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# Combining Bayesian and AI approaches for Autonomous Driving

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# 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



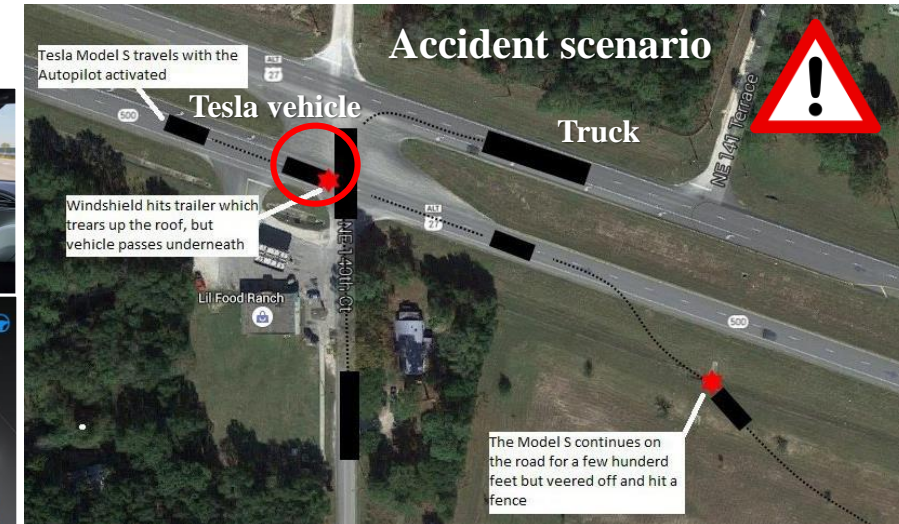
- Millions of miles have been covered in last decade, but **SAFETY** is still not guaranteed ! (*as evidenced by several accidents*)  
=> *Additional R&D work is still mandatory on 2 main research lines:*
  - *Improving “Perception & Decision-making” technologies (in particular for Robustness & Scalability 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



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

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

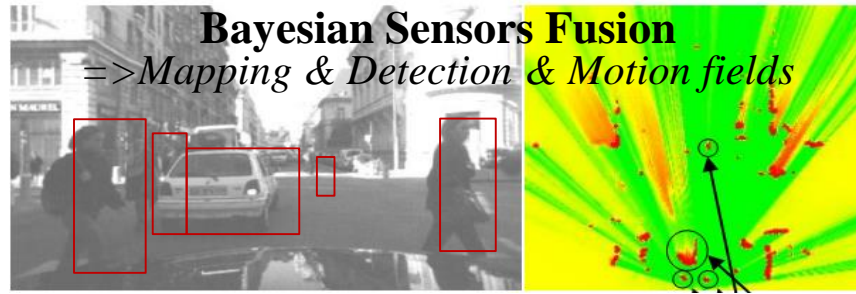
- ❑ **Main constraints:** *Dynamic & Open Environments + Incompleteness & Uncertainty + Sensors limitations & Huge amount of data to process*
- ❑ **Implementation constraints:** *Real-time processing + Software / Hardware integration*
- ❑ **Mixed traffic (Human in the loop):** *A Human-Aware Decision-making 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

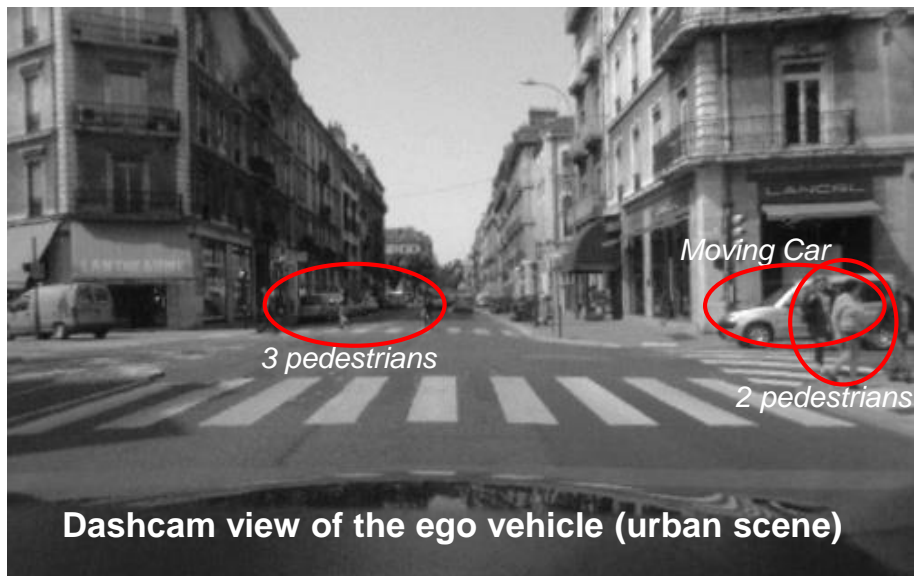
- ✓ Reasoning about Uncertainty & a Time window ⇒ Reasoning on Past & Future (predicted) events
- ✓ Improving robustness using Bayesian Sensors Fusion
- ✓ Interpreting the dynamic scene using Contextual & Semantic information
- ✓ Implementing the system using hardware accelerators (GPU, Multicores, Microcontrollers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





