Pavement Markings Guiding Autonomous Vehicles – A Real World Study

Chris Davies

Potters Industries

Problem Statement

At present, it’s unknown what factors in pavement markings are important to autonomous driving machine vision equipped vehicles.

Questions To Be Answered

- How does pavement marking
  - Retroreflectivity
  - contrast ratio
  - width
- affect the performance of machine vision?
- Are the key pavement marking factors different in a day versus night scenario?
- Are the key pavement marking factors different in a dry versus wet scenario?

Desired Outcome

If we can answer these questions, pavement markings can be engineered and applied in such a way that autonomous driving machine vision equipped vehicles will perform in a safer and more reliable manner.

Phase 1 Questions

- How far out in front of the vehicle does the machine vision system “look”?
- How large is the window of the machine vision system?
- Do these parameters change with vehicle speed?
- Do these parameters change in day versus night?

Test Method

- A test vehicle was equipped with a machine vision system.
- The system was modified such that it could be run in a static mode with varying simulated speeds.
- The system was tested in a static environment with consistent parameters (lighting, pavement retroreflectivity, etc). By placing retroreflective pavement marking panels in the view window

Phase 1 Results

- The machine vision system tested “looks” out in front of the vehicle roughly 20-60 feet.
- The optimum distance is in the 25-45 foot range at a simulated vehicle speed of 35MPH.
- The optimum distance increases to roughly 25-55 feet when the simulated vehicle speed is increased to 70MPH.
- There appears to be no difference in terms of the window sizes or optimums in a day versus night scenario.

Phase 2 Questions

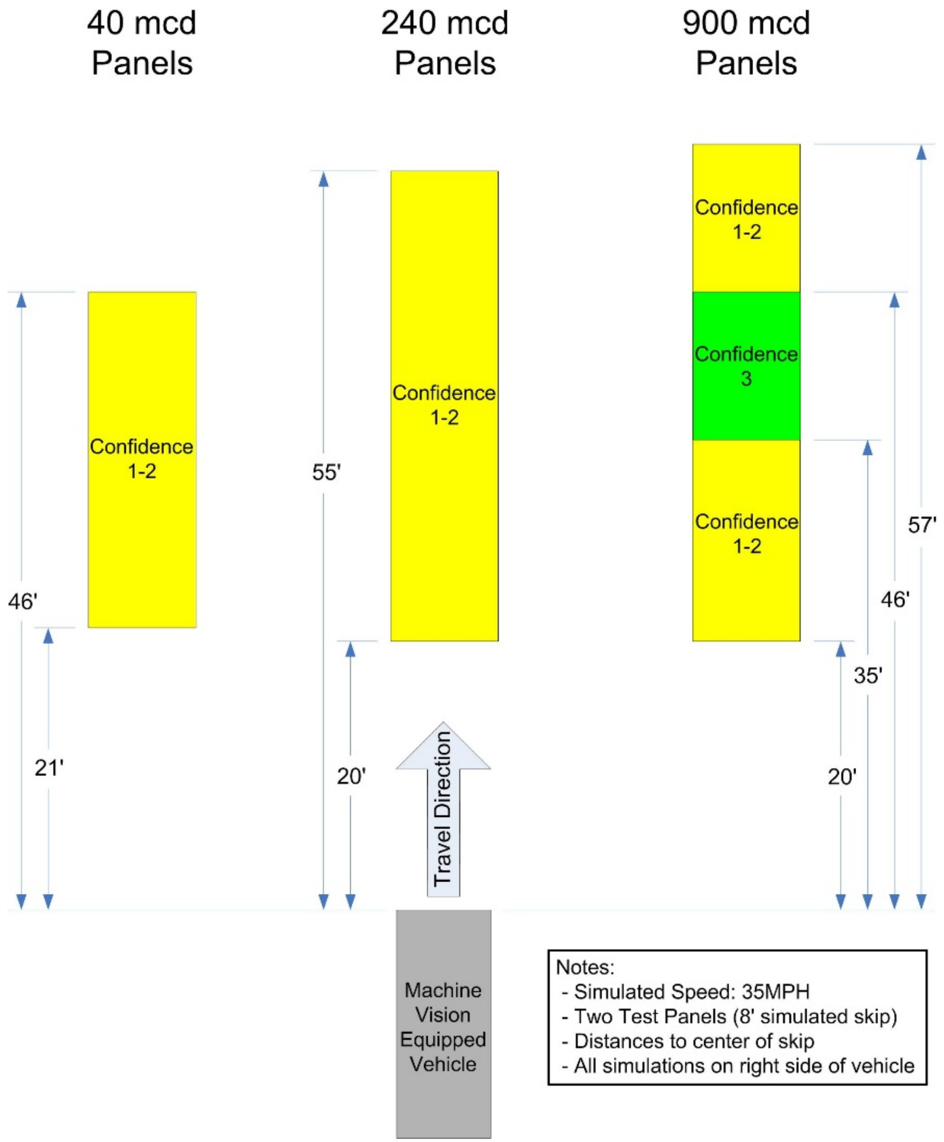
- How does the machine vision system perform against pavement markings of different retroreflectivity?
- How does the machine vision system perform against pavement markings and pavement surfaces that yield different contrast ratios?

Test Method

- The same system and test method used in the Phase 1 testing was used here.
- The simulated speed was kept at a constant 35MPH.
- Two different pavement surfaces (8 mcd and 25 mcd) were tested.

