Localizing Ground-Penetrating Radar Deep Dive

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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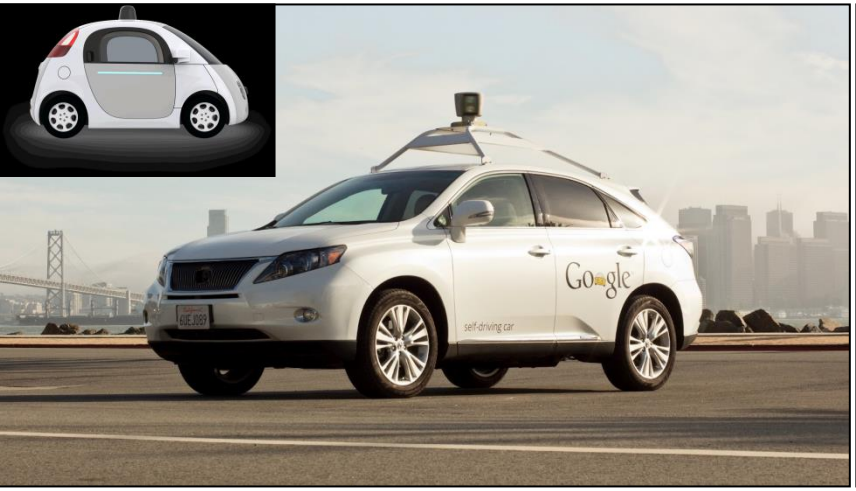
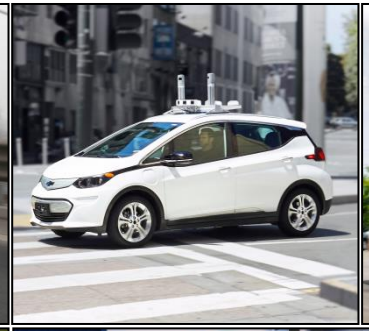
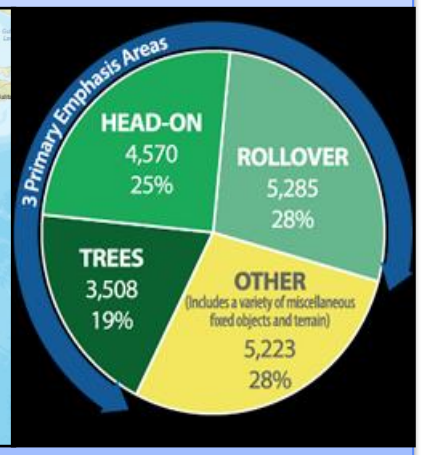
Today's Autonomous Vehicles



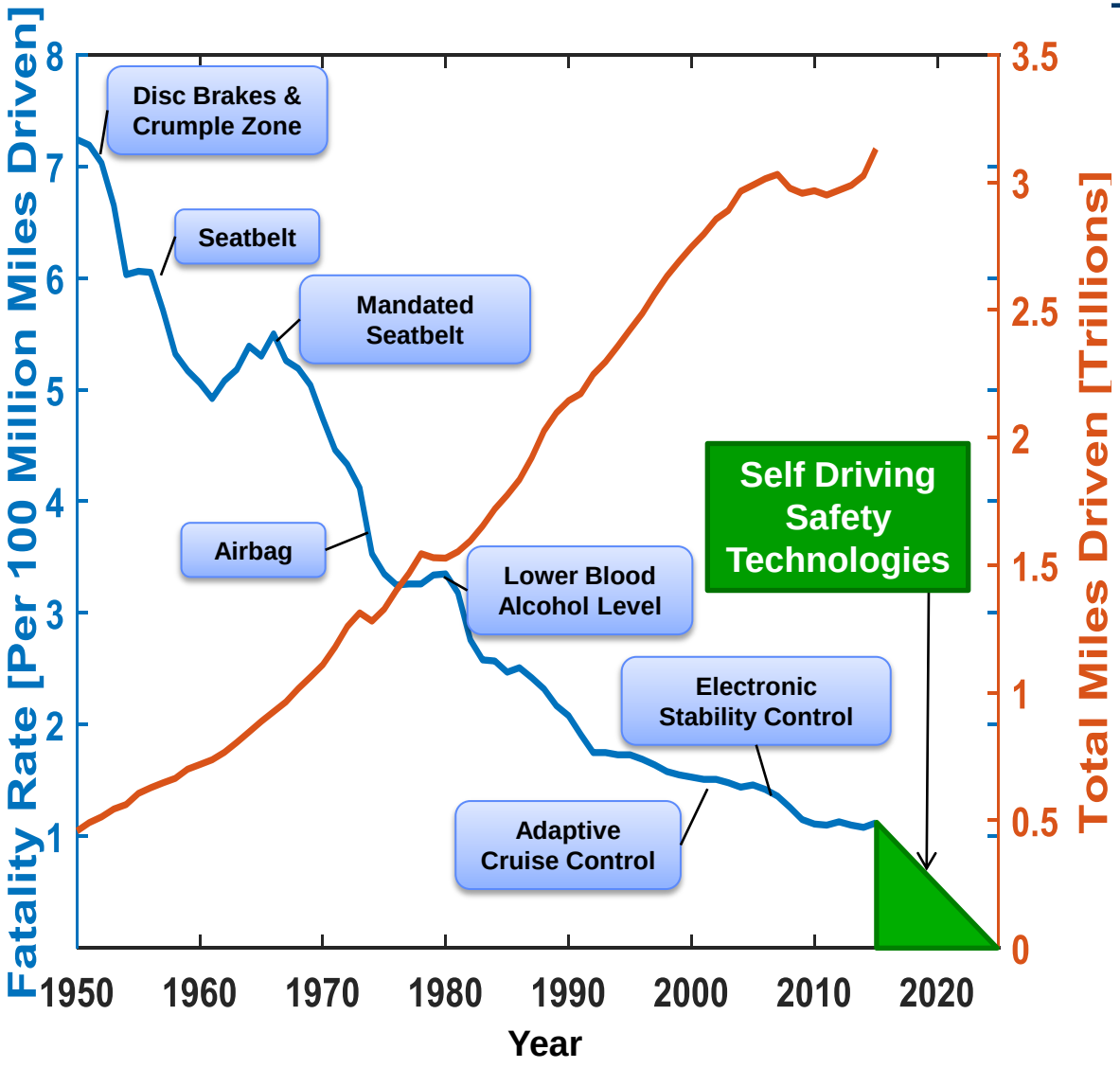


What problem is being solved by Autonomous Vehicles?

- **US Drivers:**
  - Over 3,000,000,000,000 miles driven each year
  - 35,000 fatalities per year
  - Per 100M miles driven
    - 180 crashes
    - 75 injuries
    - 1.1 fatalities
  - Over 53% fatalities due to road departures

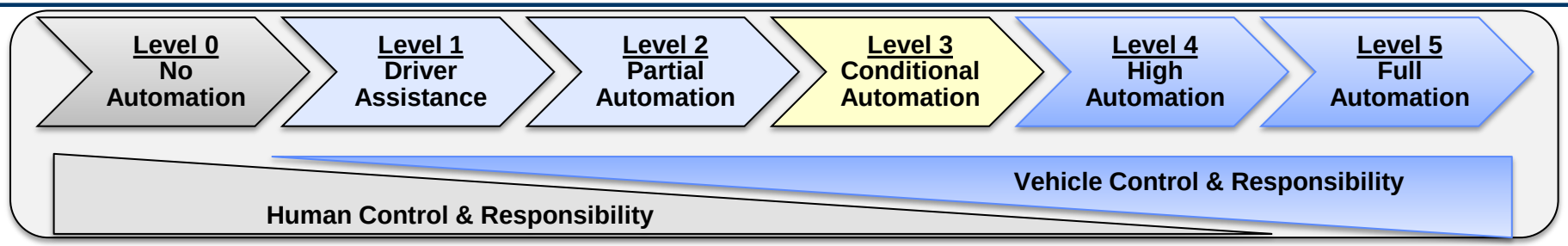


- **WorldWide**
  - Over 1,250,000 fatalities per year
  - Over 54,000,000 injuries per year



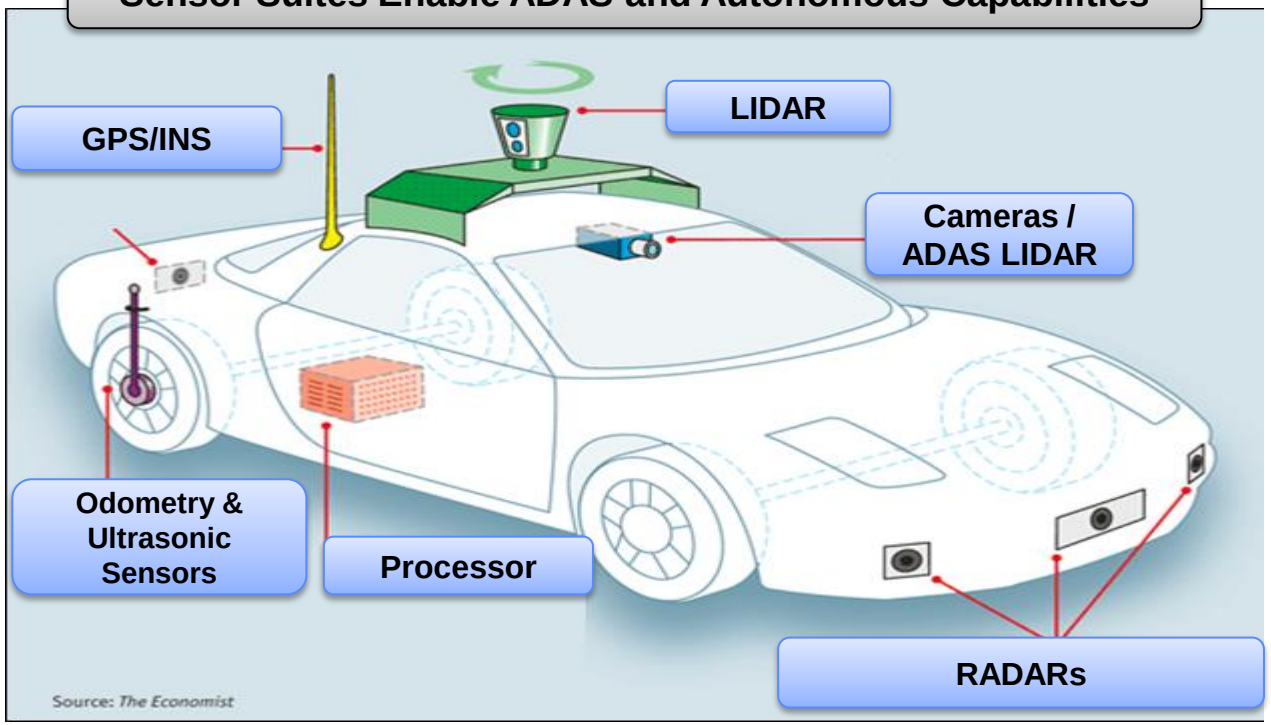
http://www-fars.nhtsa.dot.gov/Main/index.aspx
http://safety.fhwa.dot.gov/roadway_dept/
http://www.caranddriver.com/features/safety-in-numbers-charting-traffic-safety-and-fatality-data

How Are Autonomous Vehicles Solving the Problem?



