

Center for Advanced Transportation Systems

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Outline

- Society and Automobiles
- Research Challenges for Self-Driving Vehicles
- Brief Overview of our Technical Approaches
- Opportunities and Open Problems



Society and Automobiles

- About 1.2 million people die every year in automotive accidents globally
- Traffic delays are expensive.
- Loss of independence and self-esteem of senior and disabled citizens



Transportation Vision



Grand Challenge: Zero automotive fatalities



CMU's "Boss" – DARPA Urban Grand Challenge Winner

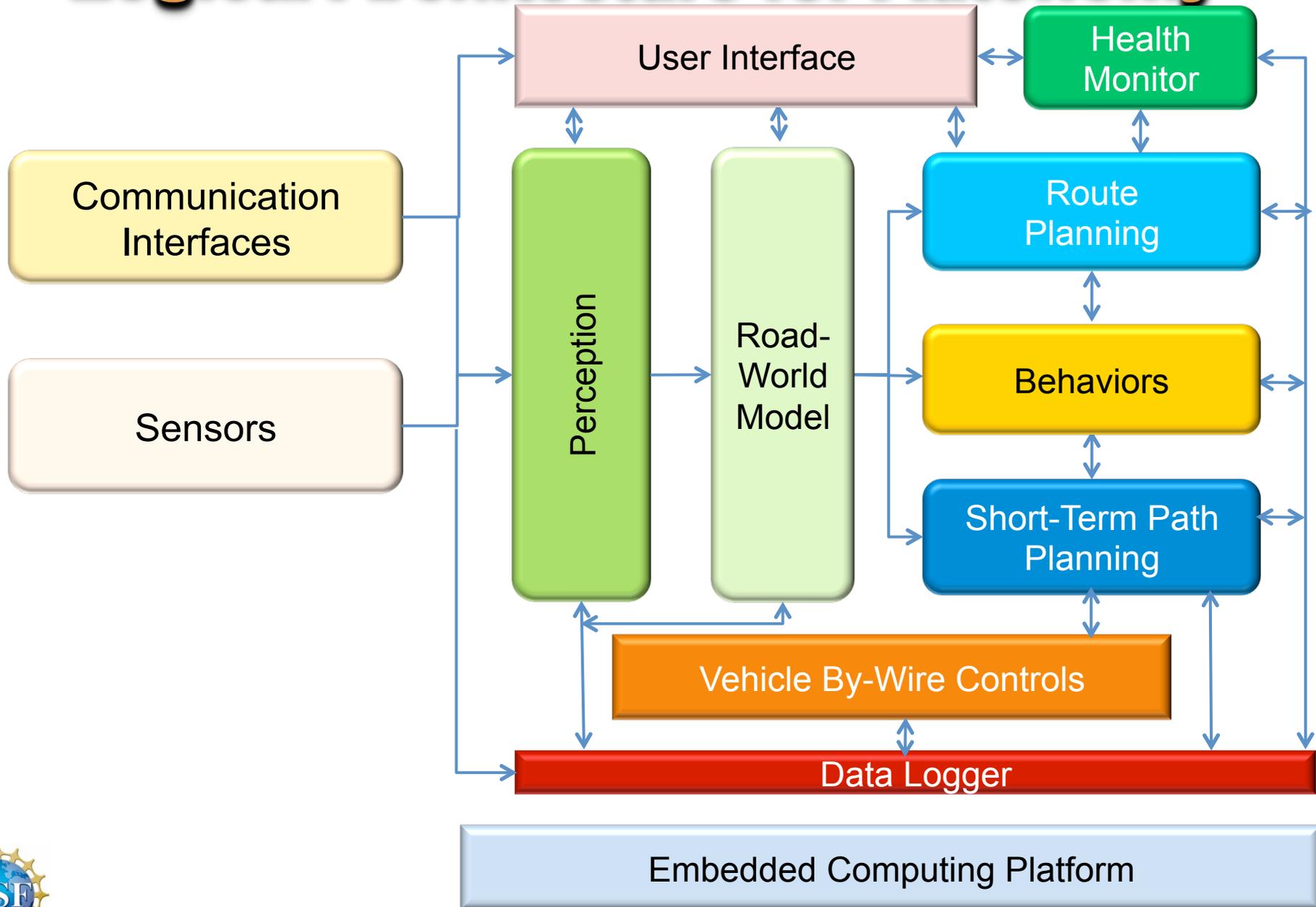


Challenges

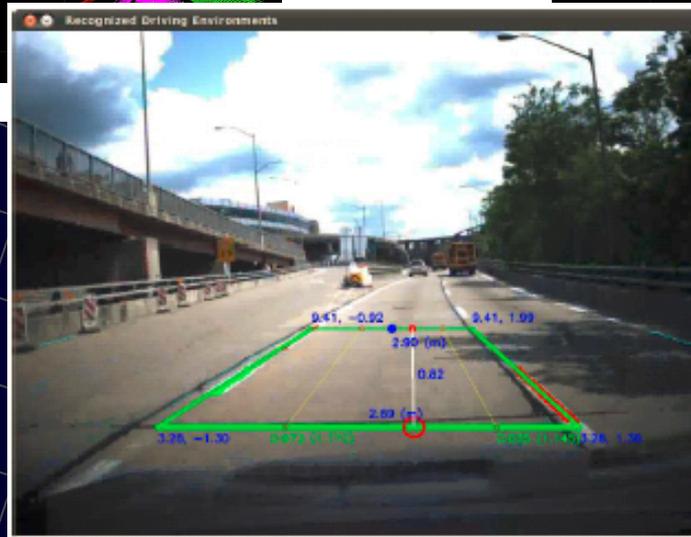
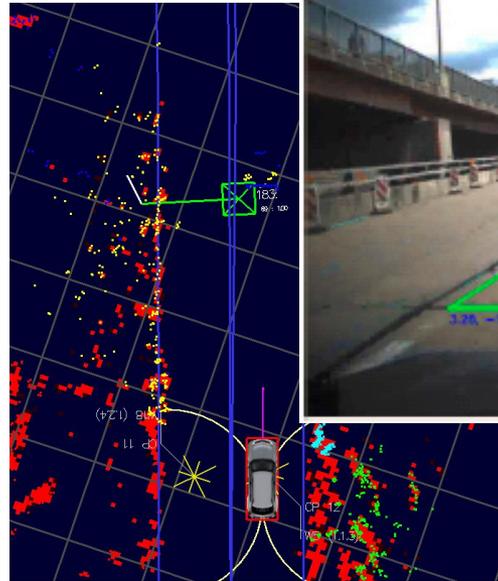
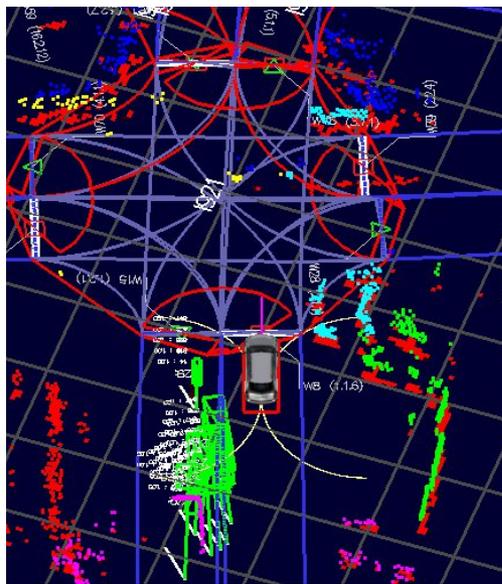
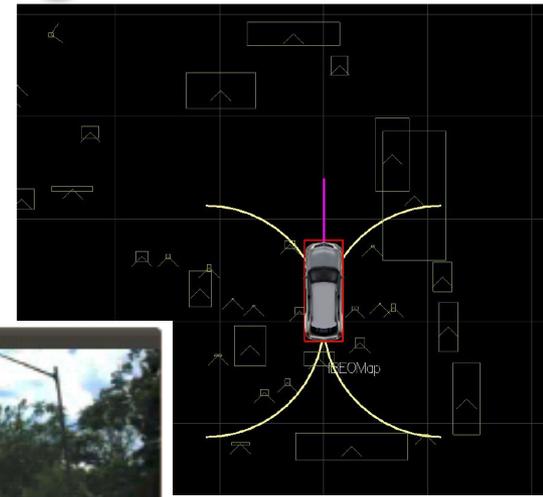
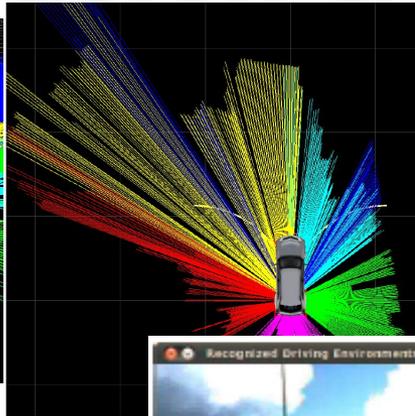
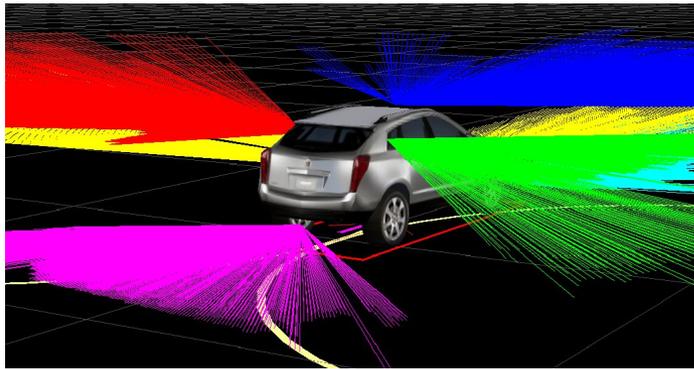
- **Exogenous:** The complexities & **uncertainties of the real world**
 - Weather, lighting, and road conditions; construction; accidents; obsolete information, loss of GPS.
- **Endogenous:** **Online and safe recovery** from failures of sensors, actuators, computing or communications.
 - Mis-calibration, wear and tear, failures.
- **Verification:** How to verify and validate correctness?
- **Interactions:** **Vehicular Networks**
- **Reliability:** cost and maintenance, customer acceptance
- **Human factors**