Phase 2 Results

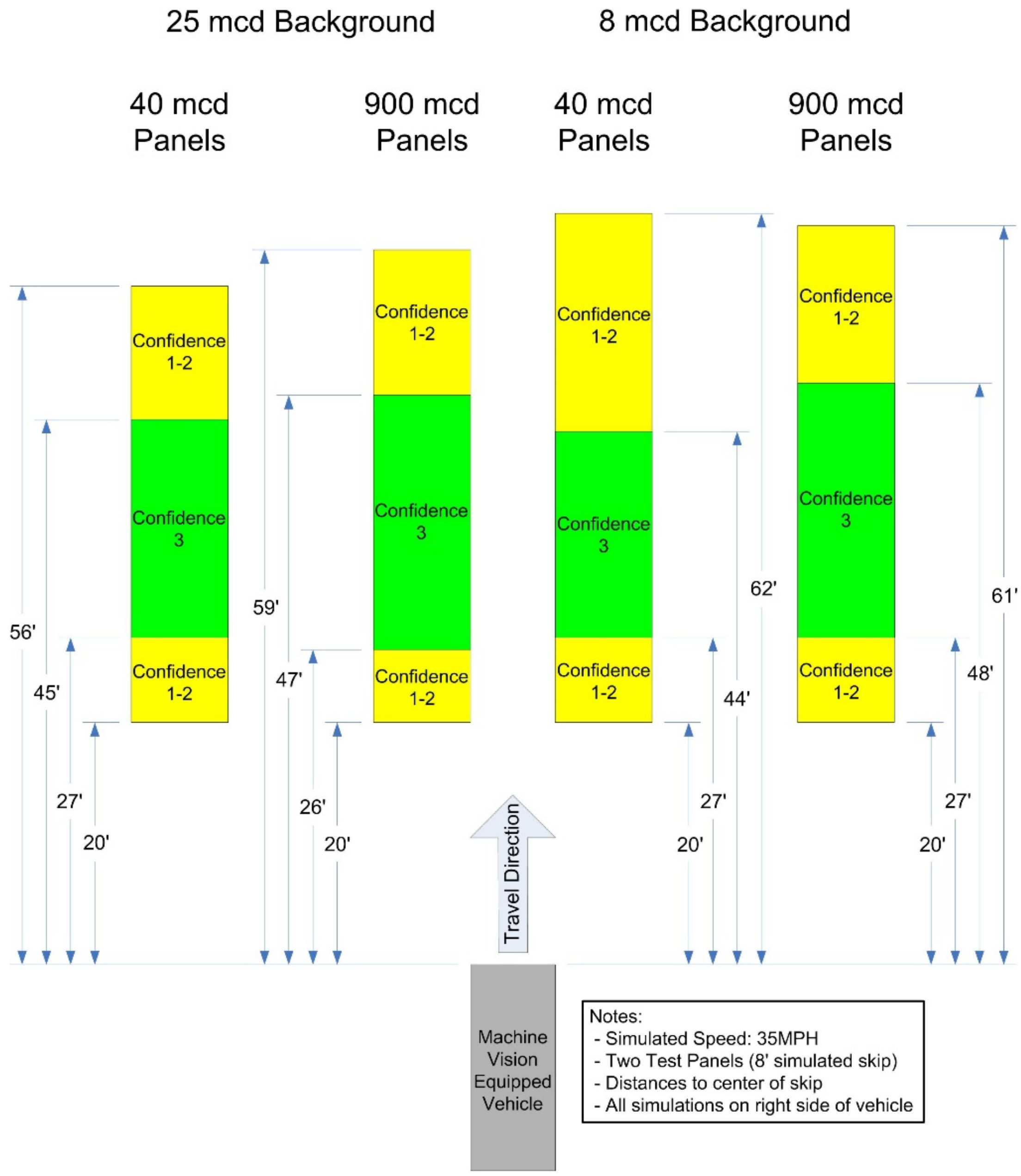
- At night, marking retroreflectivity is the most important factor.
- Retroreflectivity contrast ratio was not a factor. (The results were almost identical when tested on 8 mcd pavement.)



Nighttime Window Testing
25 mcd Pavement

Phase 2 Results

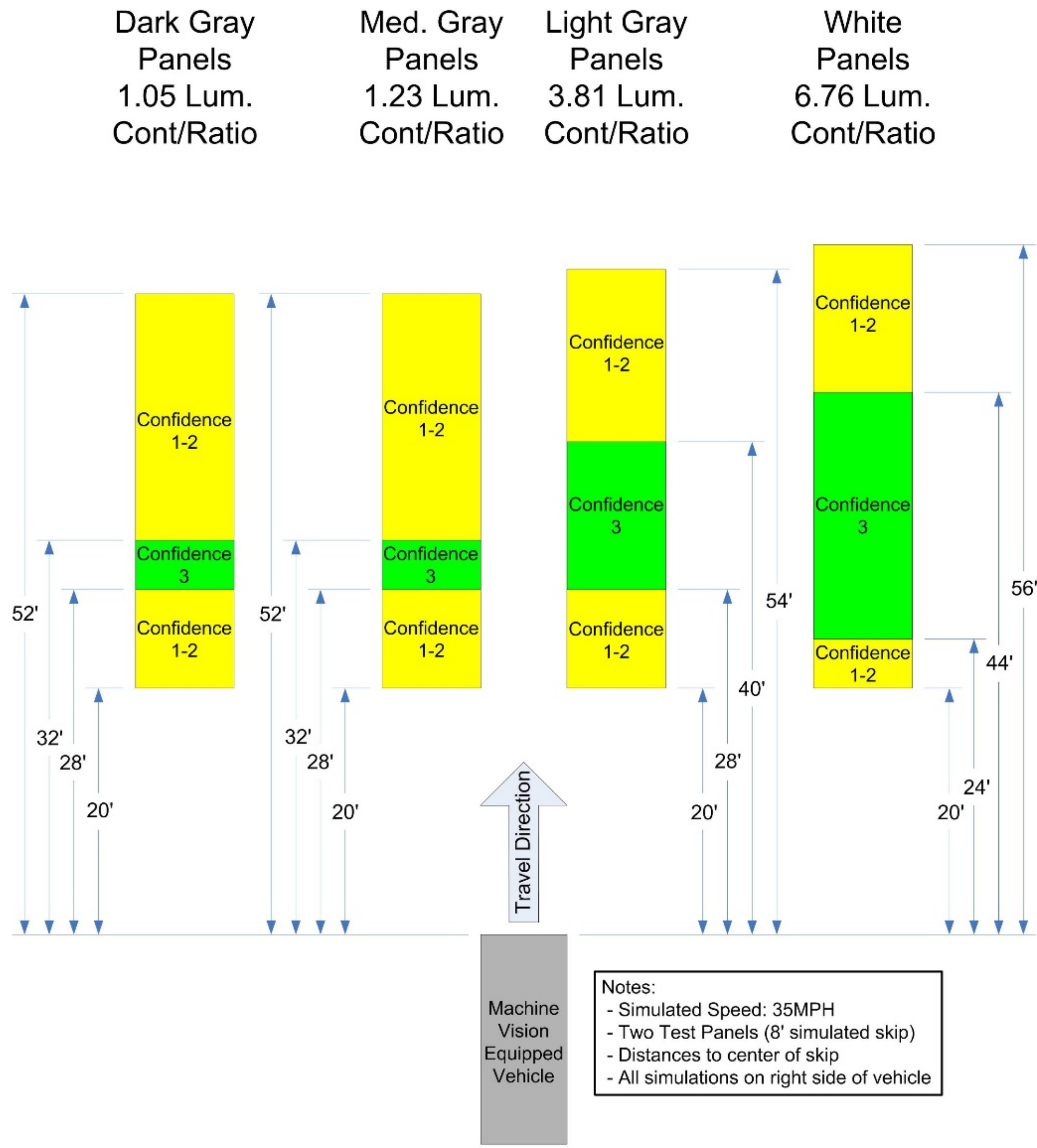
During the day, marking retroreflectivity has little impact on machine vision performance.