Advanced Driver Assist Systems (ADAS)

Sensor Suites Enable ADAS and Autonomous Capabilities



https://www.mentor.com/embedded-software/multimedia/designing-and-developing-advanced-driver-assistance-systems--adas-

http://www.economist.com/blogs/economist-explains/2013/04/economist-explains-how-self-driving-car-works-driverless

How Close Are We to Zero Accidents?

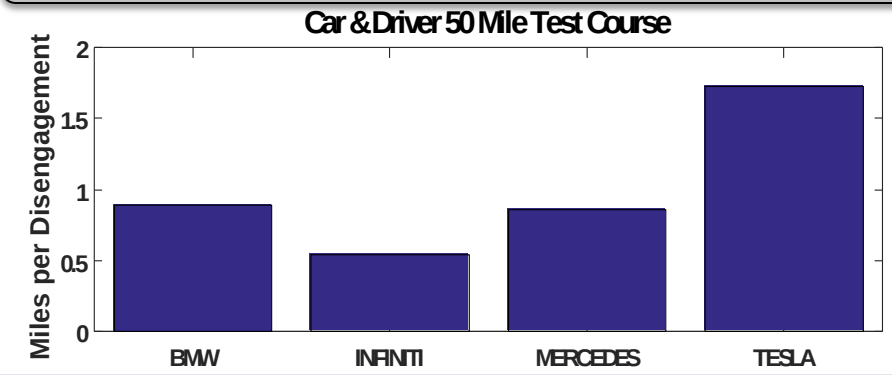
"Level 0,1, & 2" Autonomous Systems

Humans: $\frac{1\ reported\ accident}{497{,}000\ Miles}$

Forward Collision Avoidance

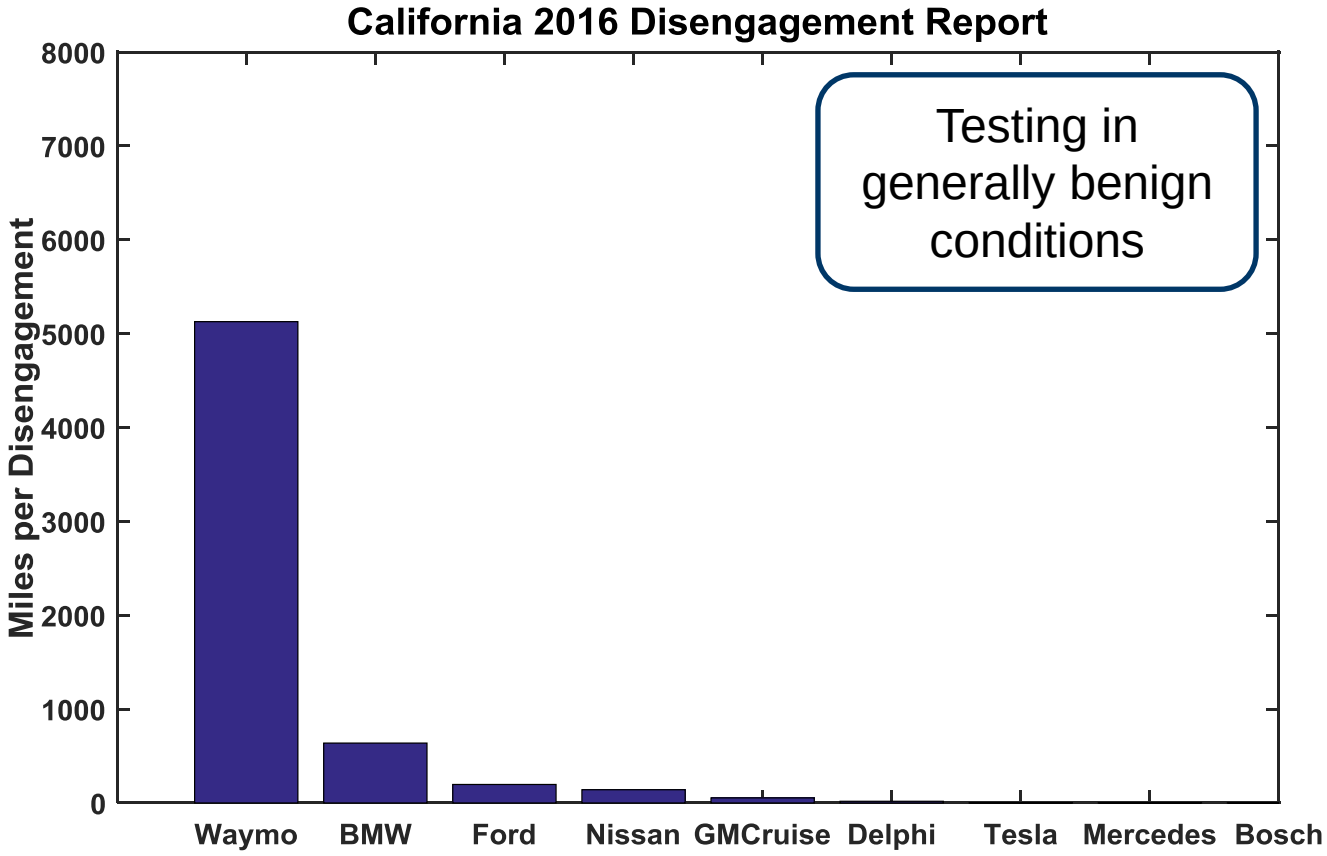
- **40% reduction in rear end collisions**
- **DOT considering mandatory inclusion**

Lane-keeping



"Level 3 & 4" Autonomous Systems

Waymo: $\frac{1\ safe\ operation\ disengagement}{7{,}700\ Miles}$



Testing in generally benign conditions

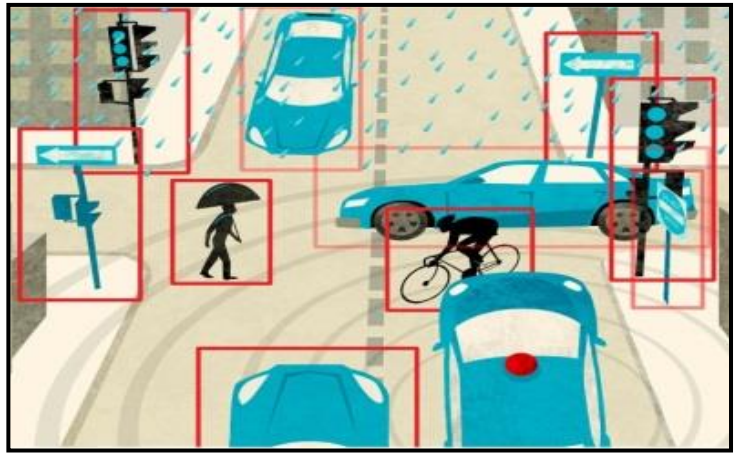
https://www.dmv.ca.gov/portal/dmv/detail/vr/autonomous/testing
http://www.iihs.org/iihs/news/desktopnews/crashes-avoided-front-crash-prevention-slashes-police-reported-rear-end-crashes
http://www.caranddriver.com/features/semi-autonomous-cars-compared-tesla-vs-bmw-mercedes-and-infiniti-feature-the-physiology-of-semi-autonomy-and-test-results-page-6

Challenges: Why aren't we there yet?

Navigation in Complex & Dynamic Environments

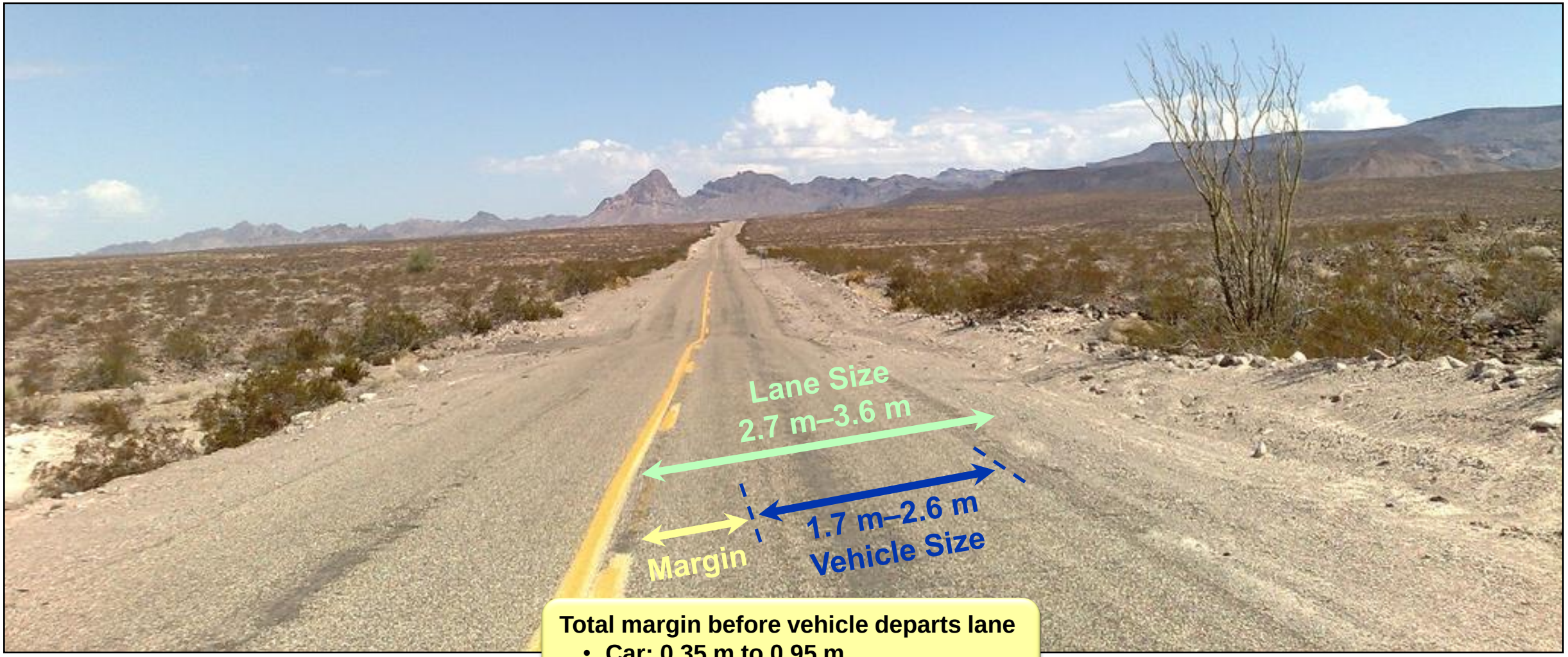
Human Supervision & Reaction Time

Perception



Localization

The Localization Accuracy Challenge



Total margin before vehicle departs lane

- **Car: 0.35 m to 0.95 m**
- **Truck: 0.05 m to 0.55 m**

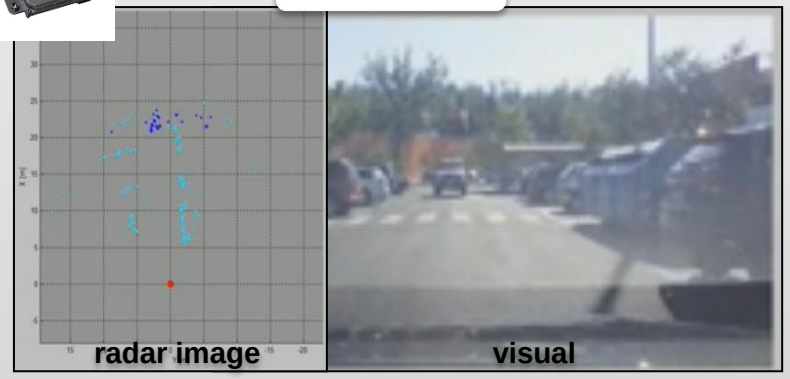
http://safety.fhwa.dot.gov/geometric/pubs/mitigationstrategies/chapter3/3_lanewidth.htm
http://ops.fhwa.dot.gov/FREIGHT/publications/size_regs_final_rpt/index.htm