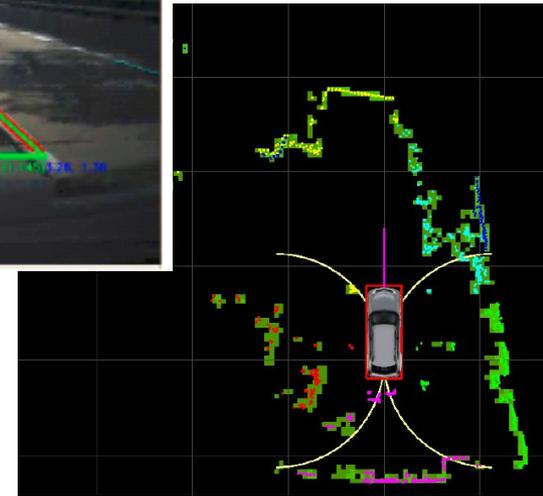
Logical Architecture for Autonomy



Sensor Fusion & Perception



Moving Obstacles



Static Obstacles

Tracking cars at intersections

Tracking cars on roadways

Encounters of the *Daily* Kind



More Encounters



Border and Shoulder Detection



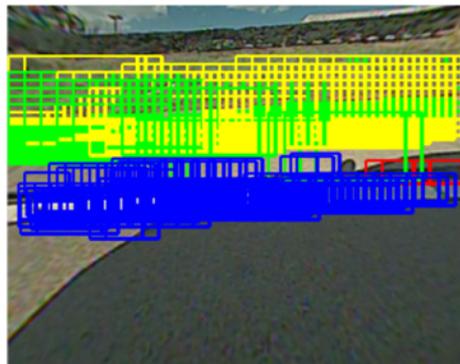
Concrete Barrier



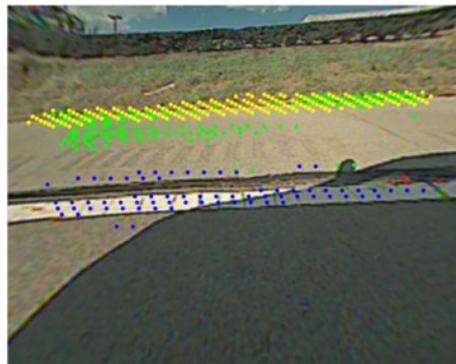
Guard Rail



Soft Shoulder



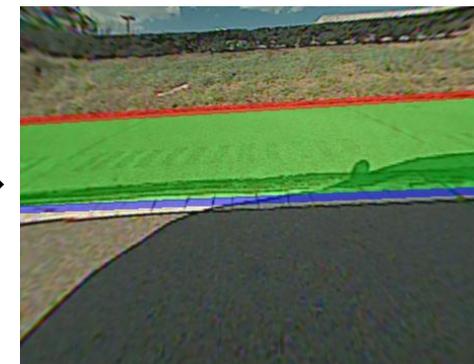
Densely Fired scanning windows



Returned Voting Points



Structured Hough Voting



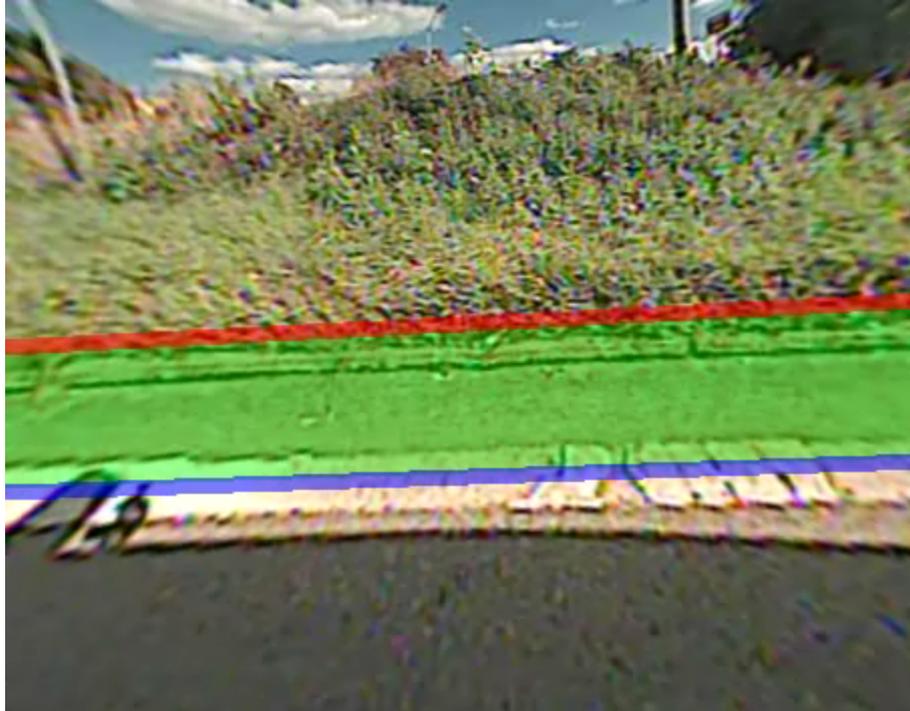
Border / lane-marking hypotheses



Thanks to: Prof. Vijayakumar Bhagavatula, Zhiding Yu

Carnegie Mellon University

Shoulder Detection Result



Verifying Embedded Code

Prof. Ed Clarke and Dr. Sicun Gao

- Our autonomous vehicle is controlled by a large C++ code base (> 450k lines in total).
 - The behavior layer is a very safety-critical part, with 24k lines of C++ code.
 - A combination of numerical computation (difference equations encoding control laws) and logical control.

How do we reason about the code directly?

Using bounded model checking and inductive invariants



Techniques → Tools

Original Code (DistanceKeeper.cc)

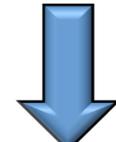
Output Logic Formula

```
// compute the minimum gap as a smooth transition from inside to outside safety zone
double minGapIn_m = 0.0;
double distanceToSafetyPoint = 10.0;
double minSeparationOutsideSafetyZone_m = 20.0;
double minSeparation_m = 10.0;

if(distanceToSafetyPoint > safetyZoneLength_m + minSeparationOutsideSafetyZone_m)
{
    minGapIn_m = minSeparationOutsideSafetyZone_m ;
} else if (distanceToSafetyPoint > safetyZoneLength_m) {
    // scale from outside to inside as we approach the safety zone
    minGapIn_m = minSeparation_m *
        (distanceToSafetyPoint - safetyZoneLength_m) /
        minSeparationOutsideSafetyZone_m * (minSeparationOutsideSafetyZone_m - minSeparation_m);
} else {
    minGapIn_m = minSeparation_m ;
}
```

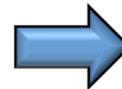
```
test]$ ../main.native dk_part.i
pIn0 := 0.0), (safetyZoneLength0 := 10.0), (distanceToSafetyPoint0
paration0 := 10.0)], ∨ [∧ [distanceToSafetyPoint0 > safetyZoneLe
parationOutsideSafetyZone0]], ∧ [!(distanceToSafetyPoint0 > safet
tanceToSafetyPoint0 > safetyZoneLength0, (minGapIn1 := minSeparati
arationOutsideSafetyZone0) * (minSeparationOutsideSafetyZone0 - mi
ngth0), (minGapIn1 := minSeparation0))]]], true]