Daytime Window Testing

Phase 2 Results

During the day, luminance contrast ratio (not retroreflectivity contrast ratio) is the most important factor for machine vision performance.



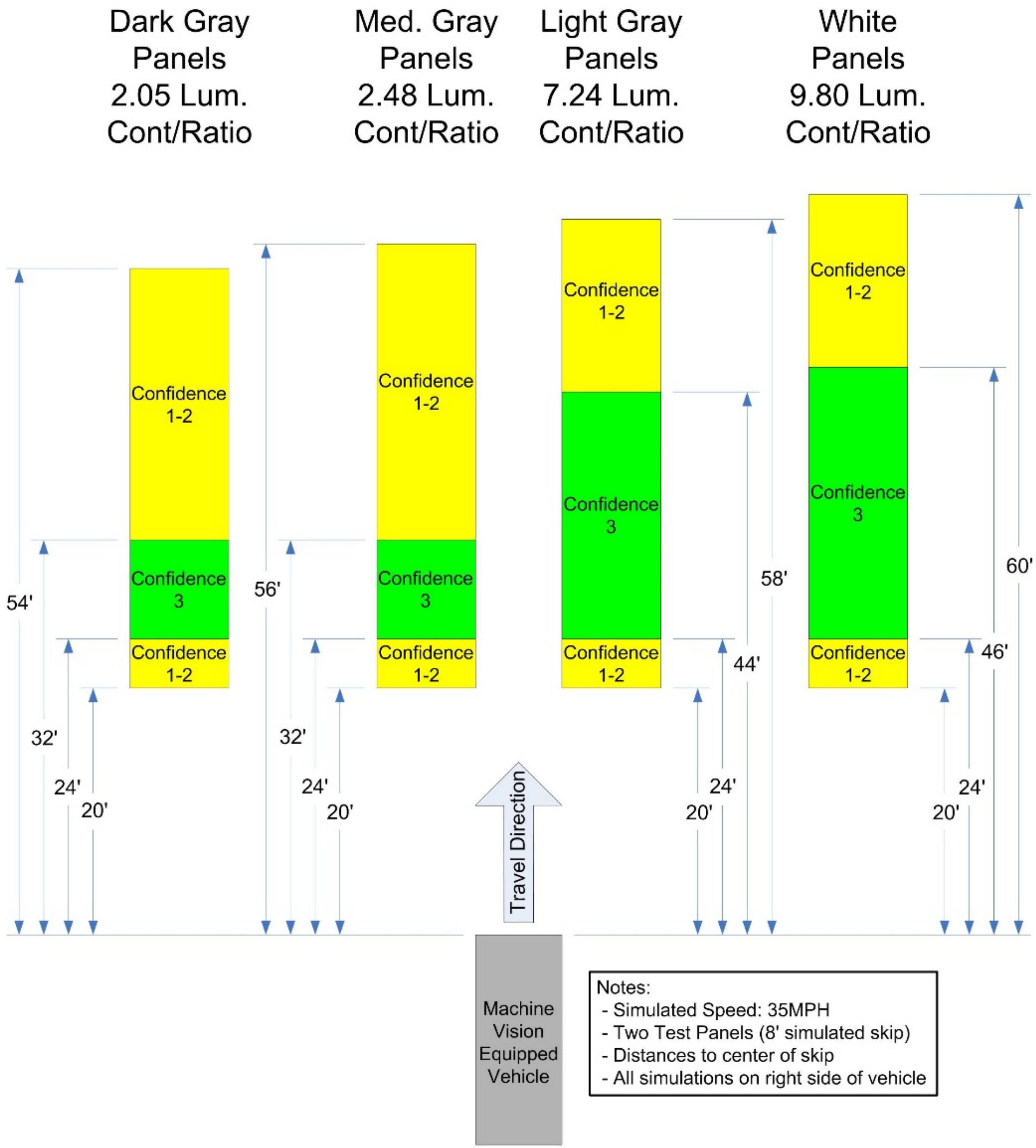
Daytime Luminance Contrast Ratio Testing – 25 mcd Pavement

Phase 2 Night Retro

- Higher Retroreflectivity increased Lane Confidence

Phase 2 Results

During the day, luminance contrast ratio (not retroreflectivity contrast ratio) is the most important factor machine vision performance.