Autonomous Vehicle Localization Sensors

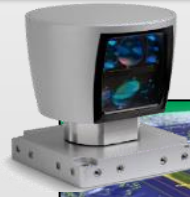
Coarse → **Fine**

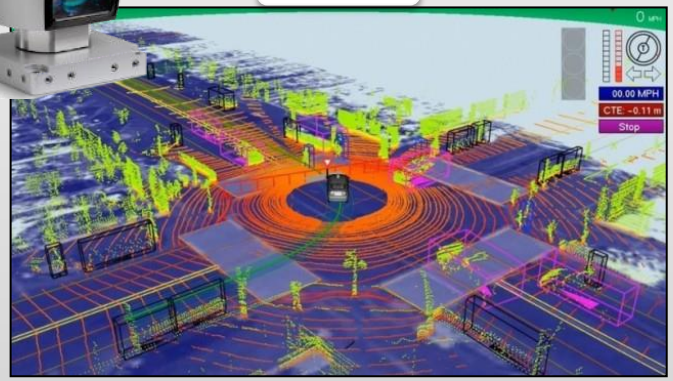
GPS

RADAR



Lidar

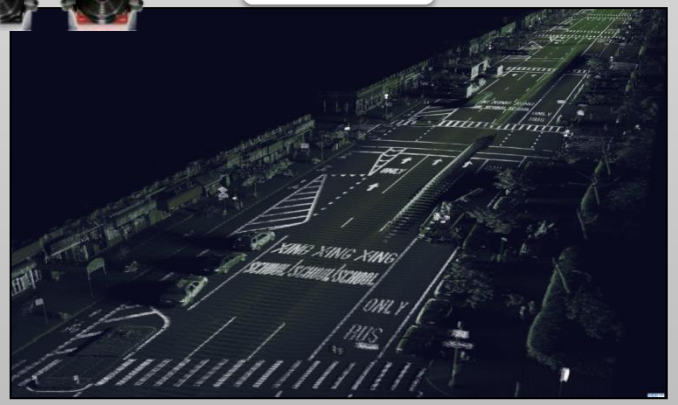




Inertial (IMUs)

Odometry

Camera



http://www.analog.com/en/analog-dialogue/articles/inertial-sensors-and-autonomous-operation-in-robots.html
http://mappingignorance.org/2014/04/07/one-way-googles-cars-localize/
http://www.planetiq.com/why-planet-iq/
http://www.automotive-eetimes.com/content/mems-inertial-sensors-provide-equilibrium-sense-your-car/page/0/2
http://www.autonomoustuff.com/product/sms-automotive-radar/

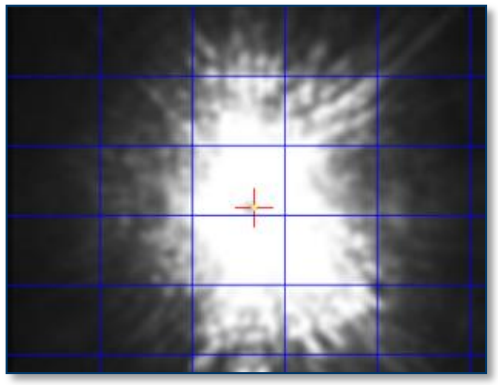
Challenges of Reliable Optical Localization

Limited or changing features

Covered Surfaces

Surface feature changes

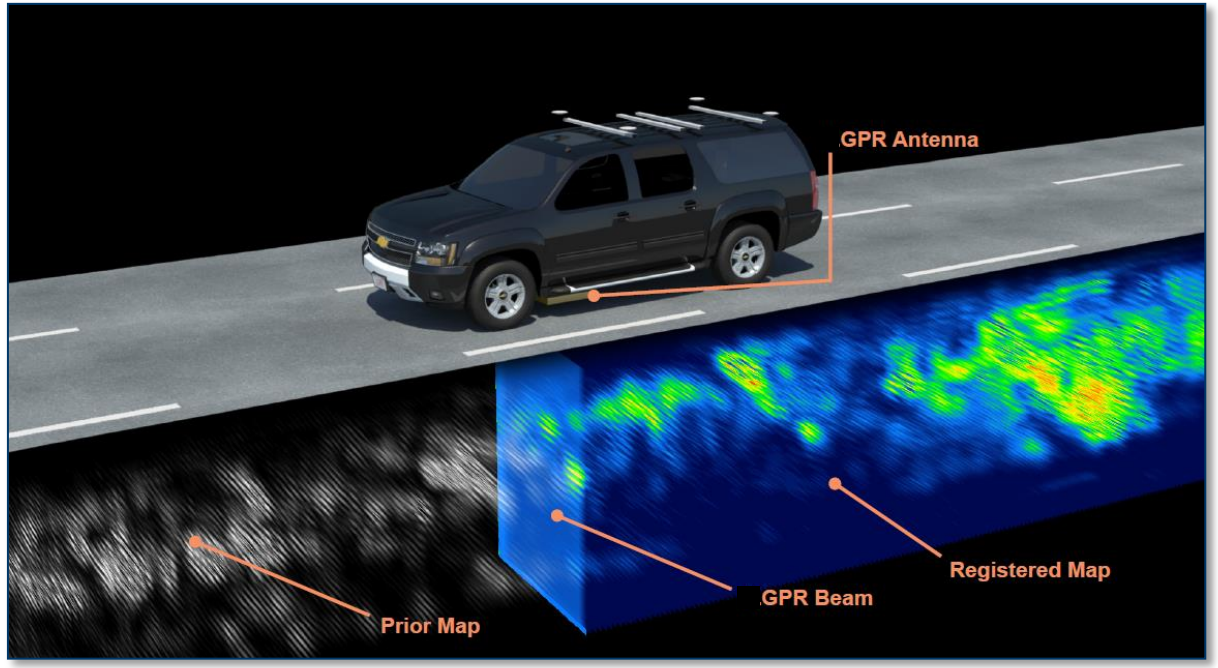
Obscuring conditions



Interference / Blinding

Typical autonomous vehicle sensor suite is challenged by a variety of adverse conditions

New Concept: Localization with Ground Penetrating Radar



- **Subsurface environment is favorable for tracking**
  - **Richly featured with soil strata, rocks, pipes**
  - **Stable over long periods**

- **Employ Ground Penetrating Radar (GPR) to "image" 3D subsurface features**
  - **Weather and dust are effectively transparent**
  - **Energy directed into ground, i.e. difficult to deny, interfere**
  - **No moving parts**

Novel Ground Penetrating Radar localization technique provides robustness

Outline

- Introduction to self-driving vehicles
- **Localizing Ground Penetrating Radar (LGPR) concept & potential**
- **LGPR technology, challenges & results**
- **The way forward**

Alternate Localization Method Comparison

	GPS/INS	Camera	LIDAR	HD Radar	LGPR
Urban					
Rain					
Dust/Fog					
Snow					
Tunnels					
Contested Spectrum (Blind, jam, interfere)					
Subsurface Changes					
Surface Changes					

Lanekeeping Ultimate Goal: <1 major failure per 3 trillion miles driven (or better)
Current systems: 1 failure per 1K to 100K miles driven in generally benign conditions.

Orders of magnitude improvement likely requires fusion of new sensor.

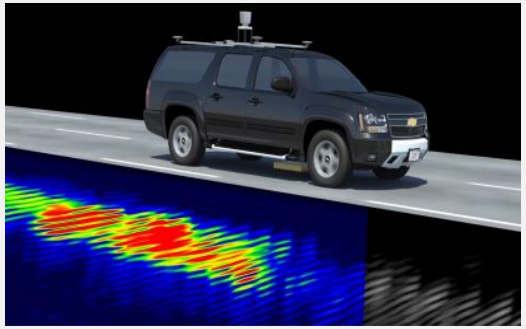
https://static.googleusercontent.com/media/www.google.com/en//selfdrivingcar/files/reports/report-annual-15.pdf

LGPR Potential: Robustness & Maps

All-Condition Lane-Keeping

Current Autonomous Vehicles

✖

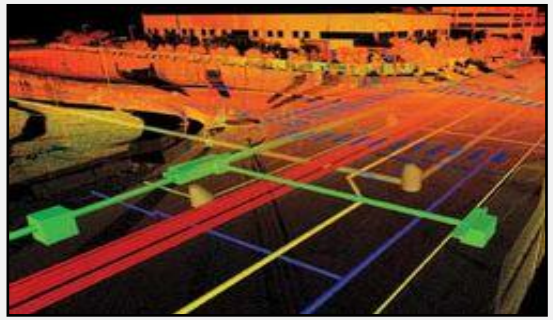


Localizing GPR

Probability of Two Independent Errors:

$$P(A \,\&\, B) = P(A) \times P(B)$$

Realtime Infrastructure Maps

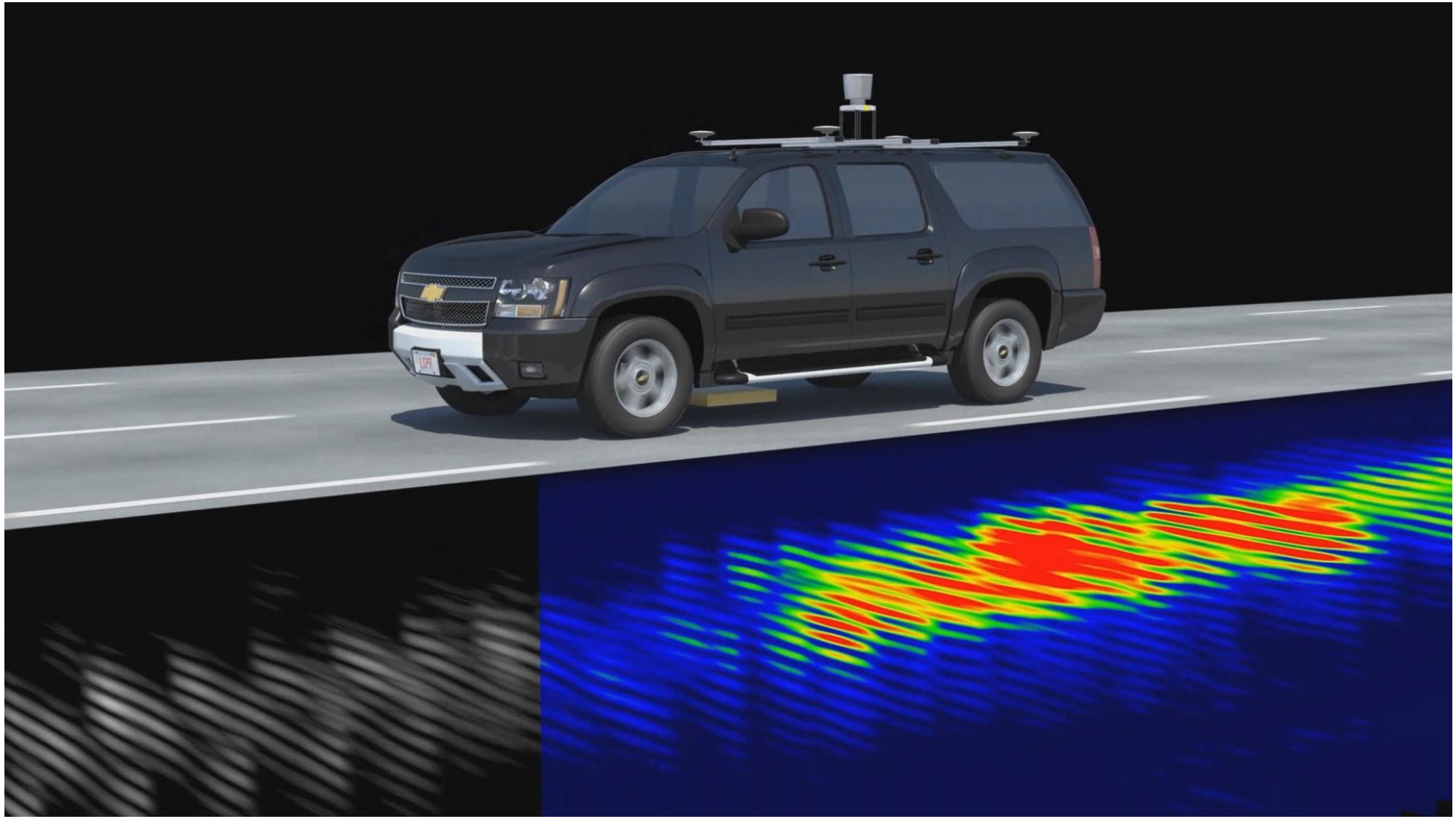


Locate Utilities

Bridge Failures

Road State

LGPR Snow Demonstration



https://www.youtube.com/watch?v=rZq5FMwl8D4

Outline

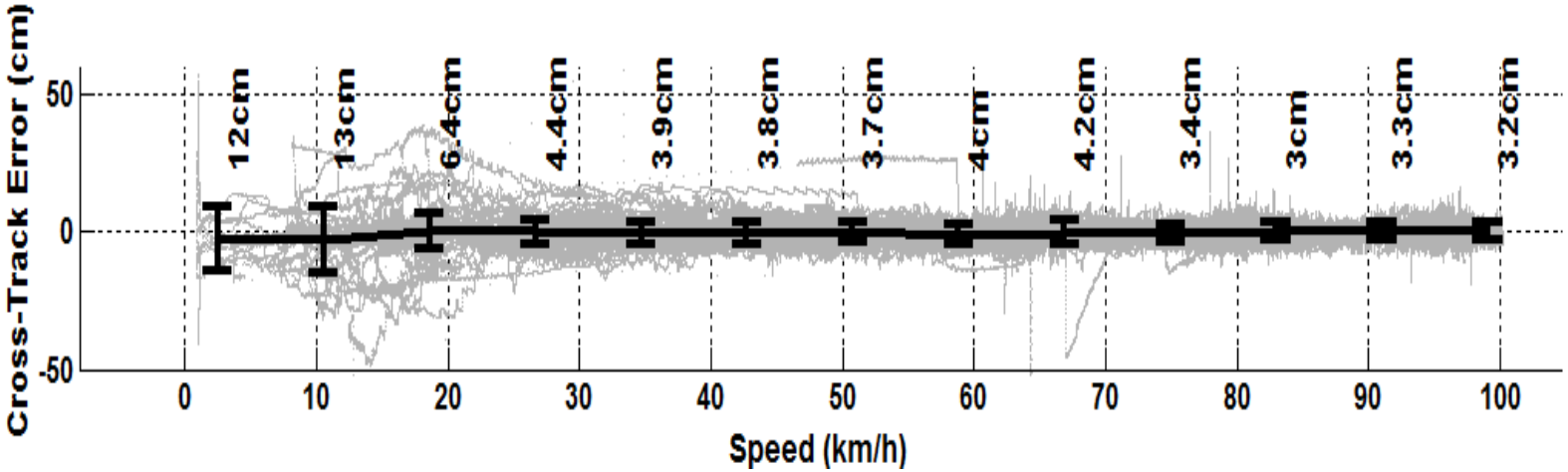
- Introduction to self-driving vehicles
- Localizing Ground Penetrating Radar (LGPR) concept & potential
- **LGPR technology, challenges & results**
- **The way forward**

LGPR Guided Autonomous Vehicle Demonstration

Rapid Prototype & Test - Highway Testing Results

	Cross-Track Error	*Along-Track Error*	*Total Error*
LGPR	**4.3 cm RMS**	**5.9 cm RMS**	**7.3 cm RMS**
Differential GPS/INS (WAAS)	**35.0 cm RMS**	**41.7 cm RMS**	**54.4 cm RMS**

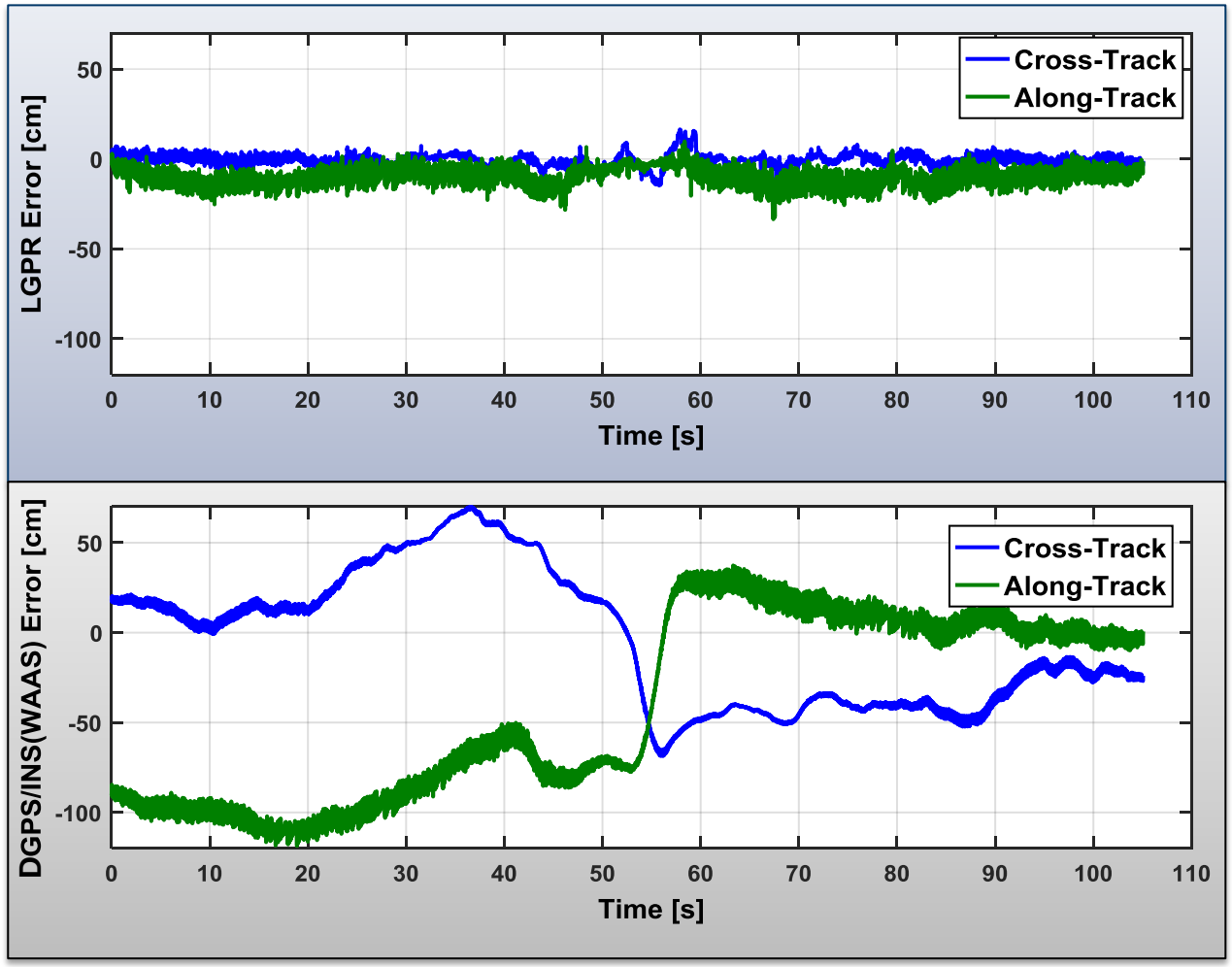
- **Test Conditions**
  - **1.6 km track on public highway**
  - **Speeds 10 mph to 60 mph (16 km/h to 97 km/h)**
- **"Truth" measurement**
  - **Real-Time Kinematic GPS base station linked to an independent GPS/INS**
  - **Local ~2 cm level accuracy**



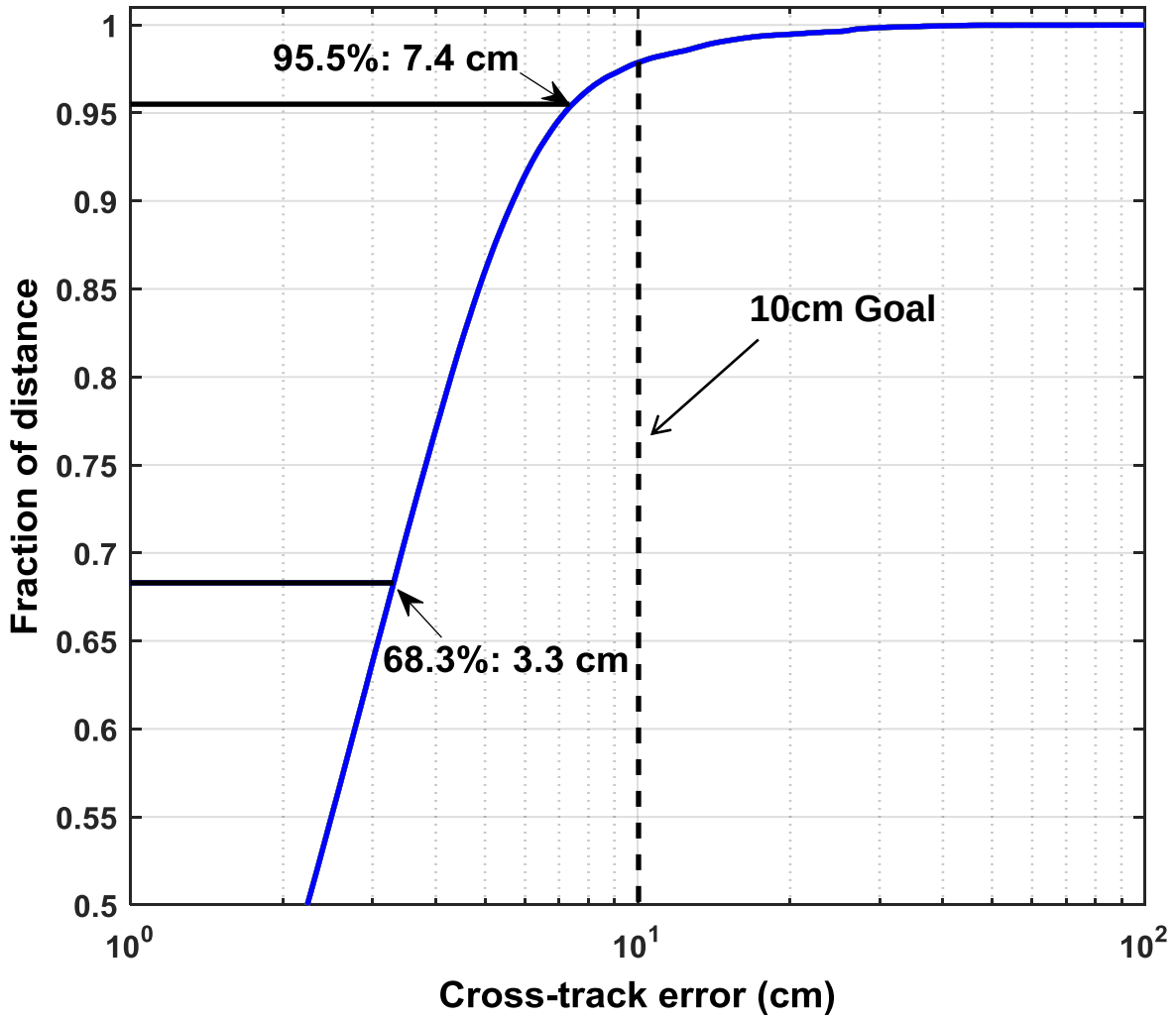
Cornick, M., Koechling, J., Stanley, B. and Zhang, B. (2016), Localizing Ground Penetrating RADAR: A Step Toward Robust Autonomous Ground Vehicle Localization. J. Field Robotics, 33: 82–102. doi:10.1002/rob.21605