# Dynamic Occupancy Grid & Bayesian Filtering

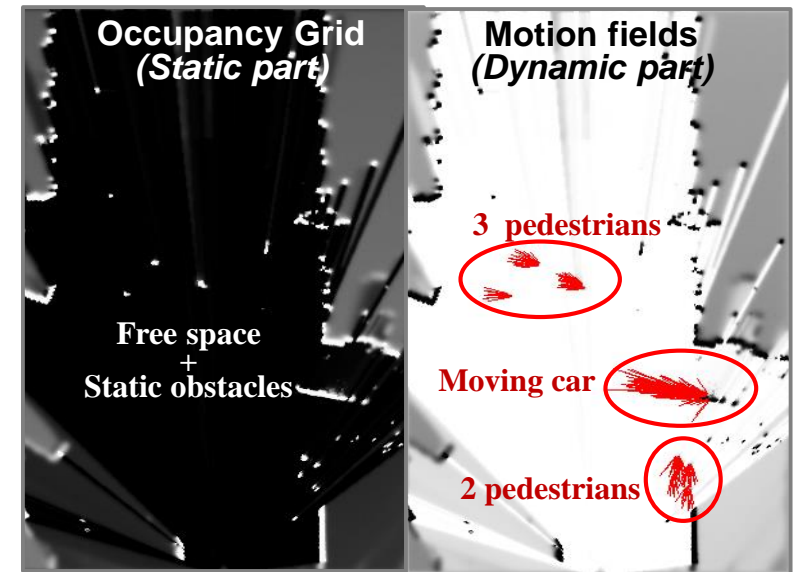
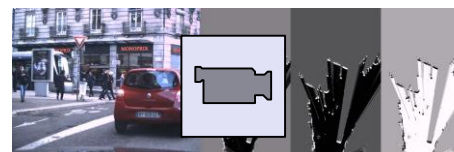
=> Use dynamic information for a better understanding of the observed scene



Sensors data fusion  
+  
Bayesian Filtering  
+  
Extracted Motion Fields



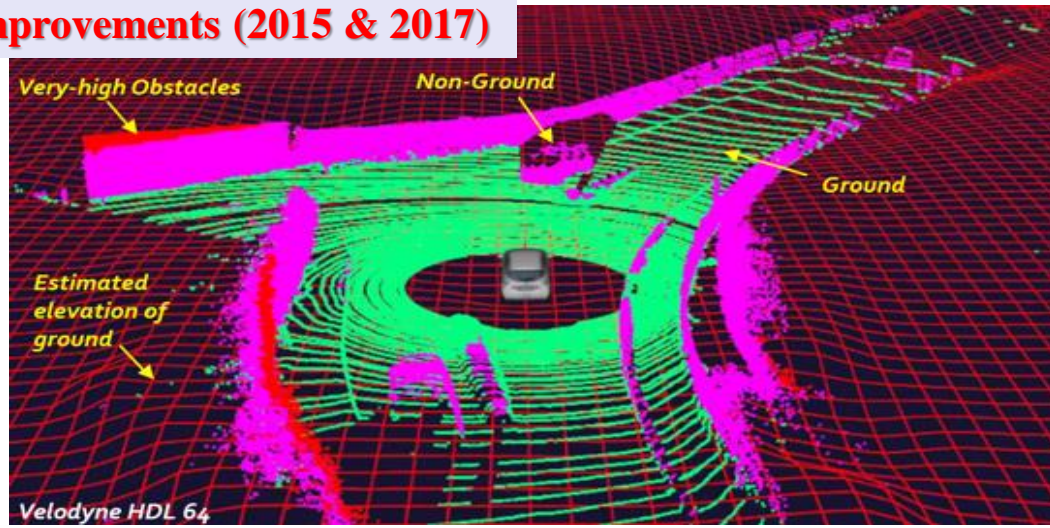
1st Embedded & Optimized version  
(HSBOF, patent 2014)