Daytime Luminance Contrast Ratio Testing – 8 mcd Pavement

Phase 3 Questions

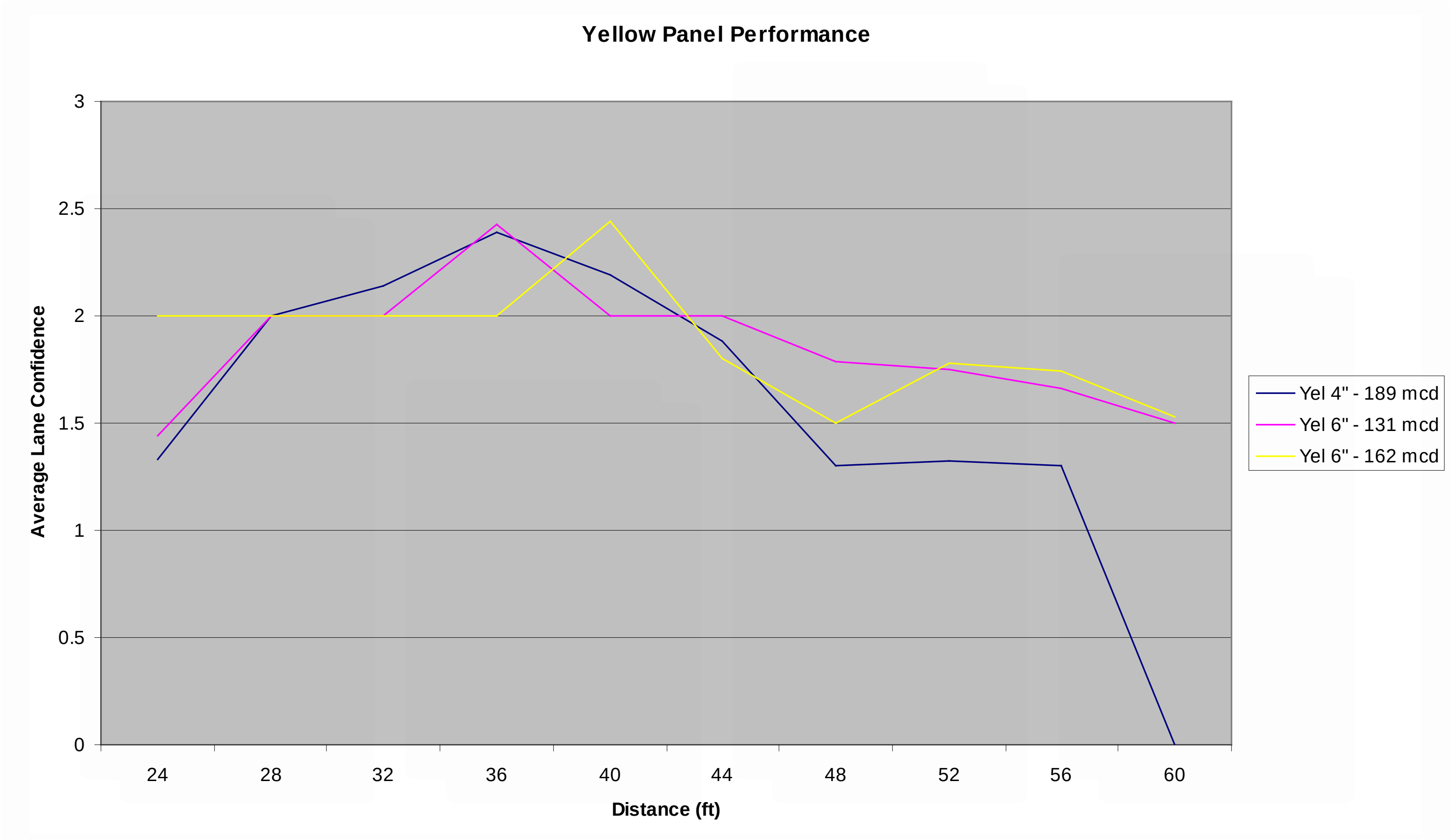
- How does the machine vision system perform against pavement markings of varying width?
- How does the machine vision system perform against various pavement markings in a wet recovery scenario?

Test Method

- The same system and test method used in the Phase 1 & 2 testing was used here.
- The simulated speed was kept at a constant 35MPH.
- For the wet recovery testing, a bucket of water was poured on the markings at the start of the test.
- All testing was done at night.

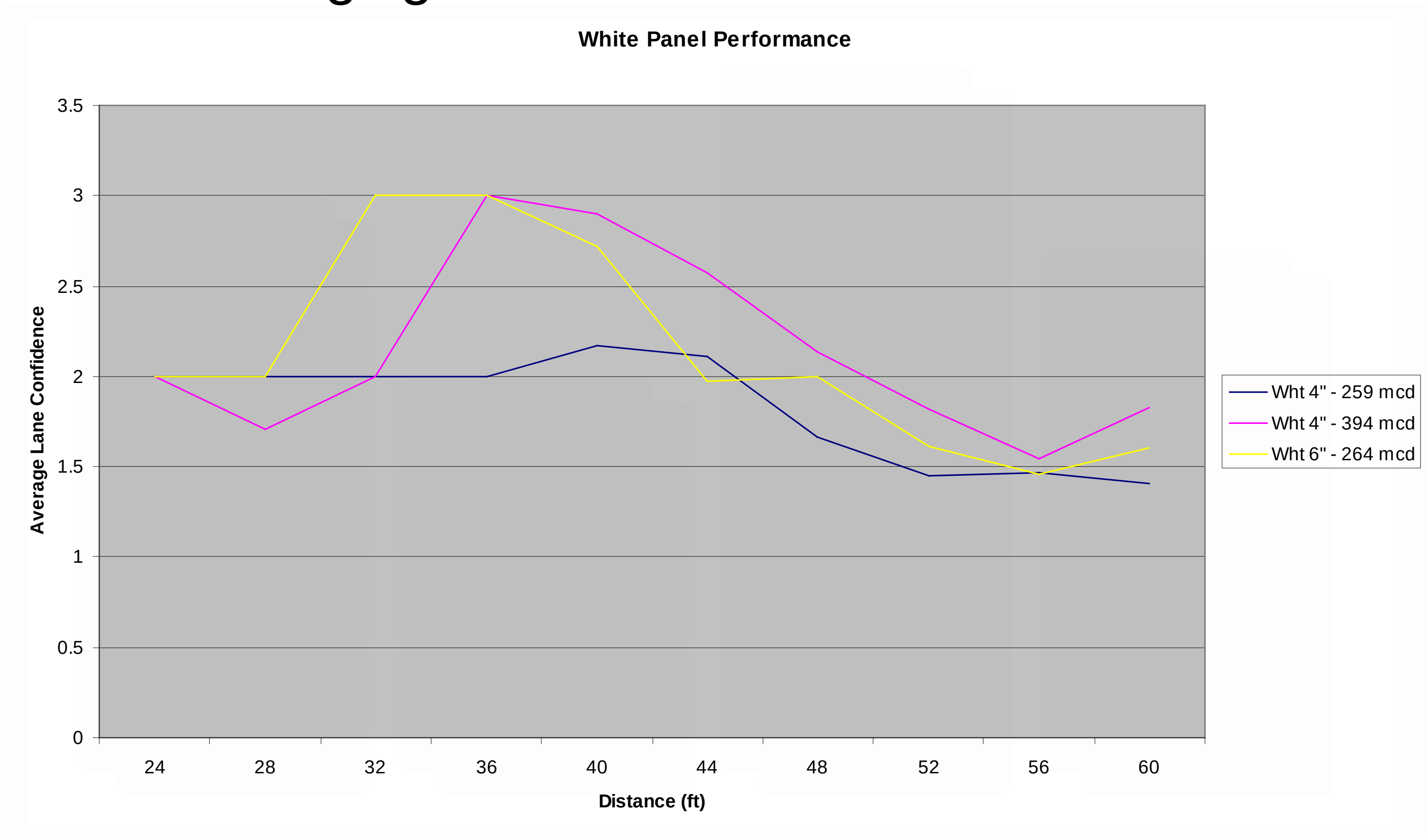
Phase 3 Results

- A 6” wide yellow panel of lower retroreflectivity performs as well (or better) than a 4” wide yellow panel of slightly higher retroreflectivity in a dry scenario – 50% more area returning light