Speed Test Performance Analysis

Typical Run Errors (LGPR and GPS/INS)

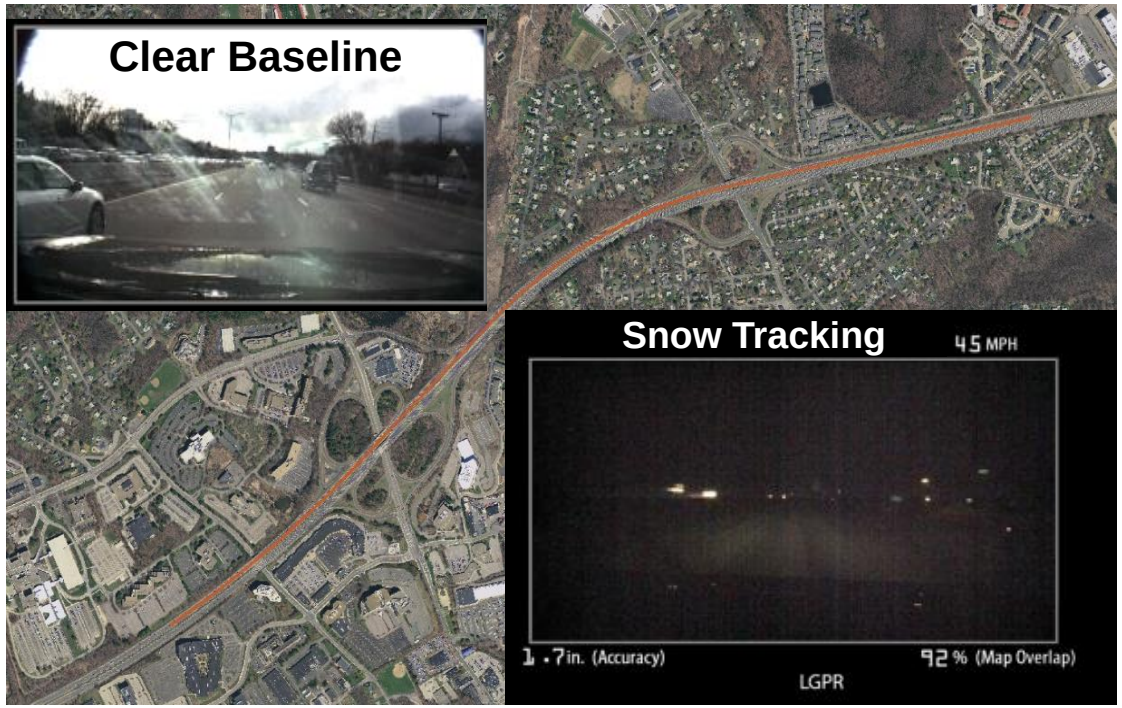


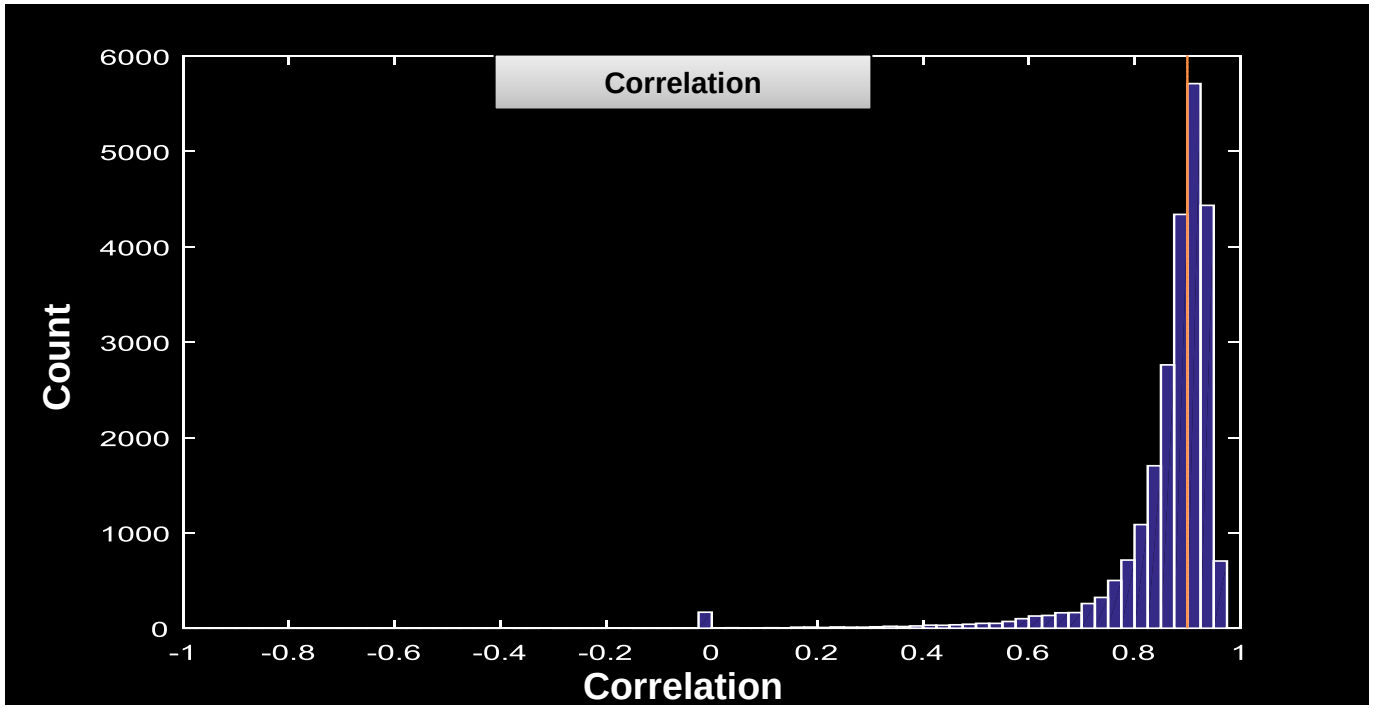
Overall LGPR Cross-Track Error



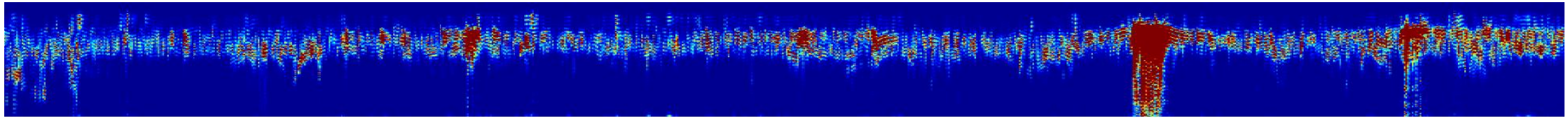
Cornick, M., Koechling, J., Stanley, B. and Zhang, B. (2016), Localizing Ground Penetrating RADAR: A Step Toward Robust Autonomous Ground Vehicle Localization. J. Field Robotics, 33: 82–102. doi:10.1002/rob.21605