## Patented system Improvements (2015 & 2017)



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

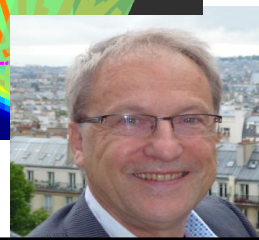
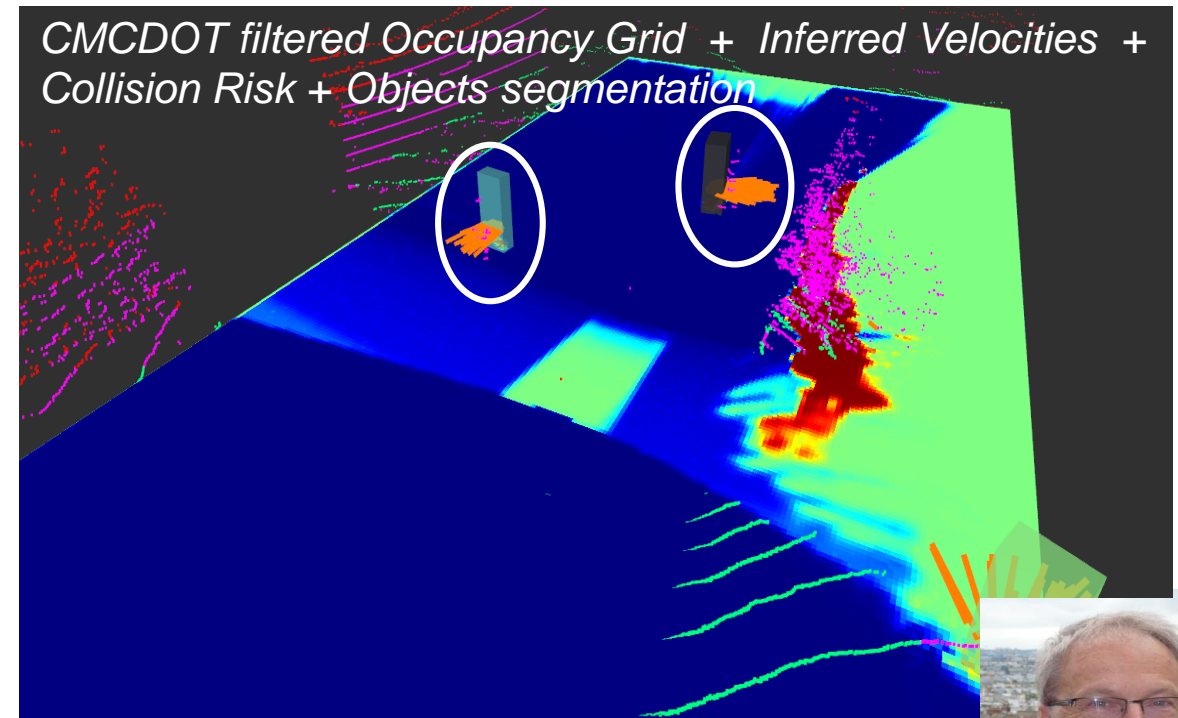
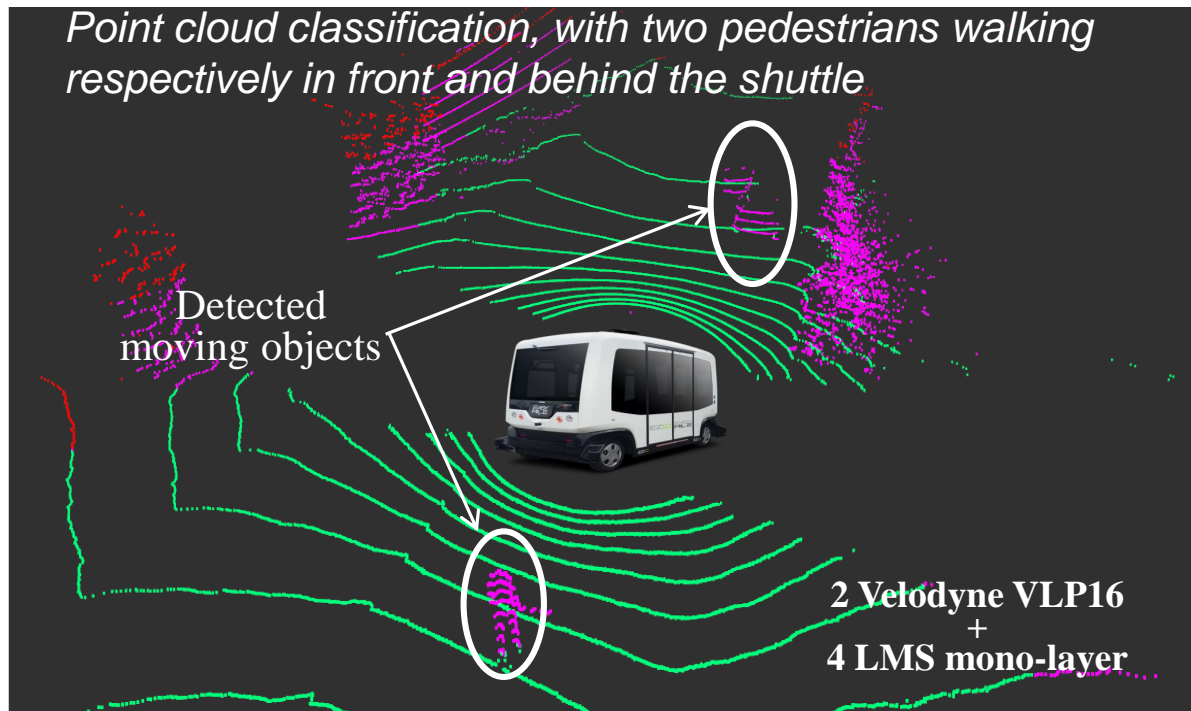
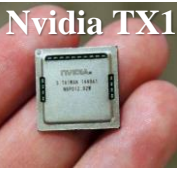


Ground Estimation & Point Cloud Classification  
(patent 2017)



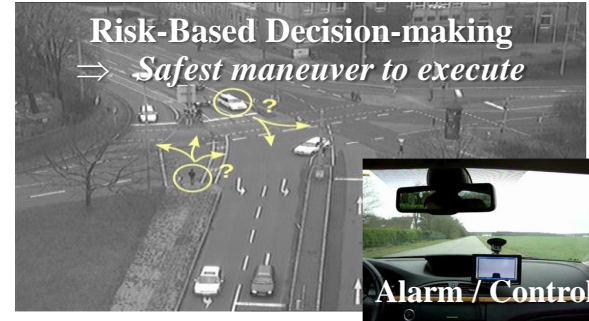
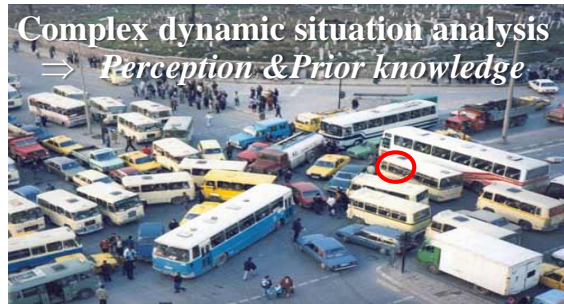