tyPoint: 0,
0,
outsideSafetyZone: 0,
th: 0
```



SMT solver dReal

available at
www.cs.cmu.edu/~sicung



```
DistanceKeeper.cc (~/verihy) - GVIM2
File Edit Tools Syntax Buffers Window Help
}
if(lastTrackingTime_ != boost::posix_time::not_a_date_ti
me)
{
    // run the control loop
    // Control loop Parameters
    const double K = trackingGain; // Proportional gain
    on gap error
    const double v0_max = 13.4; // v0 max = 30 mph

    // Acceleration Scaling Parameters
    const double acc_min=1.0;
    const double acc_max=4.0;
    const double acc_K=0.2;

    // Control loop outputs
    double v0_cmd=0.0;
    double acc_cmd=1.0;

    // Determine distance to the target vehicle

    // Start with the last tracking distance
    double bumperDistance = trackingDistance_m;
    double bumperSpeed mps = 0.0;
    // use the real distance if available
    if(trackingBumper_)
    {
        if(!useDistanceToLeadVehicle_)
        {
            RecVector2D bumperToBumperV(trackingBumperPo
se_getPoint() - frontBumperPose->getValue().getPoint());
            bumperDistance = bumperToBumperV.length();
            bumperSpeed_mps = trackingBumperSpeed_mps;
        } else {
            140,17 55%
```

```
sicung@borelsrc
File Edit View Search Terminal Help
dk_part.c:54: Warning: Body of function main falls-th
rough. Adding a return statement
[sicung@borel src]$ ../main.native test/dk_part.i
∧ [∧ [defaultAccel0 := 3.1415], (frontBumperSpeed mps0
:= 3.1415)], ∨ [∧ [frontBumperSpeed mps0 < 0.05, (frontB
umperSpeed mps1 := 0.0)], ∧ [!(frontBumperSpeed mps0 < 0.
05), frontBumperSpeed mps1 := frontBumperSpeed mps0]], ∧
[(minGapIn_m0 := 0.0), (distanceToSafetyPoint0 := 10.0), (
minSeparationOutsideSafetyZone_m0 := 20.0), (minSeparati
on_m0 := 10.0), (vehicleLength_m0 := 2.0), (vehicleRespons
eTime_s0 := 0.1), (safetyZoneLength_m0 := 10.0)], ∨ [∧
[distanceToSafetyPoint0 > safetyZoneLength_m0 + minSeparat
ionOutsideSafetyZone_m0, (minGapIn_m1 := minSeparationOut
sideSafetyZone_m0)], ∧ [!(distanceToSafetyPoint0 > safet
yZoneLength_m0 + minSeparationOutsideSafetyZone_m0), ∨ [
∧ [distanceToSafetyPoint0 > safetyZoneLength_m0, (minGapI
n_m1 := minSeparation_m0 + ((distanceToSafetyPoint0 - saf
etyZoneLength_m0) / minSeparationOutsideSafetyZone_m0) *
(minSeparationOutsideSafetyZone_m0 - minSeparation_m0))]]
], ∧ [!(distanceToSafetyPoint0 > safetyZoneLength_m0), (mi
nGapIn_m1 := minSeparation_m0)]]], ∧ [(minGapOut_m0 :=
```