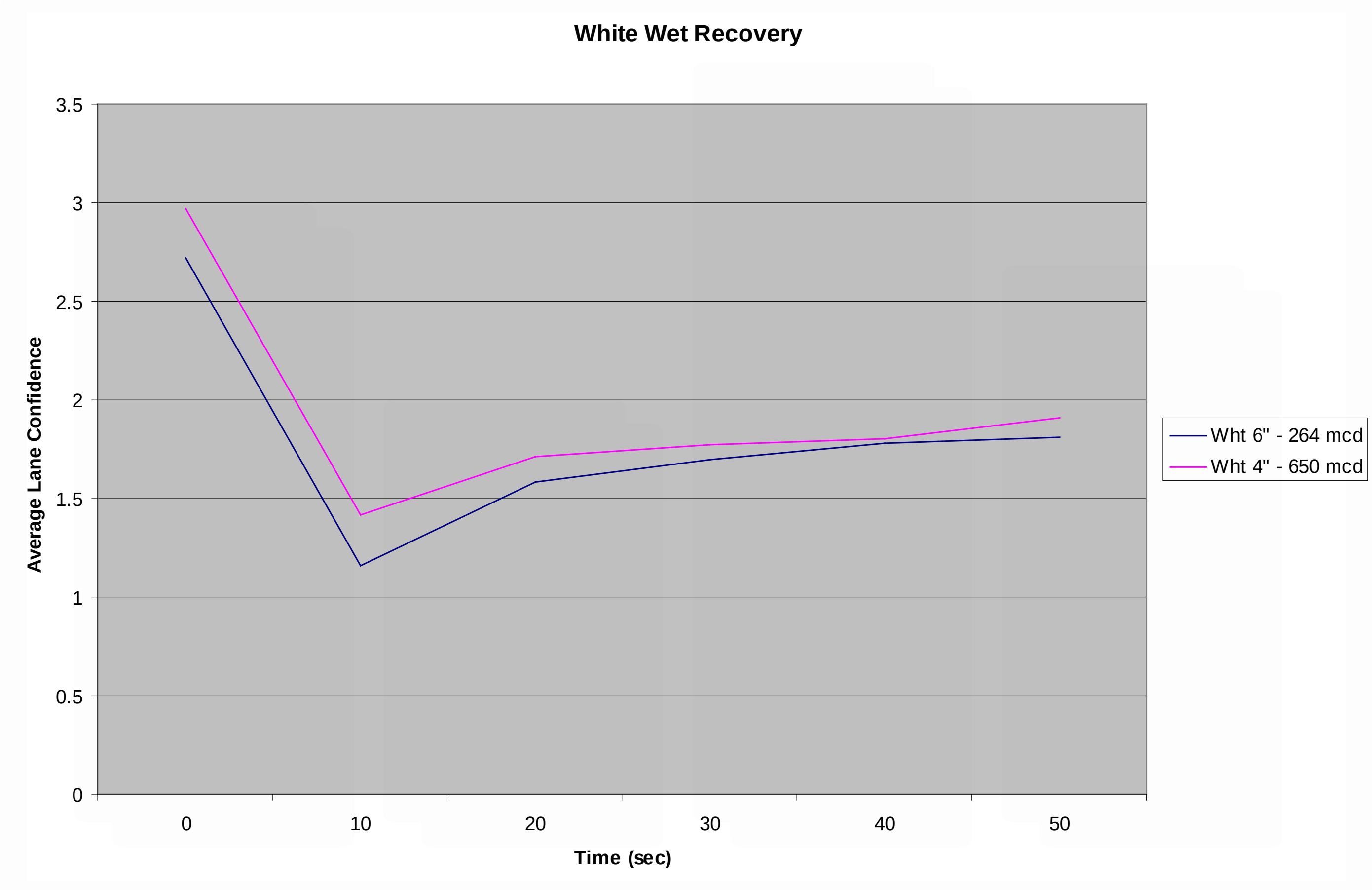
Phase 3 Results

- A 6” wide white panel of lower retroreflectivity performs as well (or better) than a 4” wide white panel of slightly higher retroreflectivity in a dry scenario – 50% more area returning light



Phase 3 Results

- A 6” wide white panel of lower retroreflectivity performs as well (or better) than a 4” wide white panel of higher retroreflectivity in a wet recovery scenario – 50% more area returning light



Next Steps

- Perform additional static testing on varying marking widths and materials to further quantify the machine vision performance in both dry and wet conditions.
- Modify test system software to get an accurate correlation between the machine vision and mobile retroreflectometer data.
- Perform dynamic testing in various conditions to confirm the results obtained during static testing.

Questions?

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Road Markings for Machine Vision
NCHRP Project 20-102(6)

Kick-Off Meeting

June 2016

Texas A&M Transportation Institute

NCHRP 20-102(6)

- Road Markings for Machine Vision
- Objectives
  - develop information on the performance characteristics of pavement markings that affect the ability of machine vision systems to recognize them
  - provide data and recommendations that the AASHTO/SAE Working Group can use to quickly develop guidelines and criteria

Texas A&M Transportation Institute

Work Plan

- Kick-Off Meeting
- Review Policies & Machine Vision Technologies
- Identify Testing Conditions
- Conduct Closed-Course Testing
- Analyze Results
- Prepare Reports

Texas A&M Transportation Institute

Current Testing Requirements

- **ISO 17361:2007**
  - No requirements on types of road markings
  - Lane markings must be in good condition and in accordance with the nationally defined visible lane markings std
  - No requirements on the environmental conditions
  - Visibility range must be greater than 1 km

- **NHTSA**
  - High contrast and uniform pavement
  - Lane marking specifications adhering to MUTCD
  - Avoiding tests in inclement weather including rain, fog, snow, hail, smoke, or ash

Texas A&M Transportation Institute

Texas A&M RELLIS Campus

Markings (Level 1)

Texas A&M Transportation Institute

Markings (Level 2)

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Markings (Level 3)

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Markings (Level 4)