- **POC 2019: Complete system implemented on Nvidia TX1**, and easily connected to the shuttle system network *in a few days* (using ROS)
- **Shuttle sensors data** has been fused and processed in **real-time**, with a successful Detection & Characterization of the **Moving & Static Obstacles**
- **Full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

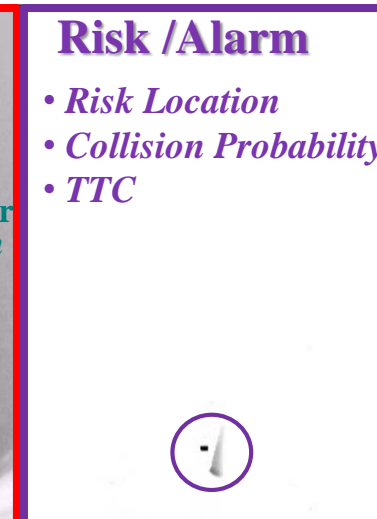
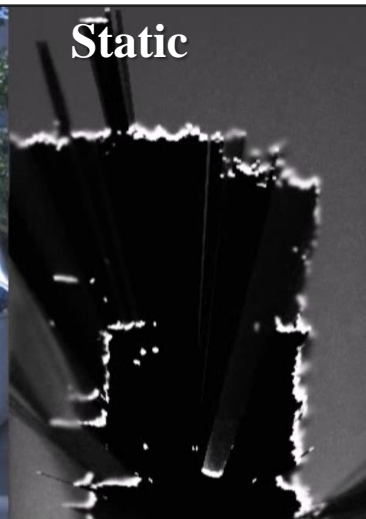
## Main Features of our approach:

- ✓ **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

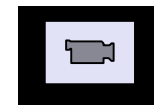
## Experimental results (Urban streets & Test track)



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

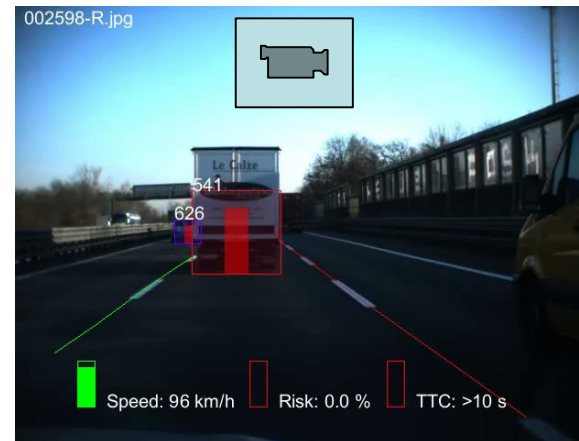
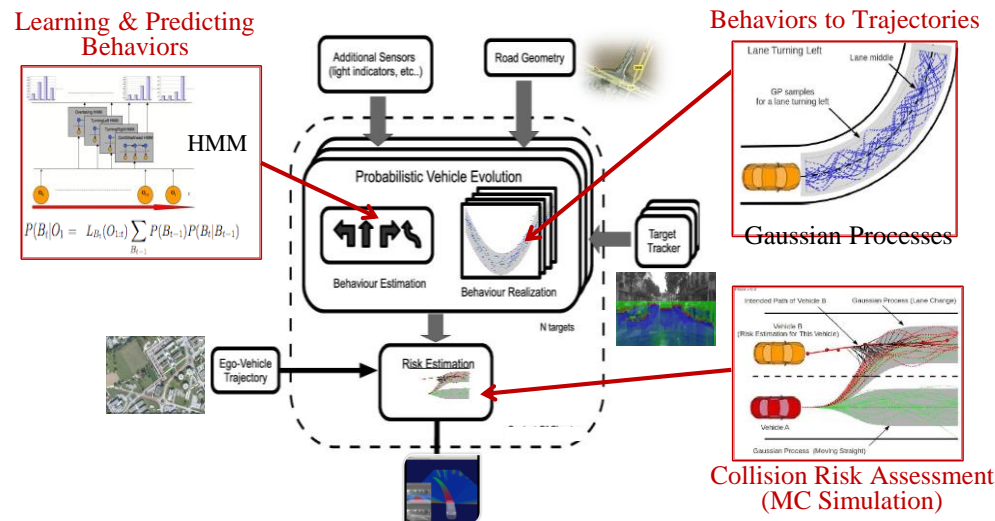


- Video: Short-term C-Risk**
- Yellow => 3s before collision
  - Orange => 2s before collision
  - Red => 1s before collision



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

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



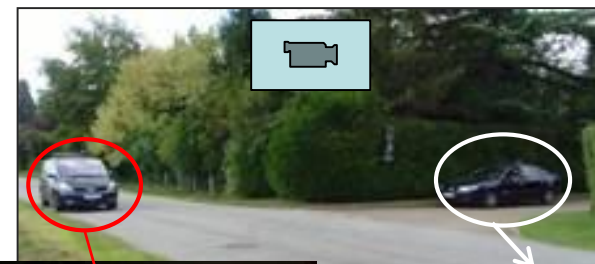
Courtesy Probayes

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

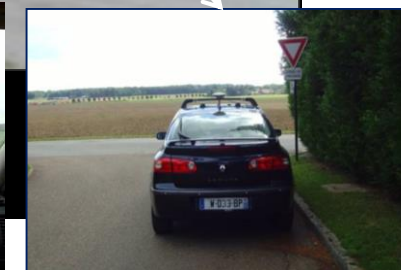
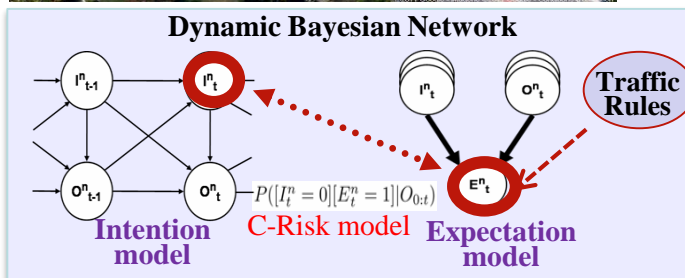
## □ Intention & Expectation (Mixed Traffic & Interactions) => Patents 2012 (Inria - Renault) & 2013 (Inria - Berkeley)



