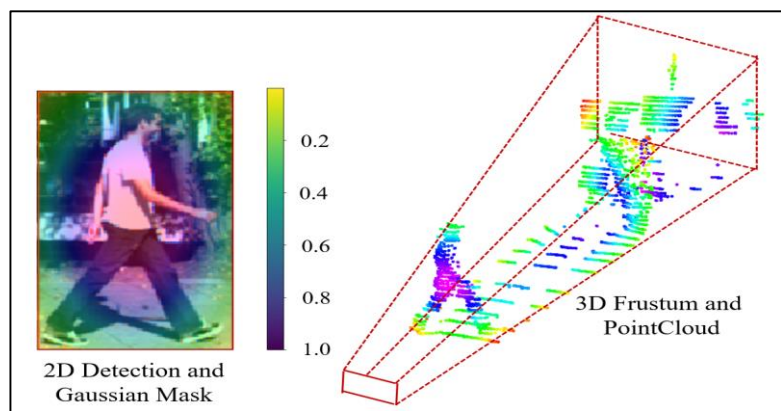
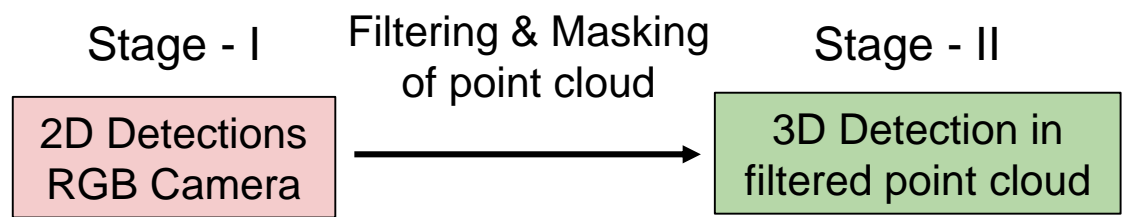
David Sierra-Gonzalez  
Starting Research Position, Inria

**Objective:** Realtime accurate detection & localization of small object like pedestrians in *3D point cloud of large-scale scenes*

**Challenge:** LiDAR only approaches have poor accuracy as pedestrians have *fewer data points and non rigid structure*

**Proposed approach: Multi-stage sensor fusion approach [1]**

- We outperform other multi-stage SOTA approaches for pedestrians BEV detection on the KITTI dataset
- Significantly faster runtime of 14 Hz.



[1] *Frustum-Pointpillars: A Multi-Stage Approach for 3D Object Detection using Lidar and RGB camera*, A. Paigwar et al, ICCV 2021 Workshop on “Autonomous Vehicle Vision” (Oct 2021)