Success: Snow Testing Results
6cm Cross-Track Accuracy

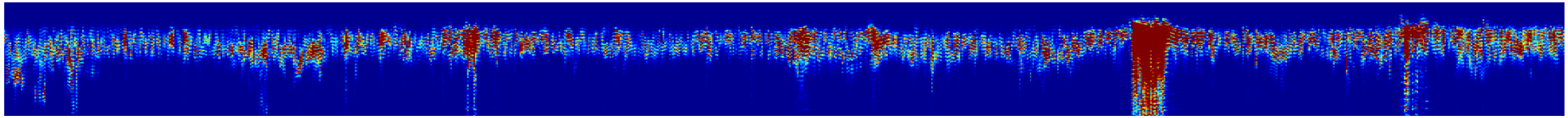




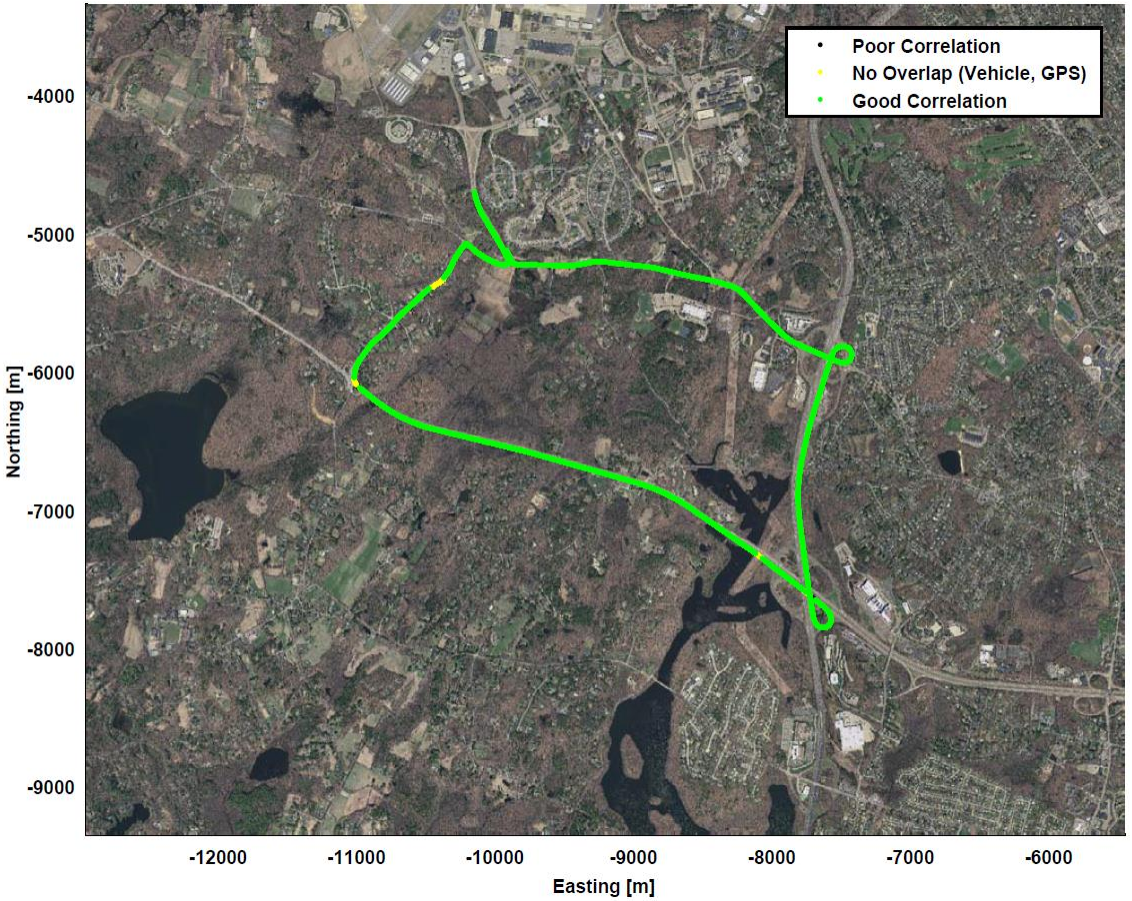
Track

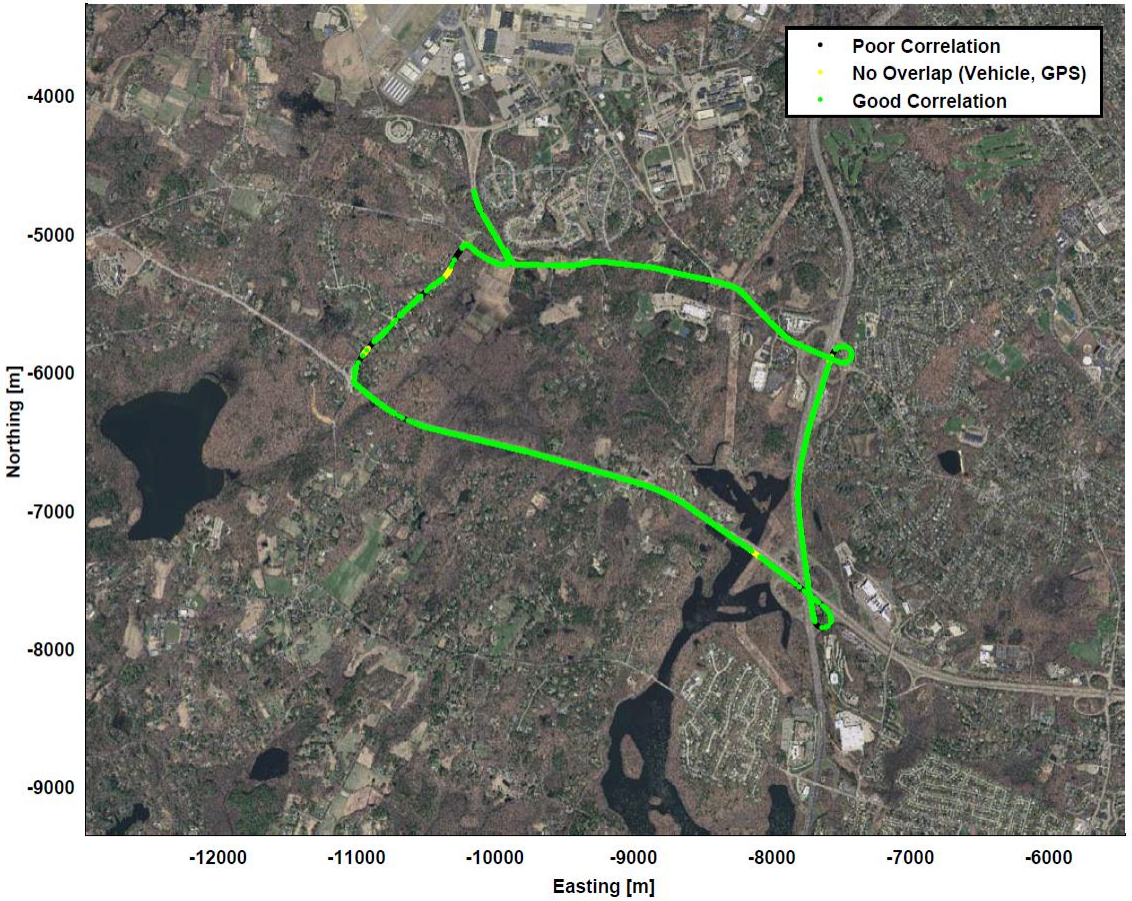


Baseline

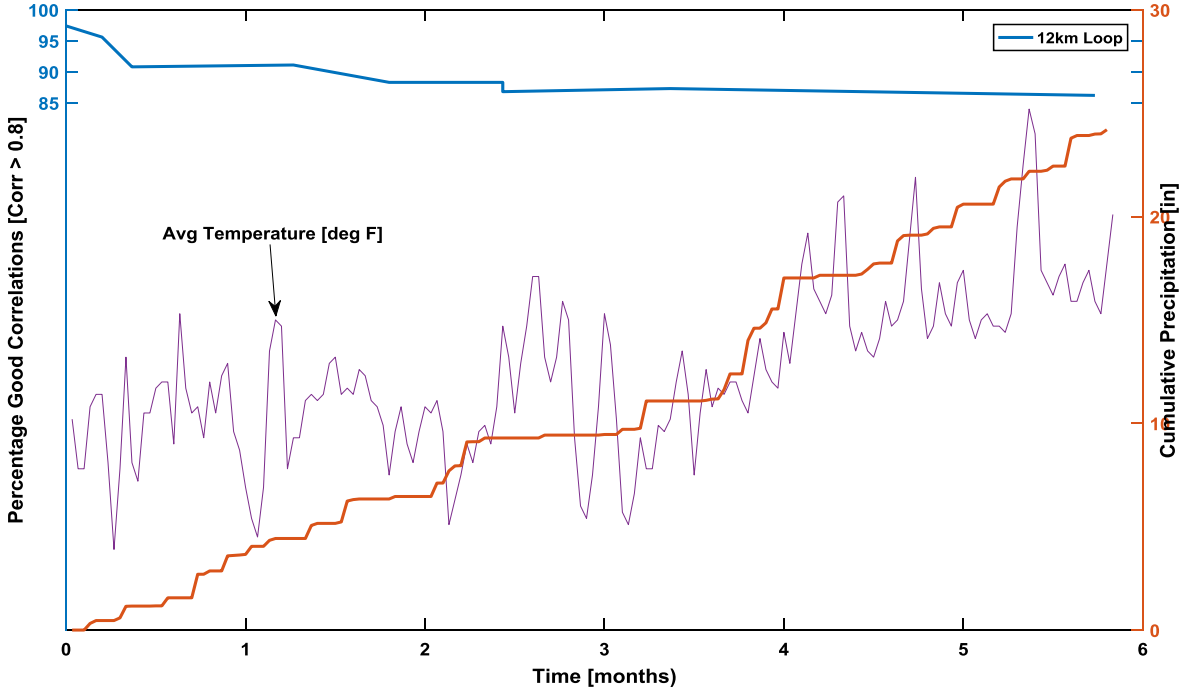


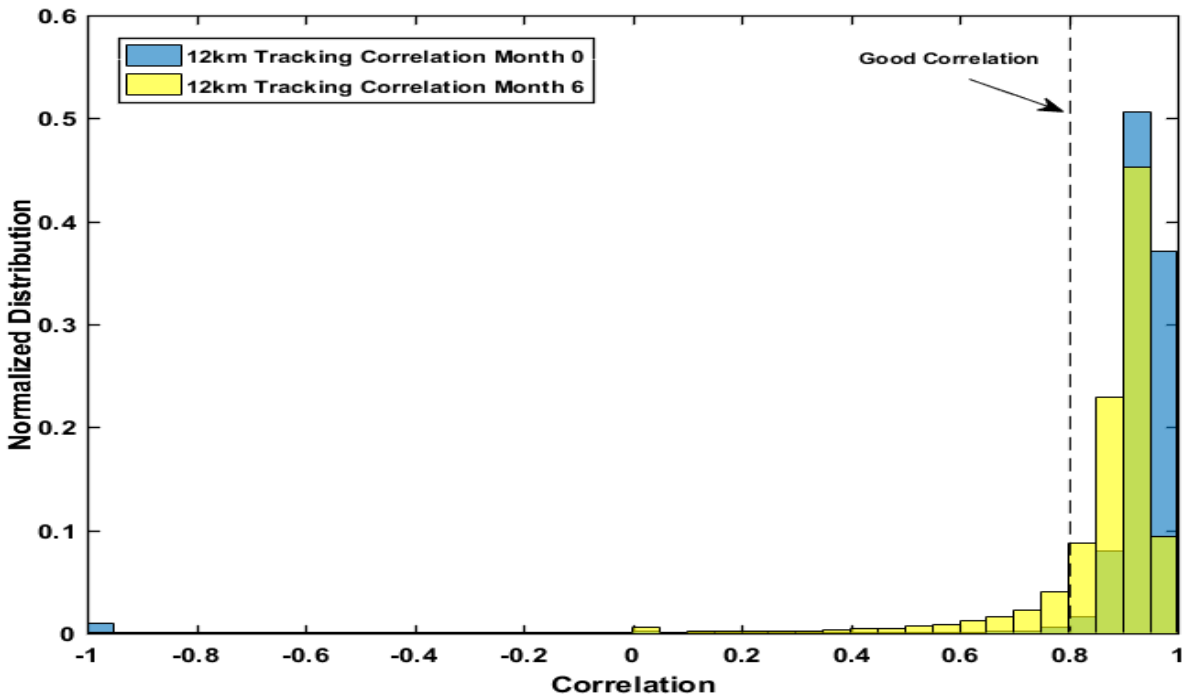
12km loop - Correlation Map - 0 and 6 Months