Human-like reasoning



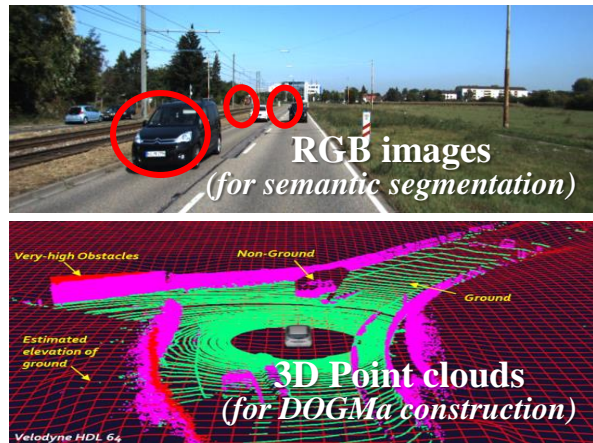
Cooperation still on-going (R&D contracts + PhDs)



# 3rd 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*



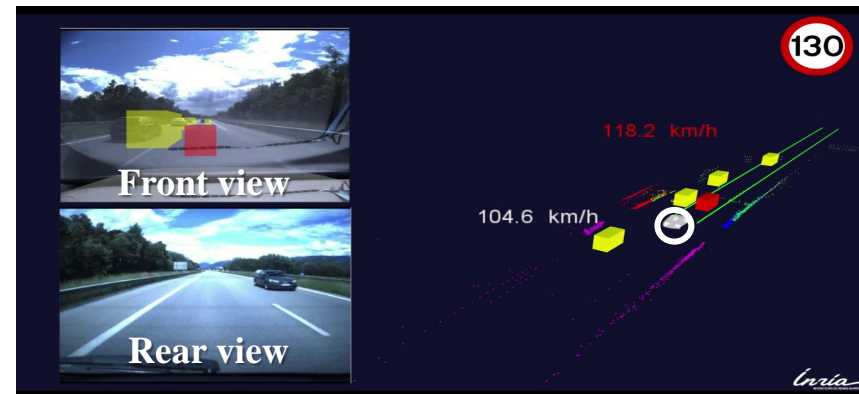
- Unknown
- Building
- Sky
- Road
- Vegetation
- Sidewalk
- Car
- Pedestrian
- Cyclist
- Signage
- Fence
- Free
- Static
- Dynamic

**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**

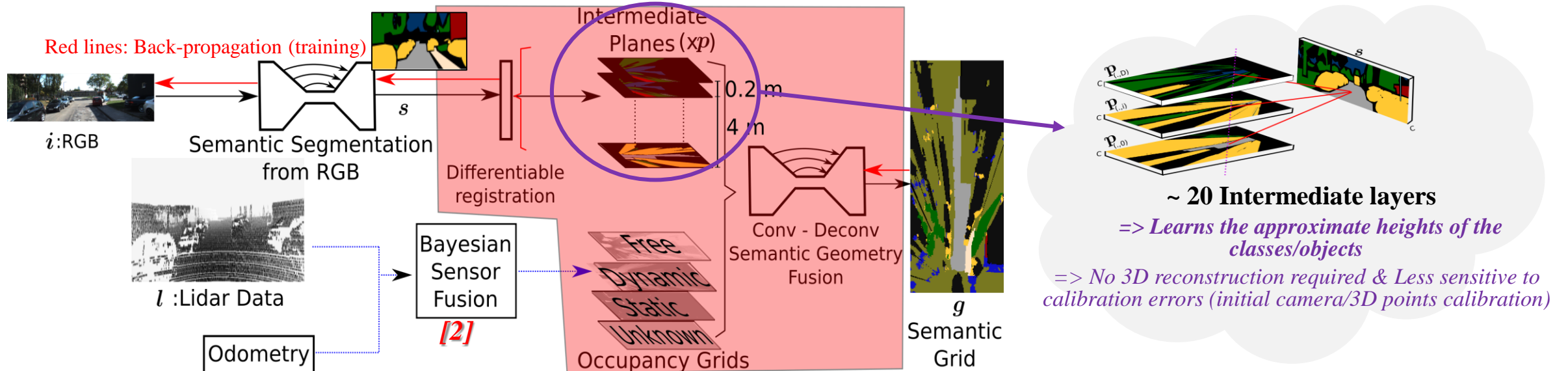
Starting Research Position at Inria Chroma team (2017-21).  
External Collaborator at Inria & Assistant Professor at Ankara Univ (since July 2021)