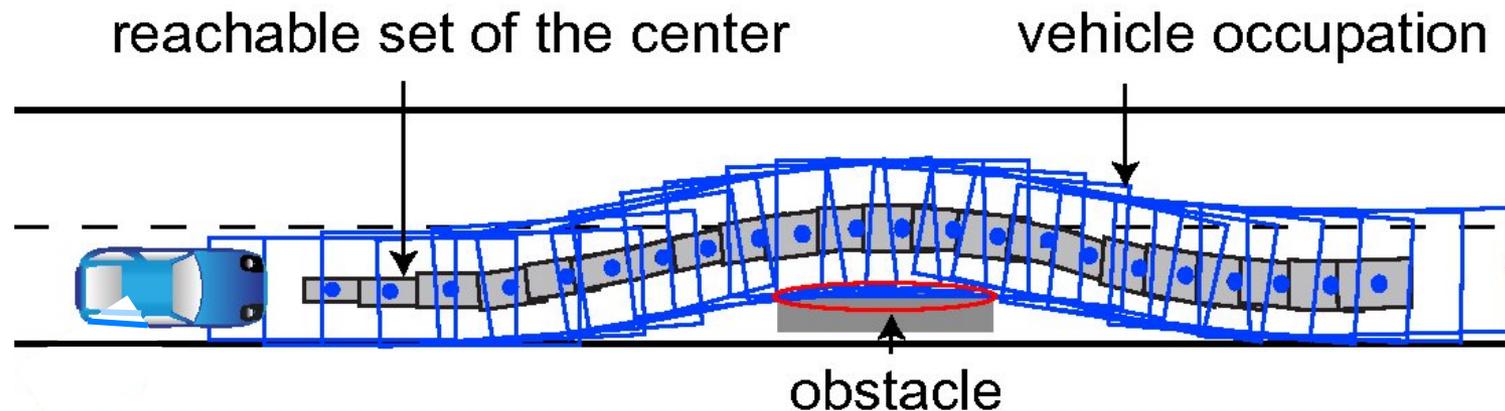
```
sicung@borel~/dReal
File Edit View Search Terminal Help
x6 is in: [-0.88225, -0.66404];
x7 is in: [-1.174, -0.8];
x8 is in: 0;
x9 is in: 0
[conflict detected]
Solved in 20ms
-----
The formula is unsatisfiable.
-----
Result returned by the dReal solver. Version: 0.1. Release
Date: March 2012.
[sicung@borel ~/dReal]$
```

Threat Assessment

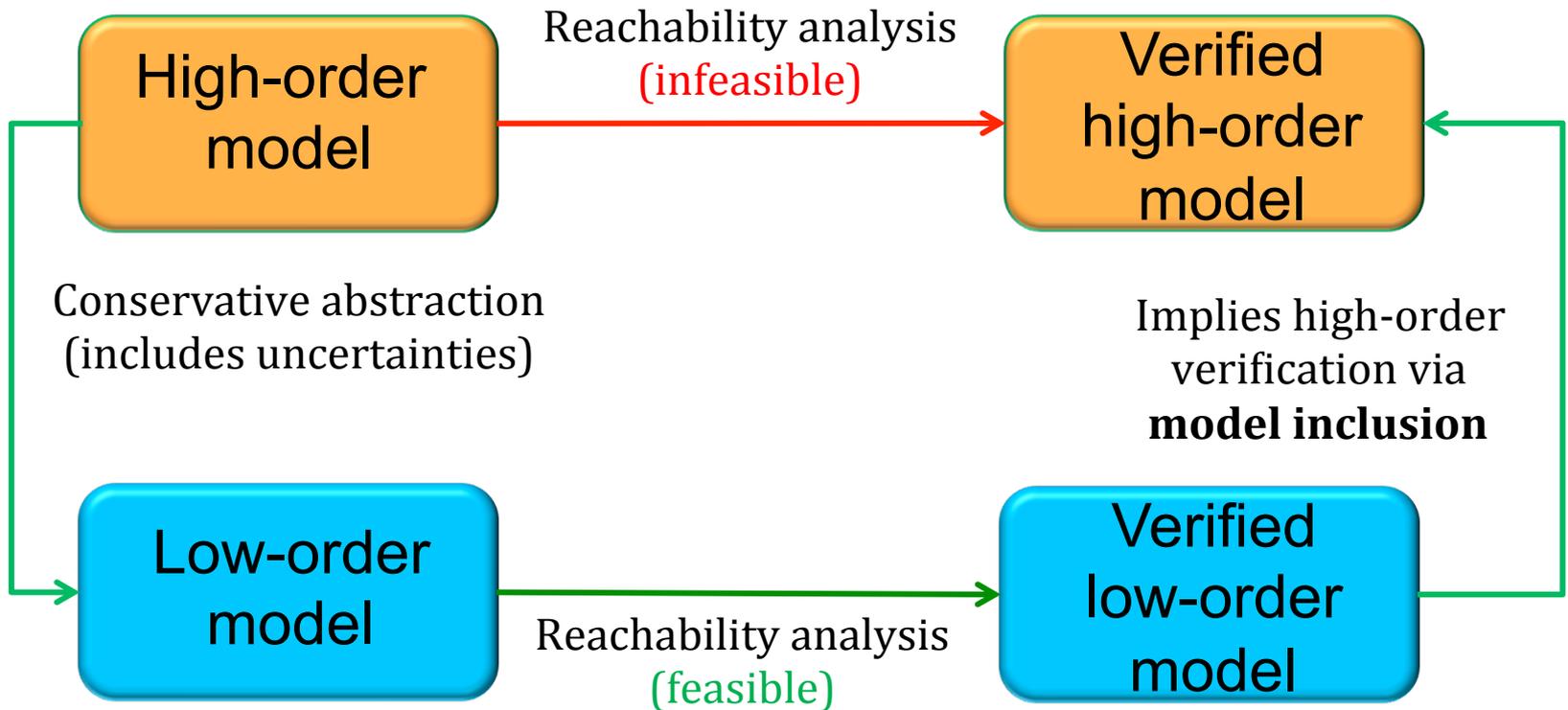
Autonomous vehicles cannot perfectly follow planned trajectories due to

- Modeling uncertainties
- Uncertain measurements
- Disturbances

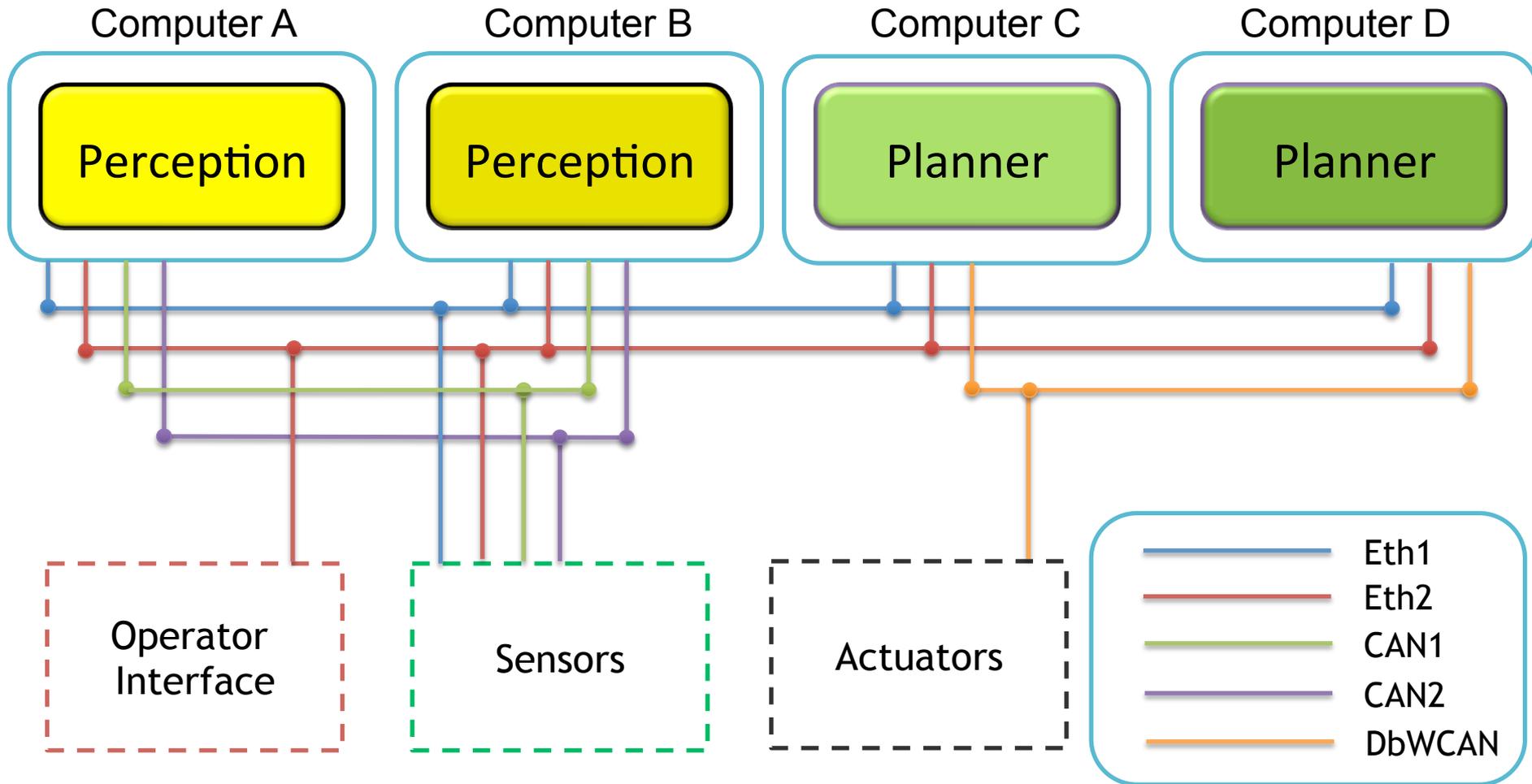
Objective: Guarantee safety when bounds on uncertainties are known