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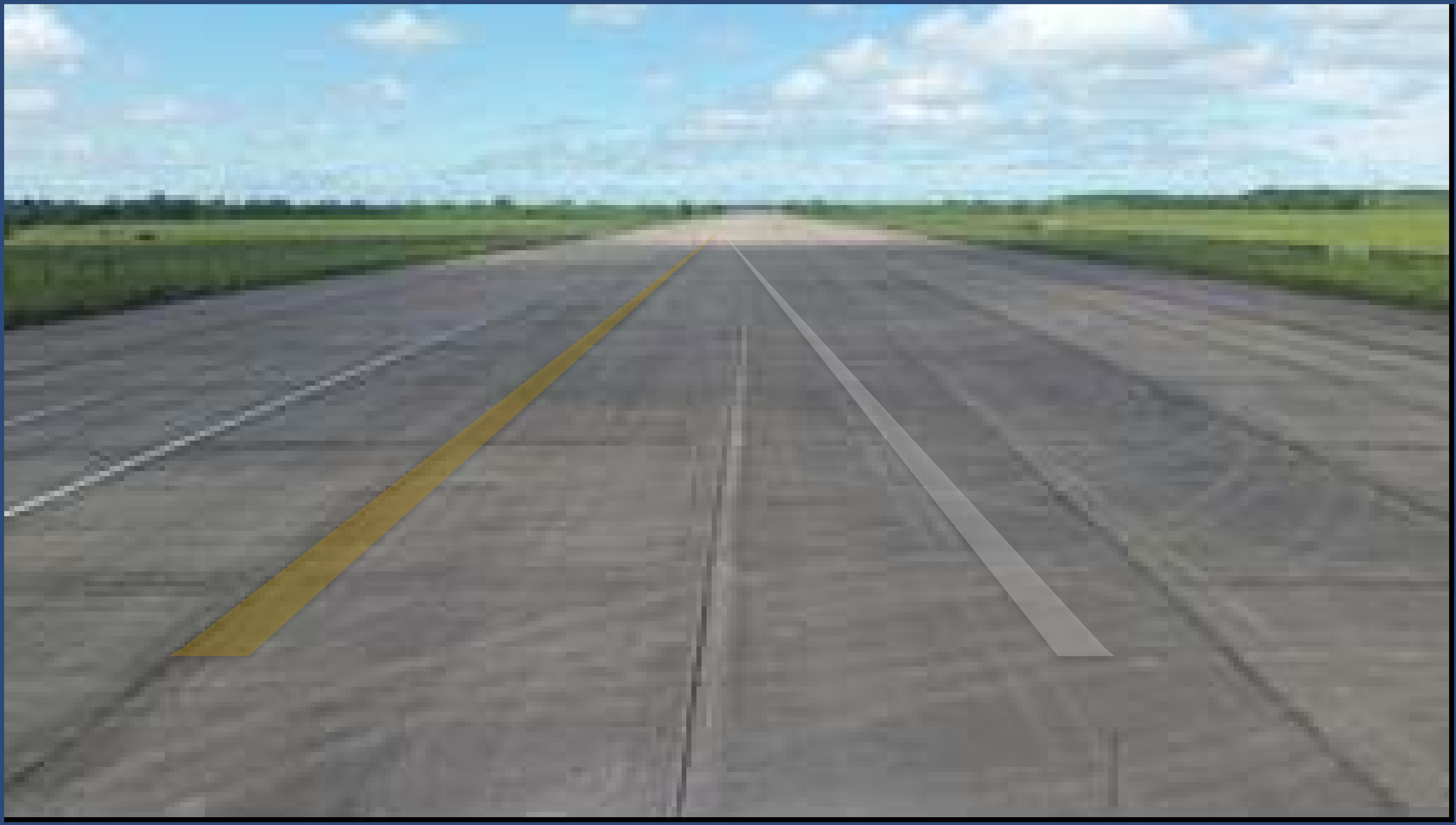
Markings (Level 5)



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Markings

- Test Markings (all 4-inch)
  - Continuous white
  - Continuous yellow
  - Skip white
  - Skip yellow
  - ~~Dotted extension white~~
  - ~~Raised retroreflective pavement markers~~
  - ~~Raised non-retroreflective pavement markers~~
  - ~~Contrast markings~~

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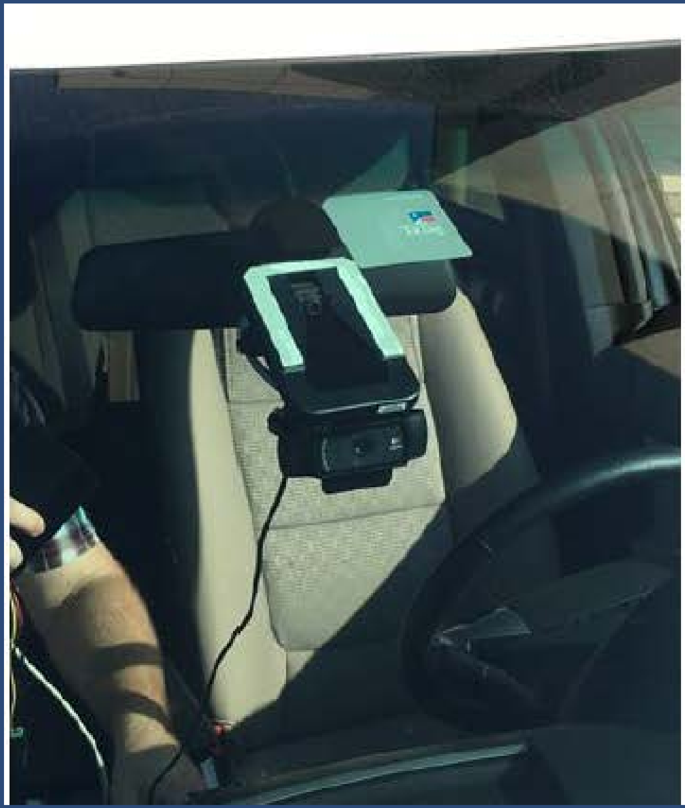
Testing Conditions

- Daytime
  - Dry and wet conditions
  - High sun position
- Nighttime
  - Dry and wet conditions
  - With and without roadway lighting
  - Tungsten-halogen and LED headlamps

Texas A&M Transportation Institute

Field Data



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SAE INTERNATIONAL

ROAD MARKINGS FOR MACHINE VISION SYSTEMS

Joint Working Group

AASHTO and SAE International

Kick Off Meeting – February 25, 2016

Follow Up Meeting – June 1, 2016

Many Challenging Conditions

- Uniform road marking criteria
- Preventive pavement maintenance treatments
- Horizontal curves
- Roadway lighting
- Nighttime conditions
- Wet conditions
- Snow conditions
- Debris
- Poor marking removal
- Shadowing

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Vehicle Machine Vision Interaction with Traffic Control Devices

Automated Vehicle Symposium 2016
Breakout Session #20: Physical Infrastructure, Work Zones and Digital Infrastructure

July 20, 2016

Toyota Motor Engineering & Manufacturing North America
Toyota Technical Center
Hideki Hada

Toyota's Approach for Automated Driving

Human driver and vehicle systems support each other
for safer and more efficient vehicular mobility.