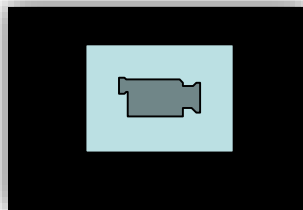
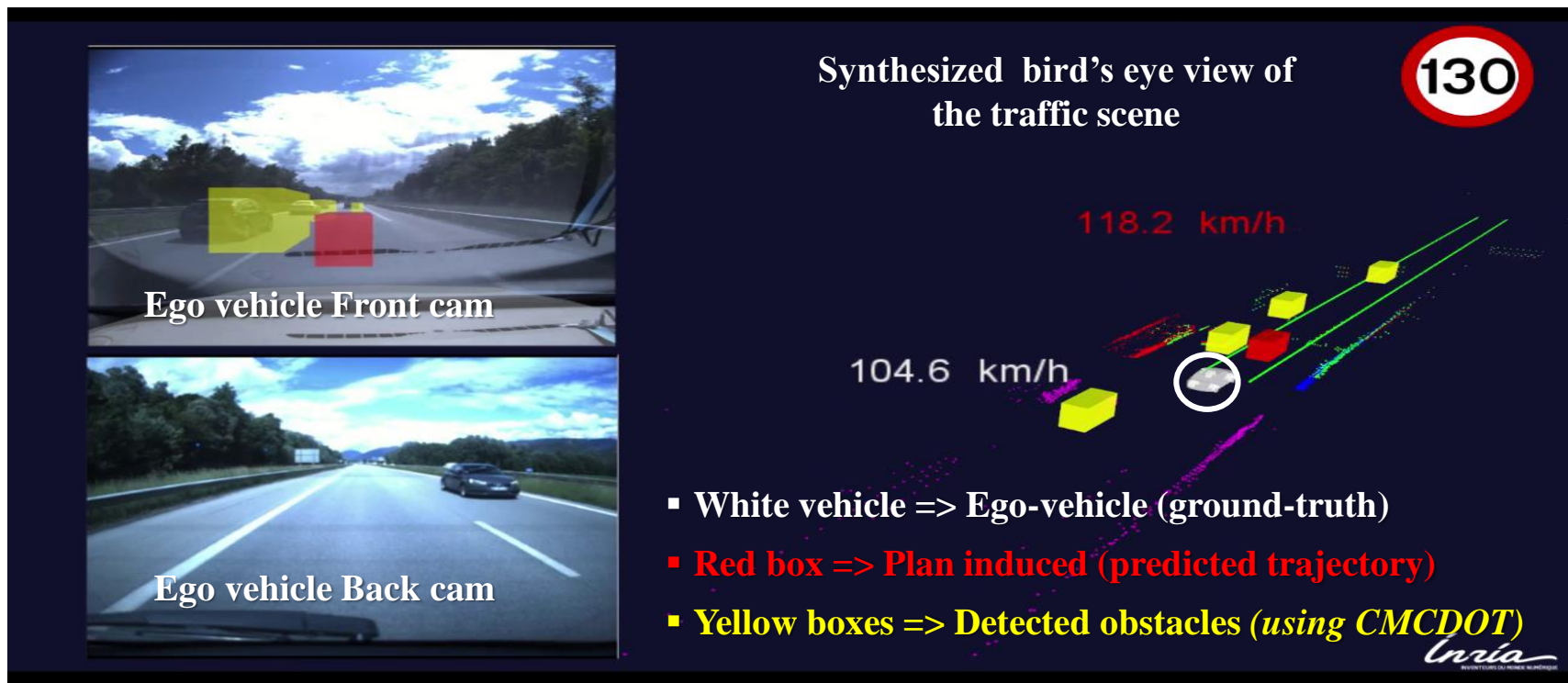
# Prediction & Decision-making level: Learning Driving Skills for AD

## 1<sup>st</sup> Step: Driver behavior modeling



David Sierra-Gonzalez  
Starting Research Position  
Inria Chroma team

- Learn Model parameters from real driving demonstrations using *Inverse Reinforcement Learning (IRL)*
- Driver behaviors are modelled using a **Cost function & Several hand-craft features** (e.g. *Lane index preferences, Deviation from desired velocity, TTC to frontal targets, Time-gap to rear targets, etc.*)
- A training set containing **“interesting highway vehicle interactions”** has been constructed using our *Lexus vehicle*
- The obtained models can be leverage to both **Predict human-driver behaviors & Generate human-like plans for the ego vehicle in mixed traffic.** [Sierra-Gonzalez et al, ICRA 2018] [Sierra-Gonzalez PhD thesis 2019]



Video: Comparison between demonstrated behavior in test set & behavior induced by the learned model



# Prediction & Decision-making level: Learning Driving Skills for AD



## 2<sup>nd</sup> Step: Motion Prediction & Driving Decisions

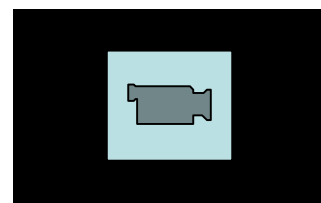


David Sierra-Gonzalez  
Starting Research Position  
Inria Chroma team

- A realistic **Human-like Driver Model** can be exploited to **Predict the long-term evolution** (*10s and beyond*) of traffic scenes [*Sierra Gonzalez et al., ITSC 2016*]
- For the **short/mid-term**, both the **Driver model** and the **Dynamics of the target** provide useful information to **determine future driving behaviors**
- Our probabilistic model fuses **Model-based Predictions & Dynamic evidence** to produce robust **lane change intention estimations** in highway scenes. [*Sierra Gonzalez et al., ICRA 2017*] [*Sierra-Gonzalez PhD thesis 2019*]

Synthesized bird's eye view of the traffic scene & Over vehicles expected intentions

- **Orange bar** => *Probability that the target executes a lane change according to the model (given the traffic situation)*
- **Red bar** => *Final lane change intention probability (fusing model-based prediction & dynamic evidence)*