**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



# Semantic Grids – Experimental Results [1]

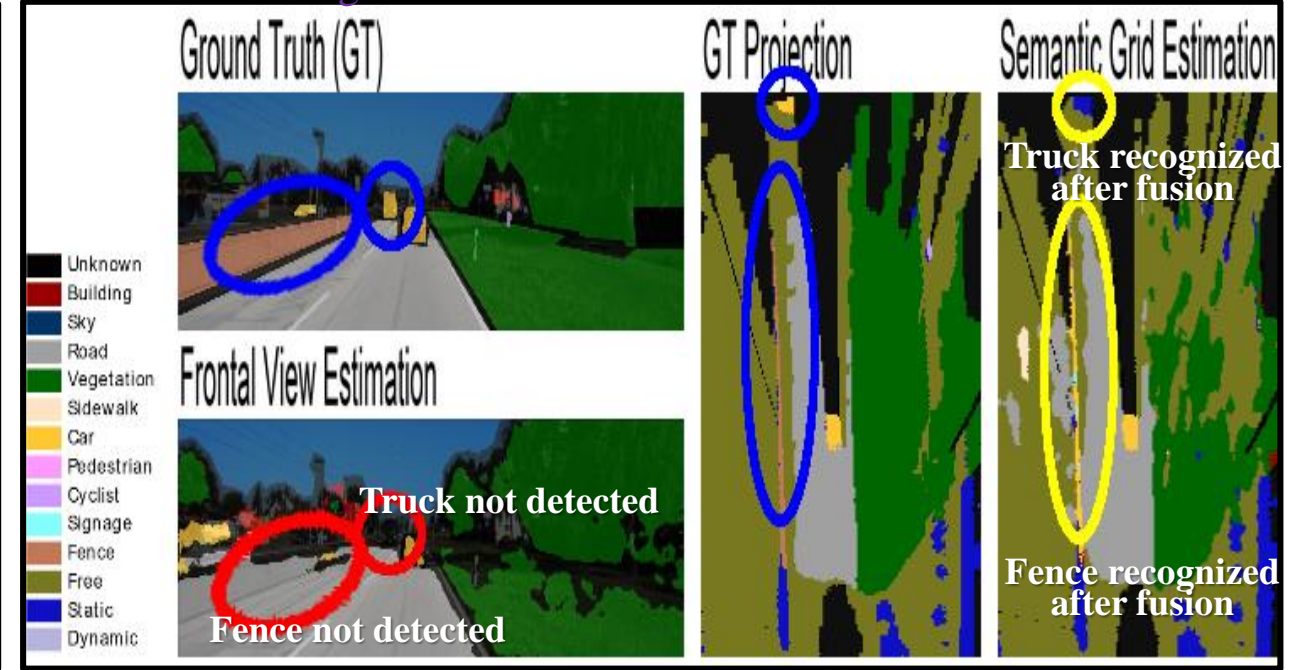
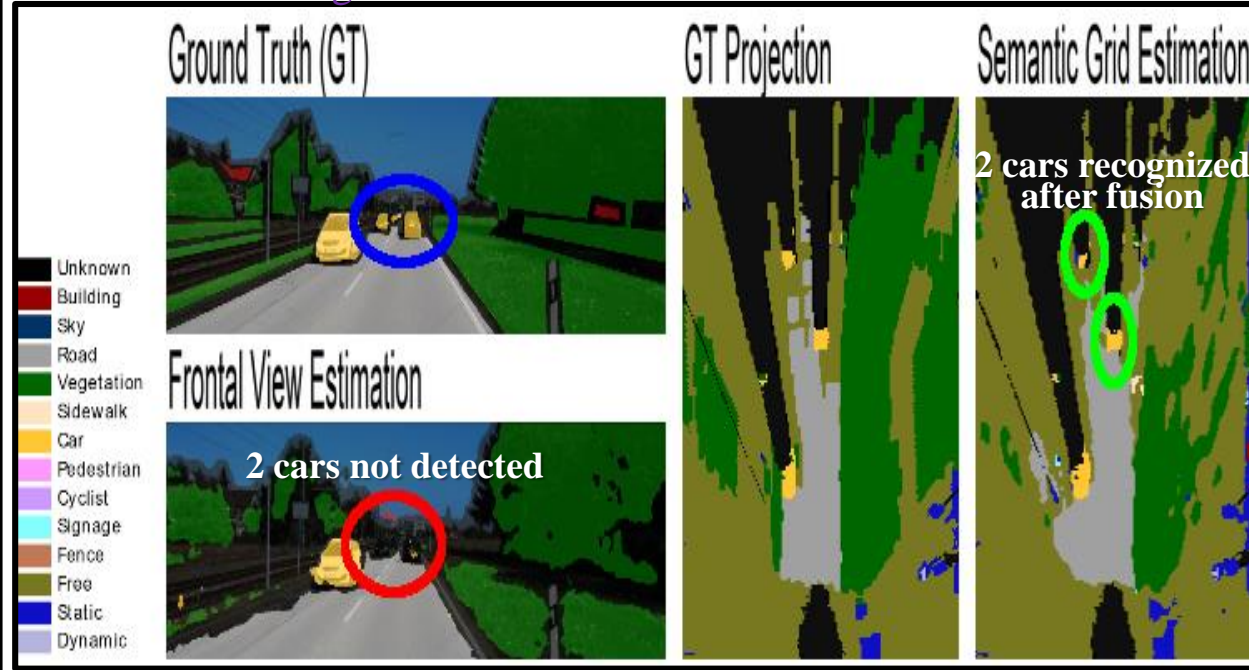
(Using Kitti dataset)