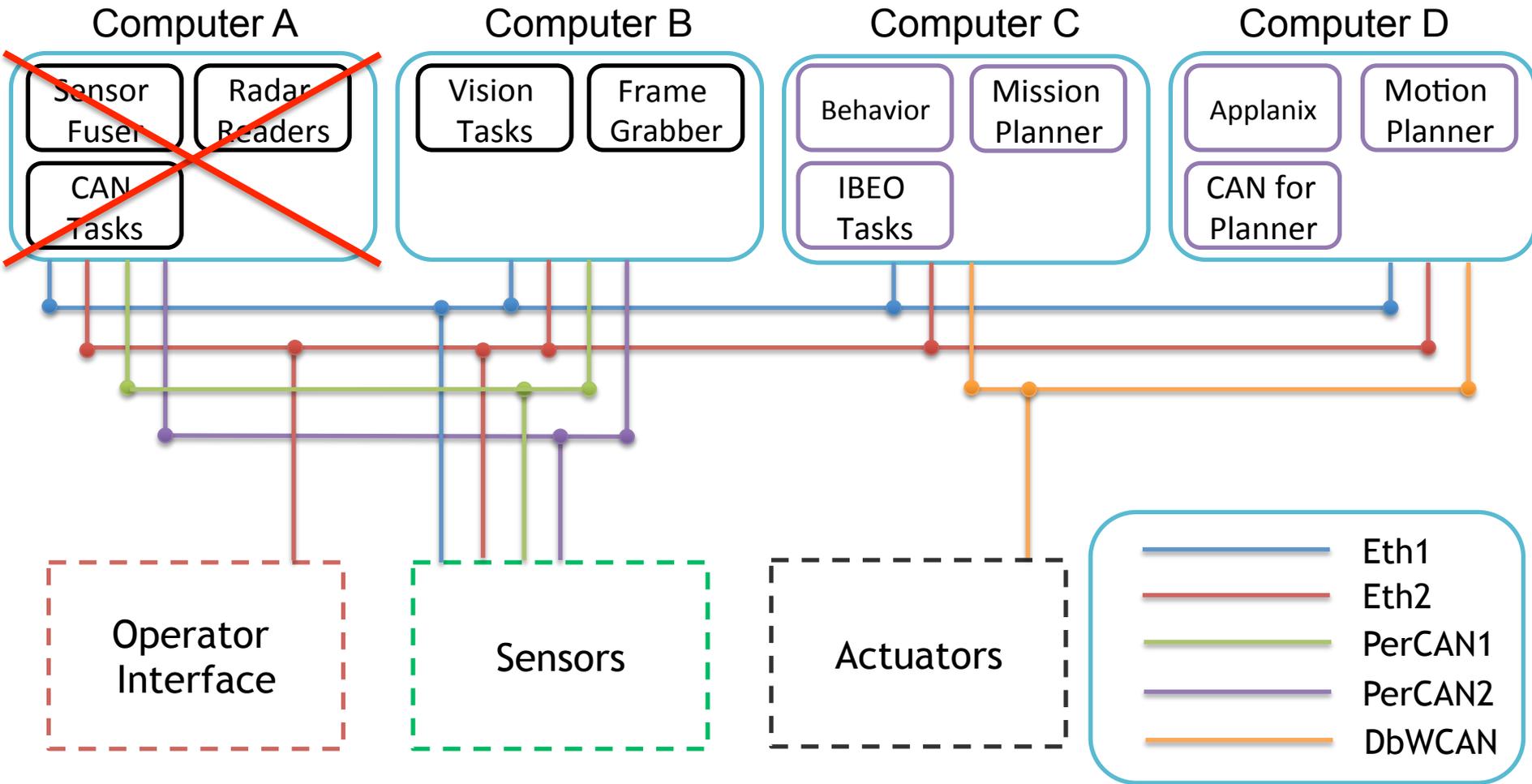
Safety Verification



Dependability

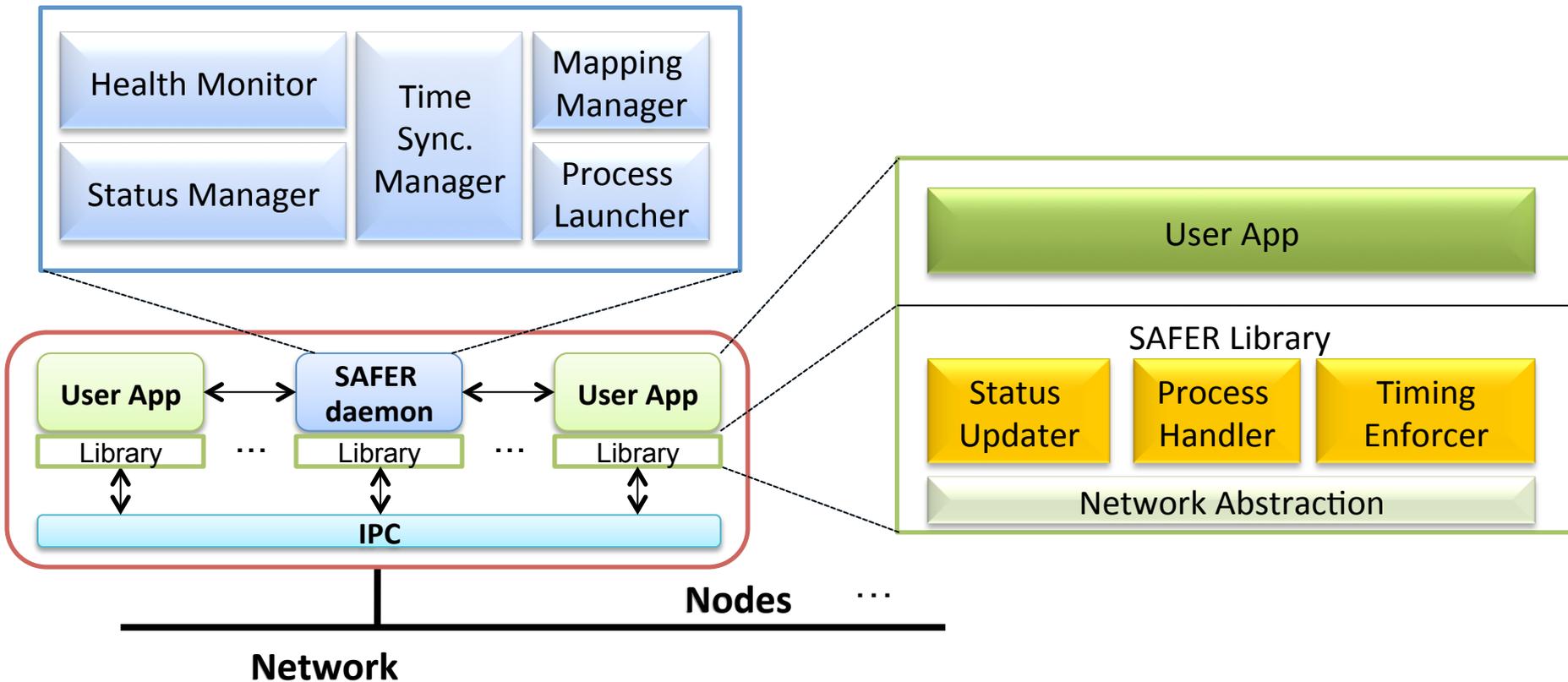


Task → ECU Mapping



The car becomes blind

SAFER Real-Time Dependability Architecture



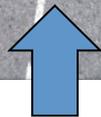