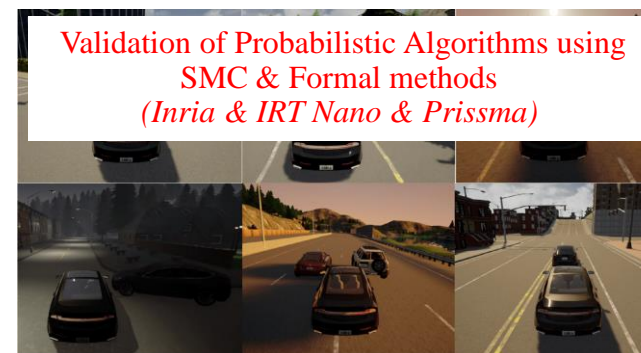
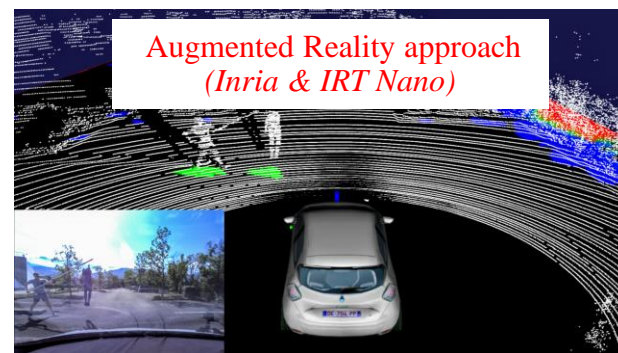


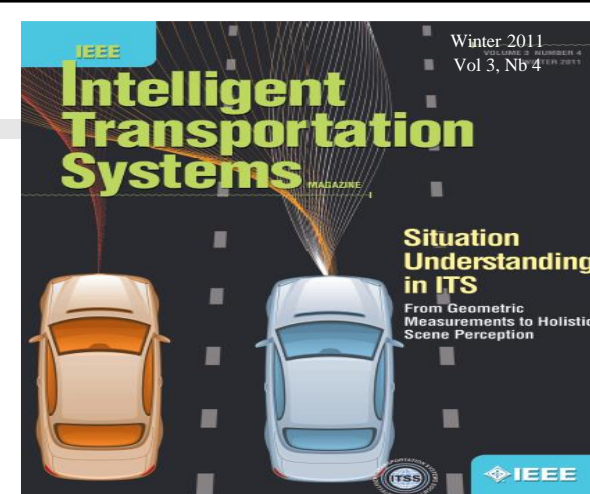
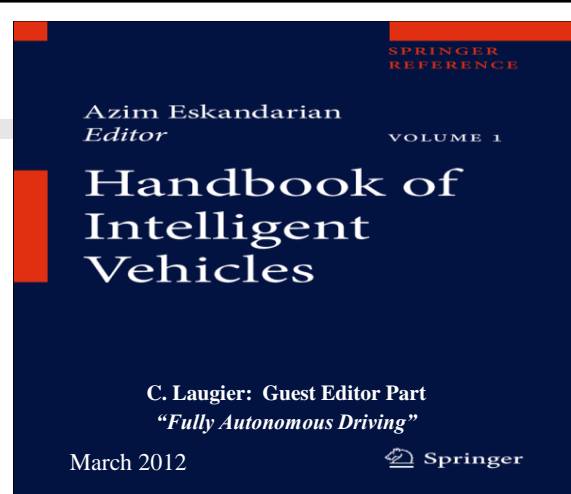
**Video:** Comparison between demonstrated behaviors in test set & behaviors induced by the both the *learned model* and the *dynamics evidence*



# Ongoing R&D work

- **Panoptic & Instance Segmentation + Domain adaptation** (*PhD student, Toyota & CPS4EU EU projects*)
- **Fusing RGB & Event cameras to improve objects detection in dynamic environments & adverse weather or lighting conditions** (*ES3CAP project*)
- **Detection & Tracking of Multiple Objects using DOGMa & Semantic Grids** (*Toyota project*)
- **Distributed Perception & Situation Awareness using Connected Vehicles & Road-Side-Units** (*PhD student, IRT Nanoelec & International industrial company, confidential*)
- **Real-time Planning & Control of Collision Avoidance or Mitigation Trajectories** (*PhD student, Renault*)
- **Validation & Certification framework combining Real Tests (in test-tracks), Realistic Simulation, Augmented Reality and Formal Methods** (*PhD student, IRT Nanoelec & Prisma project*)





# Thank You for attending my keynote speech

## Any Questions or comments ?

=> *Please use IROS 2021 conference system*