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



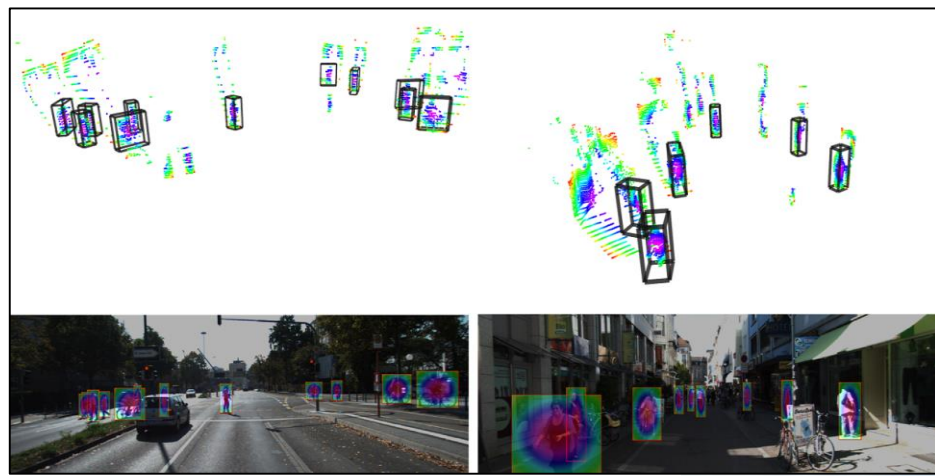
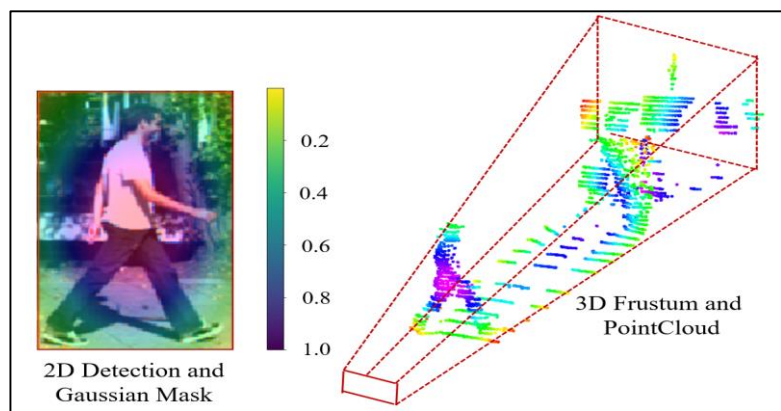
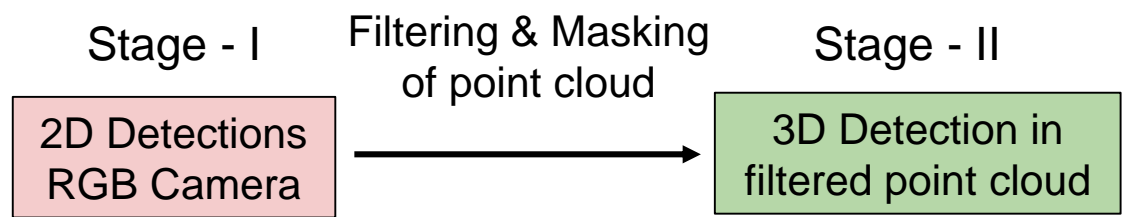
David Sierra-Gonzalez  
Starting Research Position, Inria

**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)



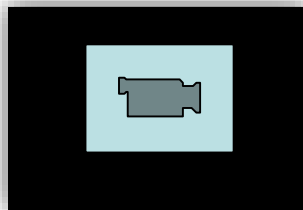
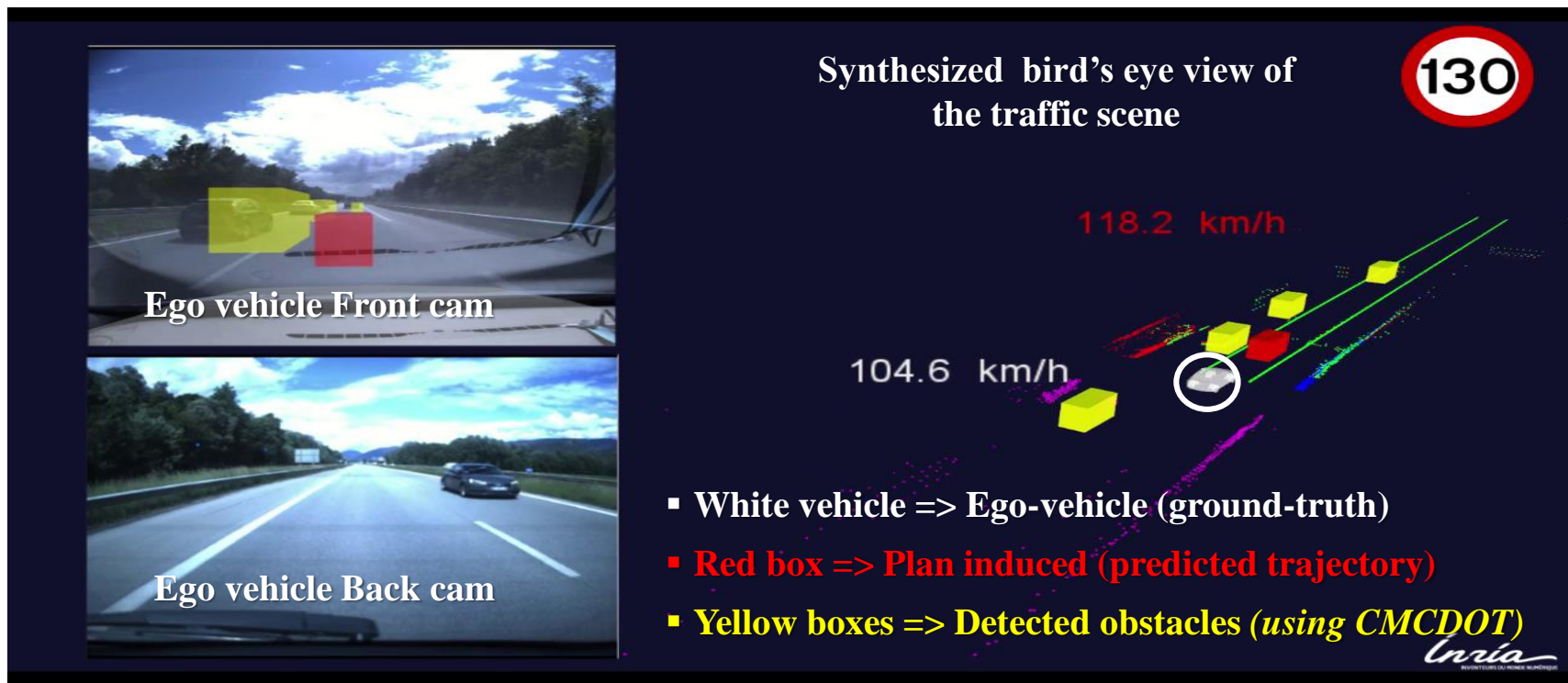
# Prediction & Decision-making level: Learning Driving Skills for AD