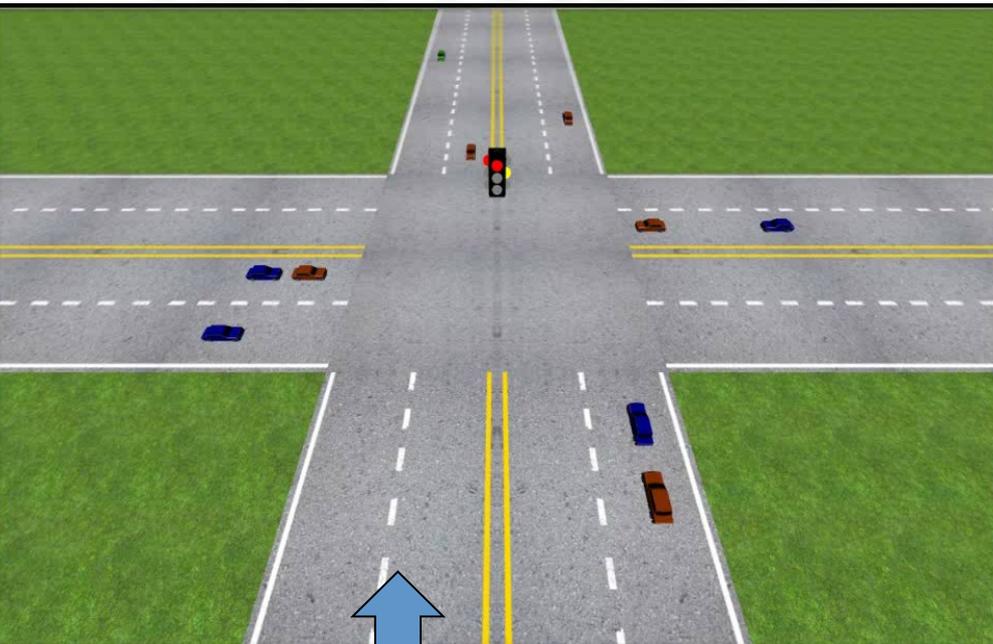
How/what do we gracefully degrade?
How do we re-deploy existing resources?



Intersection Protocols

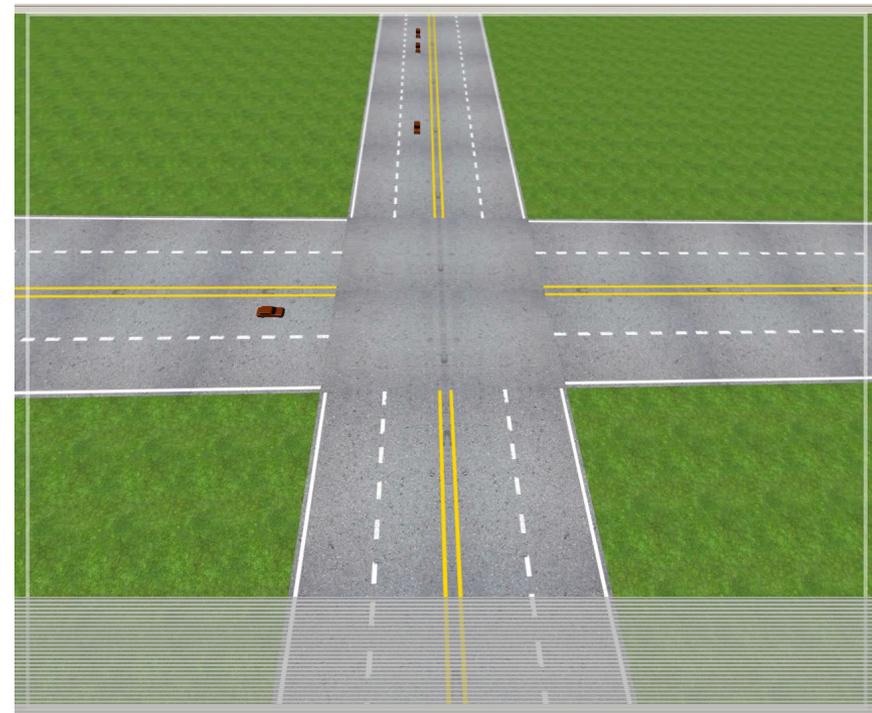
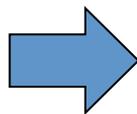