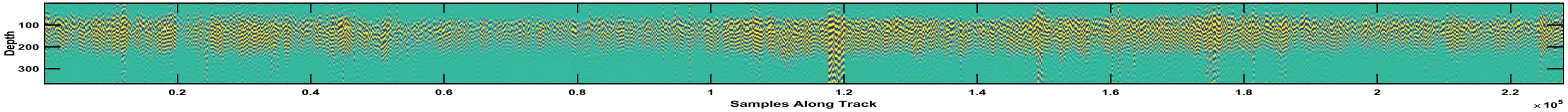




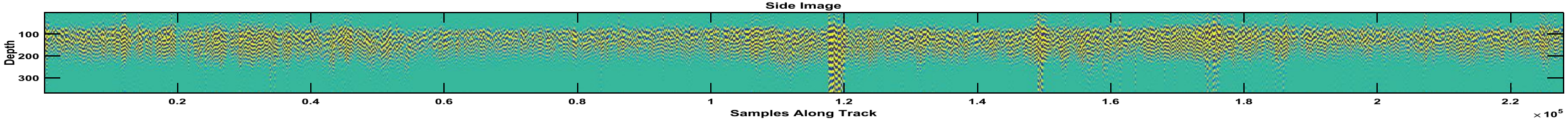
6 months – 12 km loop





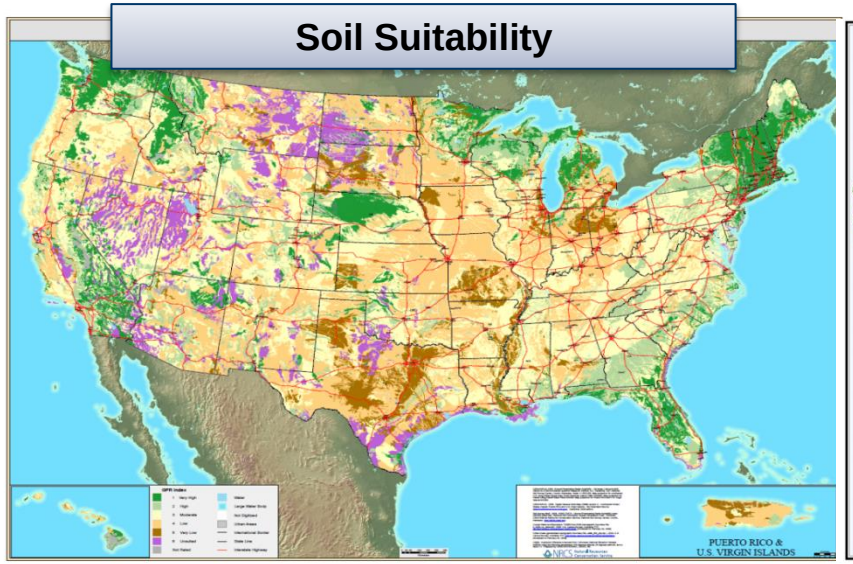


Side Image

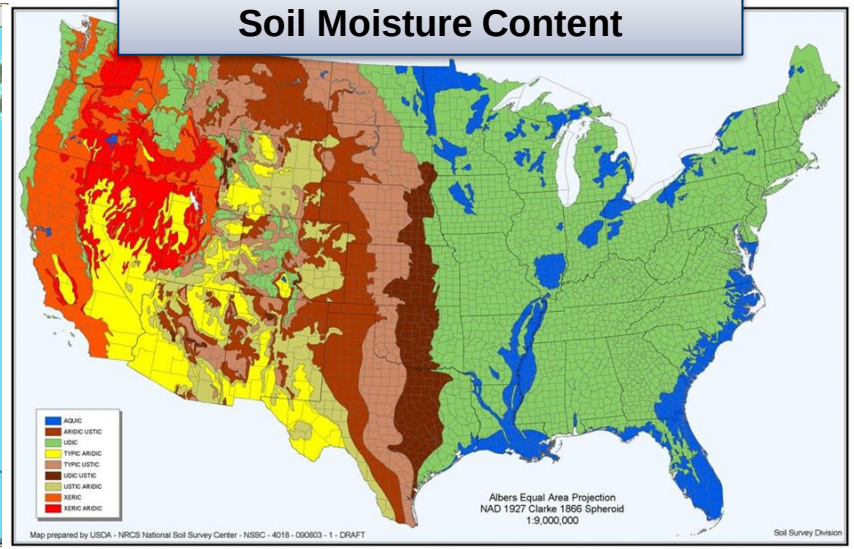


Robustness & Broad Scale Utility

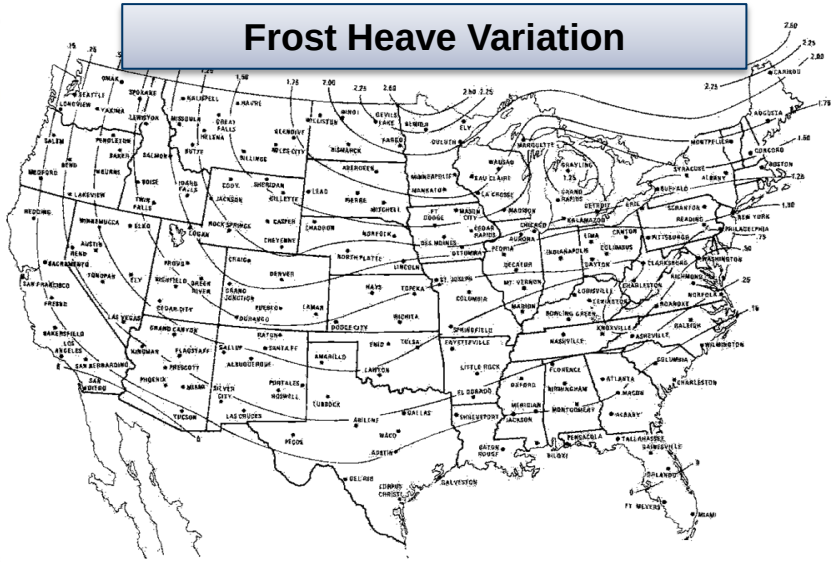
Soil Suitability



Soil Moisture Content



Frost Heave Variation



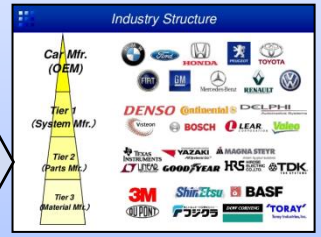
Robustness of physical design

- **A range of conditions to be tested**
- **Additional performance gains may be found:**
  - **Time series rather than single sweep correlations**
  - **High correlation matches not needed at 126Hz**
  - **Alternate algorithms**
- **Design of a low cost, mass produced system**