## 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

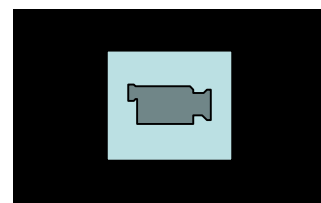


David Sierra-Gonzalez  
Starting Research Position  
Inria Chroma team

- 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)*

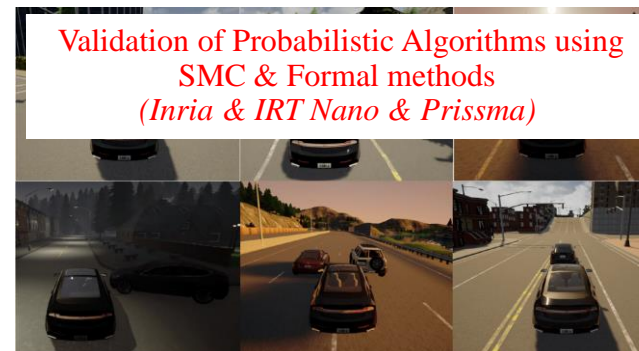
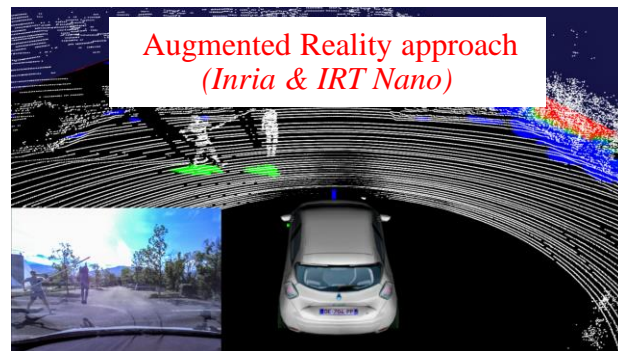


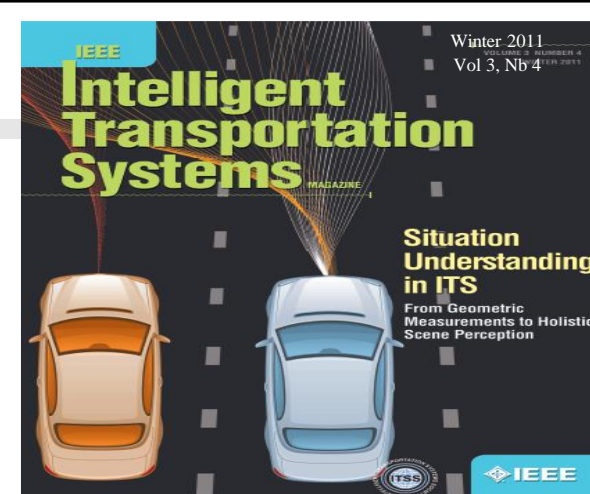
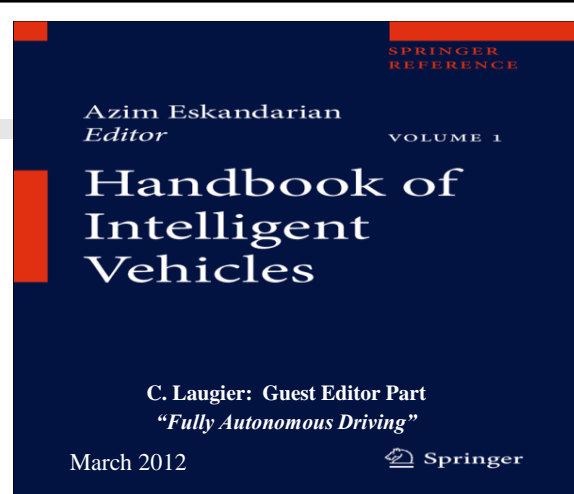
**Video:** Comparison between demonstrated behaviors in test set & behaviors induced by the both the *learned model* and the *dynamics evidence*



# 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*