V2V Protocols

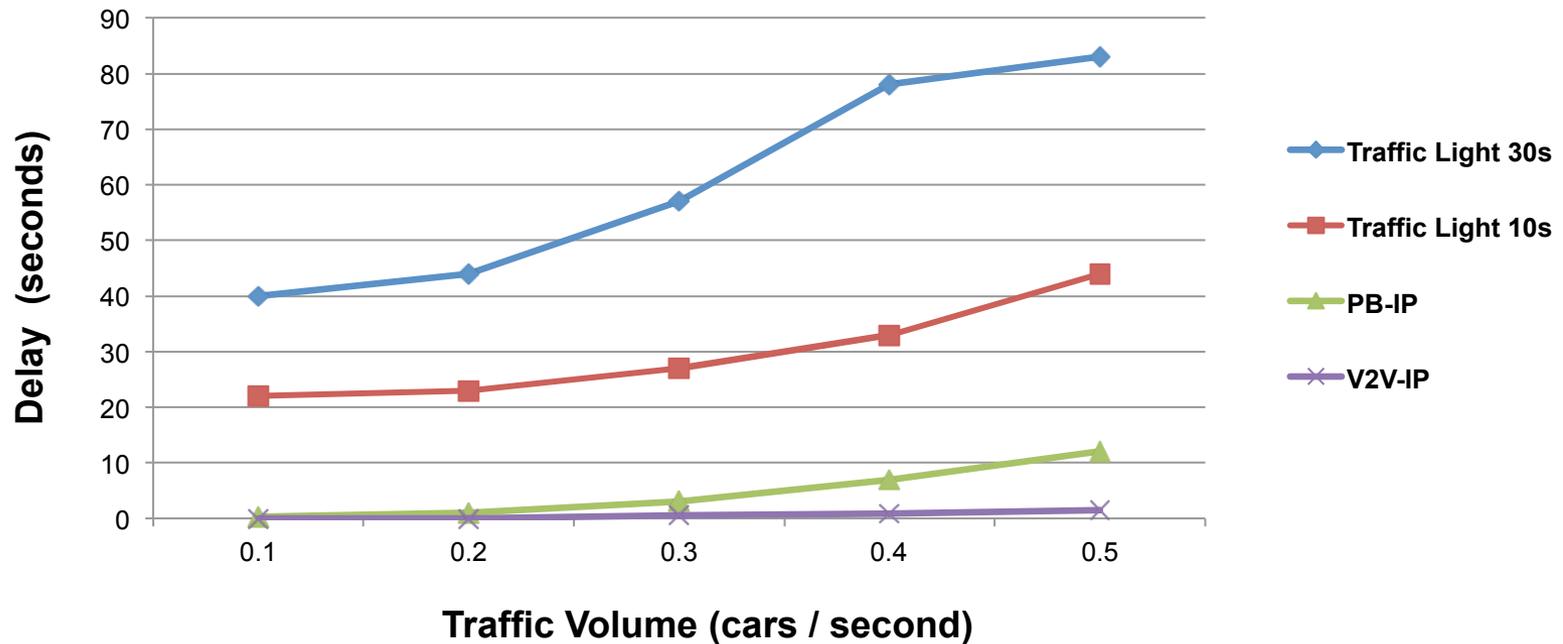


With
Traffic Lights

Using V2V



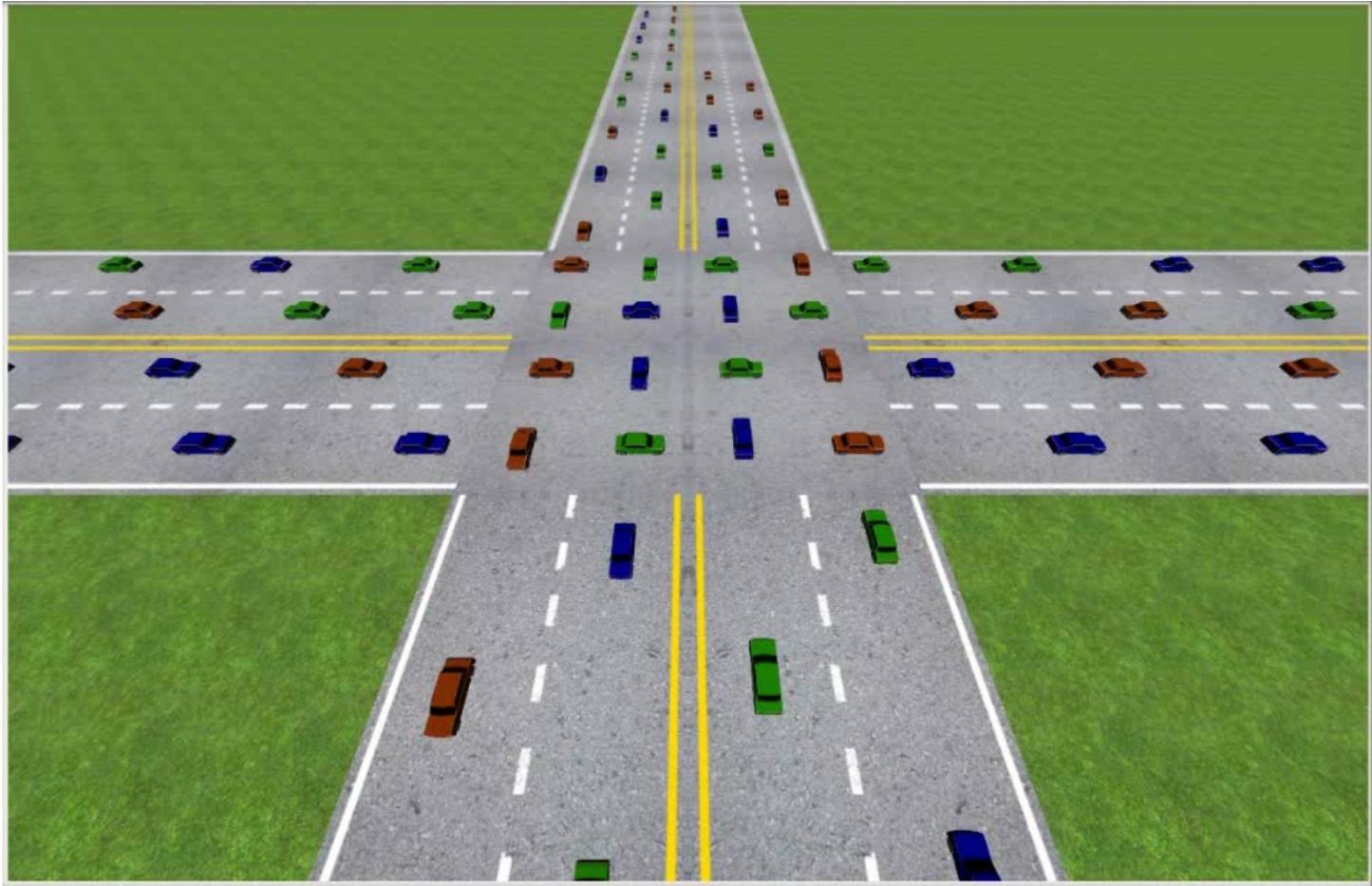
Simulation Results



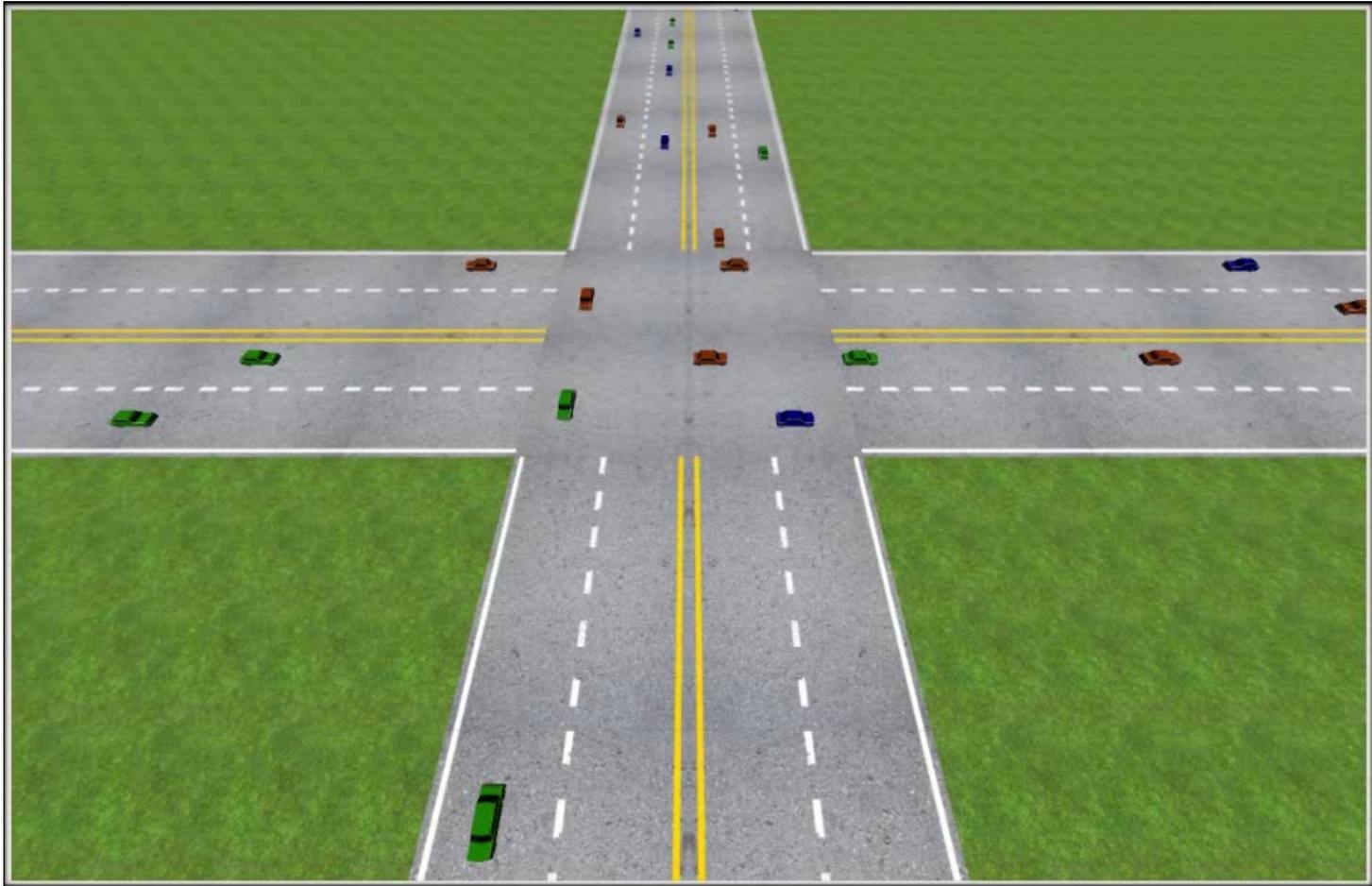
- 100% market penetration of autonomous vehicles
- Overall performance improvements over traffic light with green light duration of 10 seconds:
 - PB-IP: 77.65%
 - V2V-IP: 83.27%



The Optimal Ballroom Protocol



A Spatio-Temporal Intersection Protocol



Feasibility and Road Worthiness



Autonomous Cadillac SRX



SRX Interior



Public Roads/Highways

Bill Shuster, Chairman, US House Transportation Committee in our Self-Driving Car

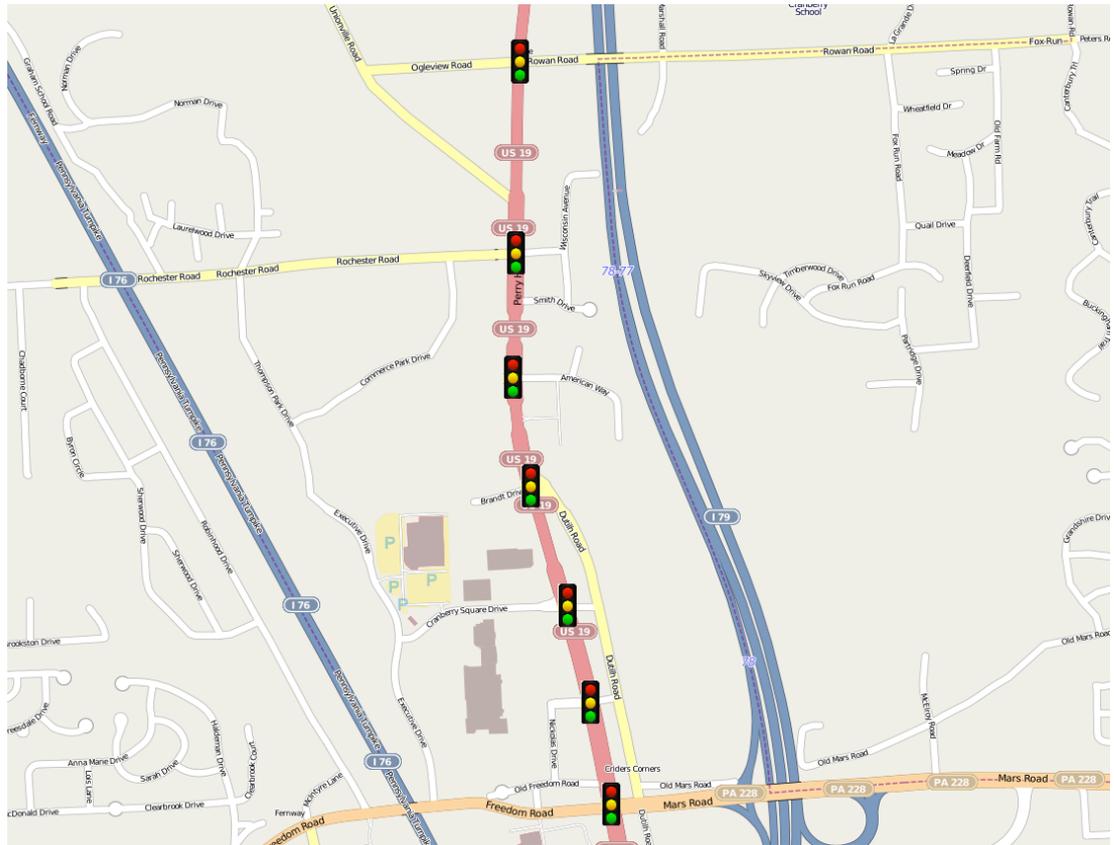


Self-Driving on Urban Roads



V2I Infrastructure near Pittsburgh

- **Cranberry Township, PA**
- Located 20 miles north of Pittsburgh, PA
- 1.8 mile stretch along Rt. 19 corridor
- 11 intersections are instrumented





THIS IS BIG: A ROBO-CAR JUST DROVE ACROSS THE COUNTRY



The Two Sides of Humans

Super Intelligence

- The **Vision** system
 - Human eye: very high resolution with depth info, iris/aperture control, focus
- The **(Re)cognition**
 - Near-insatiable
 - Identical
 - Learn from
- **(Unreasonable) Logic**
 - Logical reasoning
 - Specialized
 - Spatial awareness
 - Intuition
 - Adaptable (no hard-coded rules)



Fundamental Weaknesses

- **Distractability**
 - Dozing off, conversations, diversion of interest, intoxication

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Coordinated sensing & actuation

- Interactions: eye contact, social exchanges, game theory



Challenges → Opportunities

- Proving correctness
 - Massive interactions among complex layers

- Sensing (perception)

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- Gracful degradation and actuator adaptation

- Cooperation among vehicles and with infrastructure

- What about availability?