The LGPR Mapping Vision

1 LGPR Commercialization

Development, Technology Transfer, & Licensing of MITLL Technology



Auto OEMs & Suppliers

Map Byproducts Drive Mapping

GPR Manufacturers

Reduced Accident Rate Drives Adoption

3 Map & Data Fusion

Users Record Changes in Features

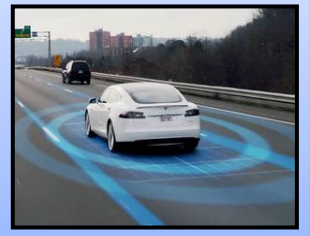
Upload Data

Improve Maps

2 Map & Data Collection

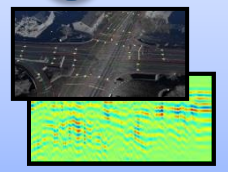
Dedicated Vehicles

Modify Existing Infrastructure



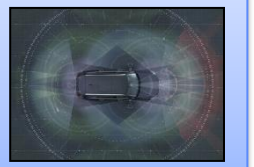
Crowdsourcing

4 Map & Data Updates



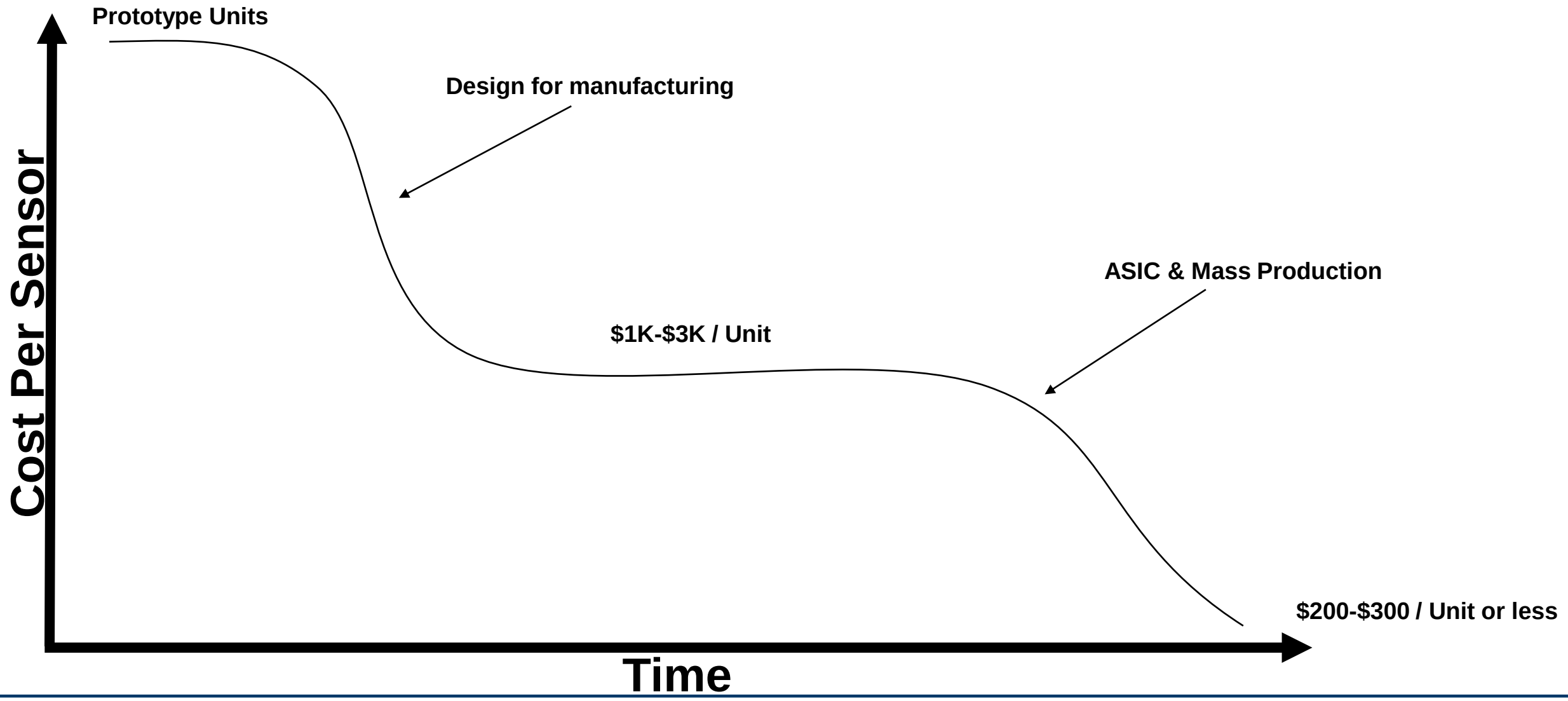
Package feature updates

Distribute & Download Data

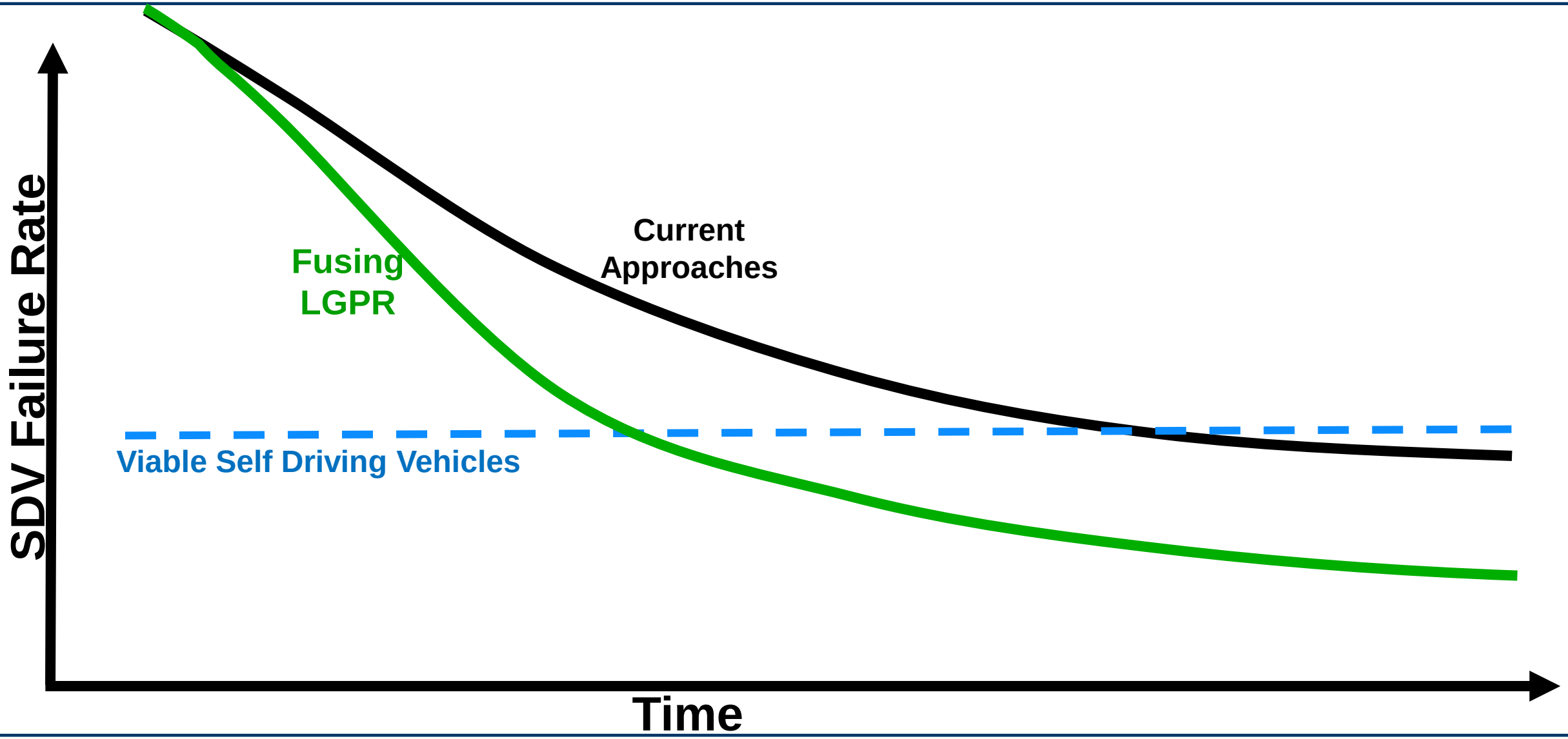


Improved Navigation

Road to Low Cost LGPR



Saving More Lives Sooner…



How to Engage

Partnerships and Technology Transfer / Licensing

- **Partnerships / CRADA's**
  - rapid risk reduction
  - collection of key metrics
  - proprietary data collections
  - inventing new concepts with exclusively licensed patents
  - options to work with commercial partners
- **Technology transfer & Licensing**
  - immediate transfer of technology and related support / licensing.
  - Enabling direct testing and use of technology

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Reference Material

- **Youtube Video:** https://www.youtube.com/watch?v=rZq5FMwl8D4
- **Journal of Field Robotics Article:** Cornick, M., Koechling, J., Stanley, B. and Zhang, B. (2016), Localizing Ground Penetrating RADAR: A Step Toward Robust Autonomous Ground Vehicle Localization. J. Field Robotics, 33: 82–102. doi:10.1002/rob.21605 http://onlinelibrary.wiley.com/doi/10.1002/rob.21605/full
- **IEEE Paper (Antenna):** Fenn, A. J., Hurst, P. T., Pacheco, J., Cornick, M., & Parad, L. I. (2013). Ultrawideband cavity-backed resistively loaded planar dipole array for ground penetrating radar. *IEEE International Symposium on Phased Array*, Waltham, MA. http://ieeexplore.ieee.org/document/6731812/
- **Patent:** Stanley, Byron McCall, et al. "Vehicle localization using surface penetrating radar." U.S. Patent No. 8,949,024. 3 Feb. 2015. https://www.google.com/patents/US8949024
- **Press Release:** http://www.ll.mit.edu/news/LGPR-AVS-licensing-agreement.html

International Transport Forum

Key Results from the ITF - OECD Roundtable on Truck Automation

Dr. Tom Voege, Policy Analyst
International Transport Forum

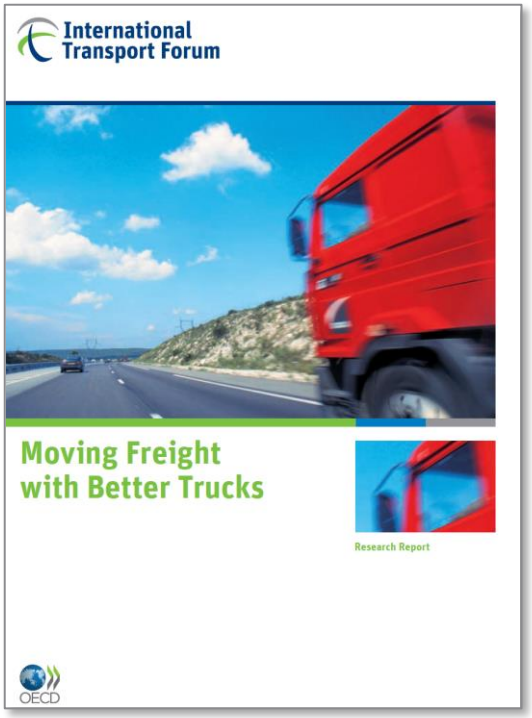
Automated Vehicle Symposium AVS, July 2017, San Francisco
Breakout 6: Trucking Automation - Key Deployment Scenarios

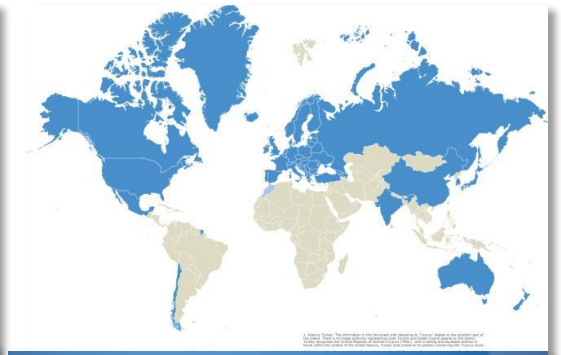
OECD

International Transport Forum

The International Transport Forum of the OECD

Think Tank	Annual **Summit**	Intergovernmental **Organisation**





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Related recent ITF-OECD work

Roundtable Commercial Vehicle On-Board Safety Systems

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CPB Project Data-led Governance of Road Freight Transport

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Managing the Transition to Driverless Road Freight Transport

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Roundtable Overview

- Chair: Peter Sweatman, CAVita
- Location: USDOT, Washington D.C.
- Date: 5-6 January 2017
- Discussion Papers:

1. Peter Sweatman, CAVita Partners, **"Evolution of Technology for Commercial Vehicle Safety"**
2. John Woodrooffe, University of Michigan (UMTRI), "**Enablement of Management and Logistics"**
3. Mårten Blix, Research Institute of Industrial Economics, **"Structural Change and Freight Transport Labour Market"**
4. Christopher Poe, Texas A&M, **"Commerce-Ready Infrastructure and Urban Environment"**

Key Issues

- What specific technologies for automation exist, covering platooning and full automation?
- What are specific implications of the technology options on infrastructure and human factors?
- How can such a system interact with manually operated passengers cars and trucks?
- How can potential wider societal and economic benefits be locked in, without additional risks?
- How do these systems need to be regulated, driven by industry or governments?
- What are the policy implications, how are liability, security and privacy concerns being addressed?

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1. Autonomous trucks are likely to be the first use case of AV technology

- Long distance road freight make extensive use of motorways, less complex environment
- AV may achieve safe commercial operation on motorways earlier than on other roads
- Negative labour impacts of higher levels of automation should not be understated
- Opportunities for carriers and consumers to benefit from substantially lower costs
- Thus substantial incentives for long distance road freight to be the first use case for AVs

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2. Harmonised regulation is more important for autonomous trucks than other AVs

- Across jurisdictions, both subnational jurisdictions within countries and international borders
- Susceptible to multiple regulatory frameworks applying to a single trip
- Could result in cross-border freight operators needing multiple on-board systems in vehicles
- The existing work within relevant bodies to harmonise regulations needs to accelerate
- Otherwise risk of losing some of the benefits that autonomous trucks could provide

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3. Existing regulations can accommodate AV technologies up to a point

- Because technologies up to SAE 2 assist rather than replace drivers, existing frameworks are well placed to accommodate them
- Existing road rules, vehicle standards and type approval processes can all deal with this level of automation relatively well
- This provides a short period in which regulators can obtain further information before needing to regulate higher levels of automation

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4. Existing regulations can be stretched further to accommodate higher level AVs

- Concepts such as the “driver” and “control” of a motor vehicle are central
- Assumes human in control, sometimes implicit and not explicit, creates room for interpretations
- Originally designed for human, the term “driver” could include multiple drivers or software
- Existing regulations can accommodate technology up to SAE level 4, albeit imperfectly

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5. There are advantages to stretching existing regulatory frameworks

- Consistent with industry views preferring adapting existing regulation over creating new frameworks locking in a standard that is too high or too low
- Stretching is a relatively easy mechanism by which to ensure that automated vehicles conform to the same norms as human driven vehicles
- Interpreting existing regulations can avoid more advanced AV technologies being held back by a lack of progress in regulatory reform

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6. Stretching existing regulatory frameworks has its disadvantages and limits

- Stretching the interpretation of legislation of regulations is a blunt instrument
- Not specifically for regulating autonomous trucks, as a result unintended consequences are likely
- Broad interpretation would see SAE level 4 technology legal to operate on public roads today
- Despite safety concerns about technologies and potential political backlash in case of accidents

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7. Especially for trucks automation will create disruptive employment issues

- Substantial labour impacts are likely to arise as a result of advanced AV technology, particularly in the road freight sector
- Substantial job losses amongst drivers, within a decade, job losses in the order of 1 million people in each of Europe and North America are possible
- Unlike in other circumstances that have occurred previously, drivers displaced by automation may struggle to find alternative employment

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8. Government interventions affecting speed of introduction and support to drivers

- Establishing a temporary transition advisory board to advise governments on these strategies
- Permit system to influence speed of introduction of AV technology and the associated job losses
- Economy-wide support of underemployed drivers such as universal income policies
- Industry specific support consistent with good practice for general unemployment support
- System to be funded by the main beneficiaries of the advanced AV technologies

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9. Potential for data-led governance of the road freight sector generally

- Increasing gap between policy goals and the regulation actually implemented
- The effects range from undesired outcomes not originally foreseen to enforcement challenges
- Clear potential of data-driven approaches for regulating and enforcing road freight transport
- More targeted, flexible regulatory frameworks and more efficient enforcement mechanisms possible

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10. Specific challenges for data-led regulation of the road freight sector generally

- Leveling the playing field
  - Technology readiness
  - Policy approaches
  - Economic development
- Need to shorten
  - Implementation times of technologies and systems
  - Time lag of policy and regulatory responses
- Additional issues due to innovation requiring new roles and responsibilities of stakeholders

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11. Recommendations for data-led regulation of the road freight sector generally

- Embrace the concept of data-led policy making and consider move towards implementation of innovative data-driven regulatory approaches
- Data handling and processing requires cross-sectoral approaches, using new technologies, systems, and developments in data science
- Wider and more unstructured big data sets might be less applicable (big data)
- Automation of road freight vehicles is likely to be a game changer for data driven policy

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Thank you for your attention!

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