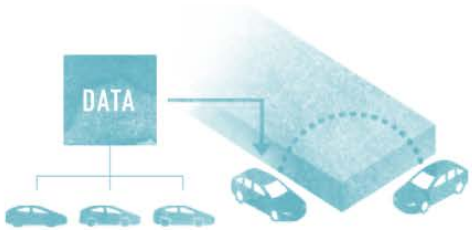
MOBILITY
TEAMMATE
CONCEPT
Automated Driving Tech.


Automated Highway Driving Assist
ITS World Congress (Detroit, 2014)

Driving Intelligence

Driving Intelligence

Inter-connectivity



Connected Intelligence

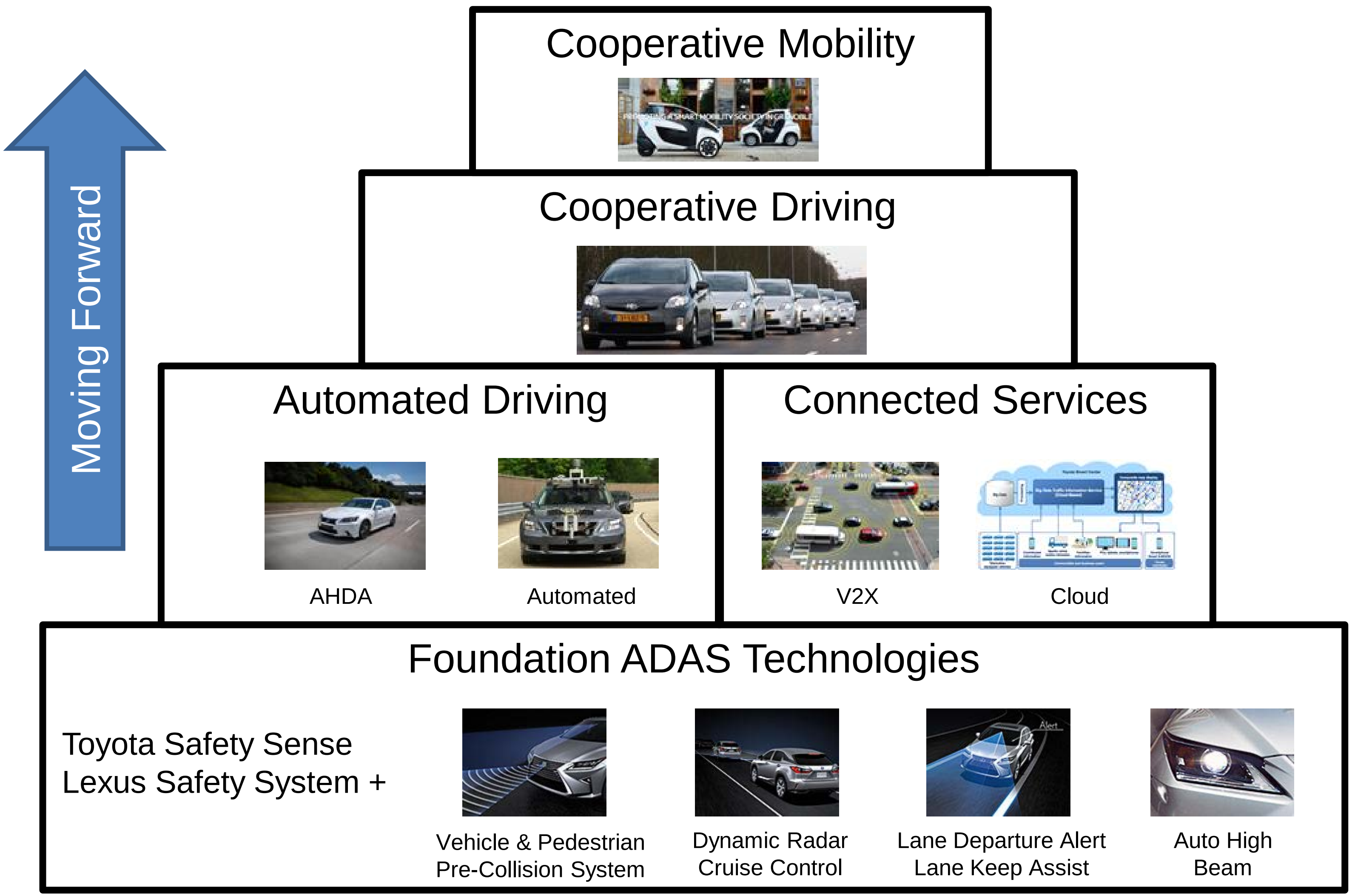
Cooperation between human and cars

Interactive Intelligence

http://www.toyota-global.com/innovation/automated_driving/

Building Blocks for Automated Driving

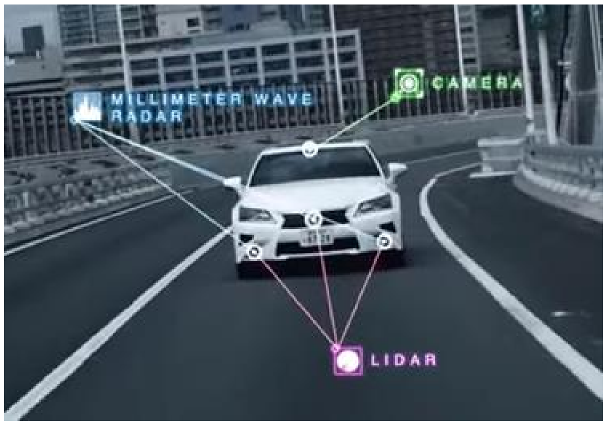
Automation is an important piece for a better mobility



On-Board Sensors for Automated Driving Systems

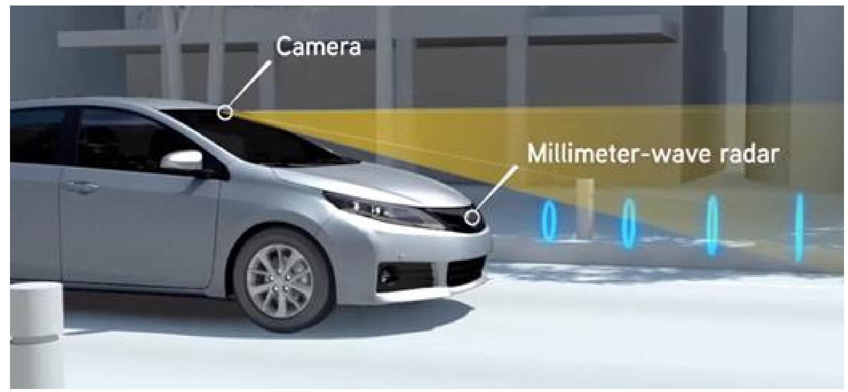
Automated driving system uses signals from ADAS sensors

<u>Automated Driving</u> On-Board Sensors



http://www.toyota-global.com/innovation/automated_driving/

<u>Driver Assist</u> On-Board Sensors



Vehicle & Pedestrian Pre-Collision System

Dynamic Radar Cruise Control

Lane Departure Alert

Auto High Beam

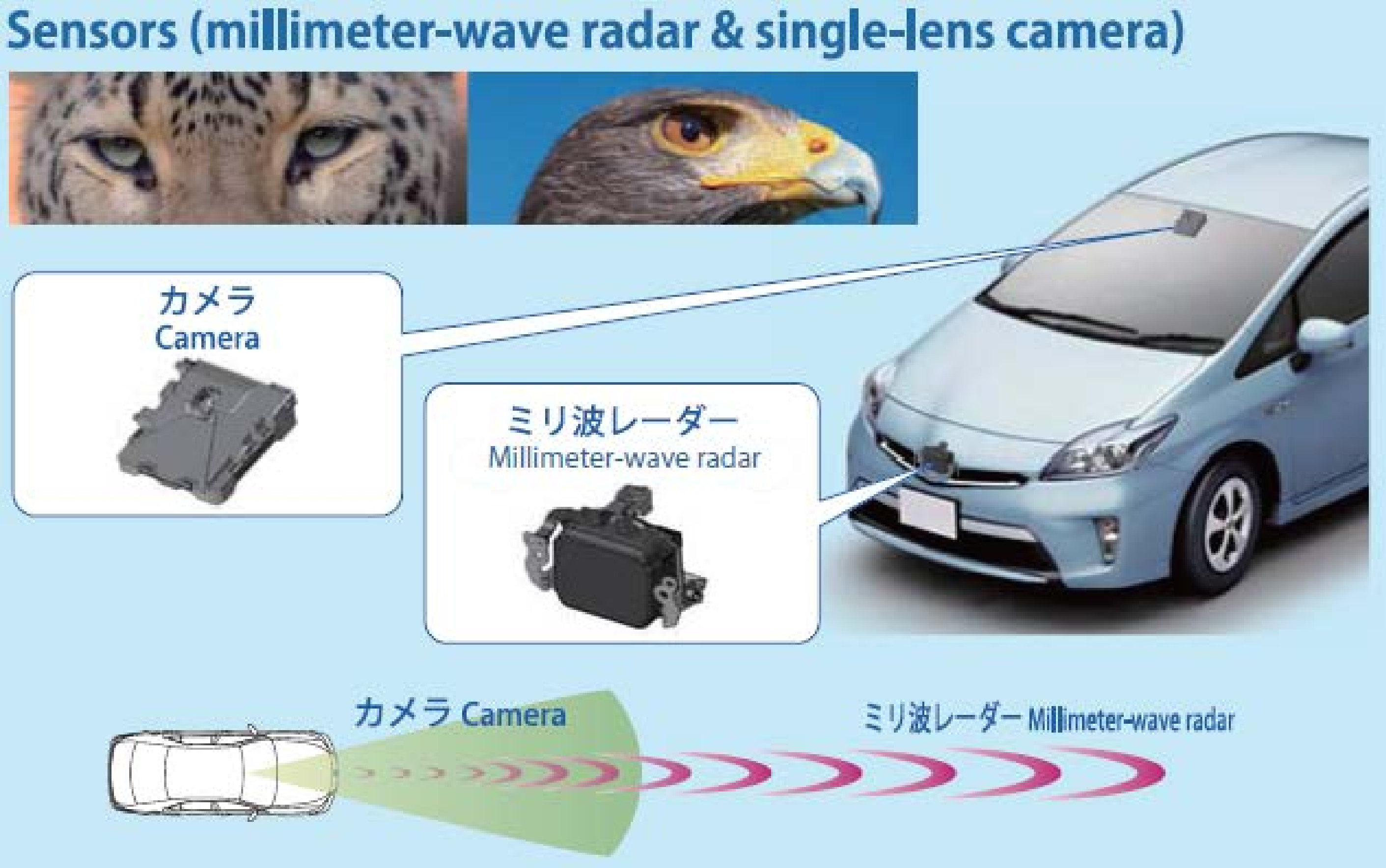
Toyota Safety Sense
Lexus Safety System +

http://www.toyota-global.com/innovation/safety_technology/toyota-safety-sense/
http://www.lexus.com/models/RX/packages#lexus-safety-system

On-Board Sensors for ADAS

Camera & radar are main sensors for current ADAS

LSS+ (Lexus Safety System +), TSS P (Toyota Safety Sense P)



Government-Industry Initiative to Deploy ADAS

On-board sensors will be more common in a near future

September 11, 2015
Initial AEB Announcement

U.S. DOT to add automatic emergency braking to list of recommended advanced safety technologies in 5-Star Rating system

NHTSA 45-15
Monday, November 2, 2015
Contact: Kathryn Henry, 202-366-9550, Public.Affairs@dot.gov

Technology helps drivers brake to avoid or mitigate rear-end crashes

WASHINGTON - The U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) today announced that beginning with model year 2018, the agency will update its 5-Star Rating System to include automatic emergency braking (AEB) as a recommended safety technology, providing consumers with new information on technology with the potential to prevent rear-end crashes or reduce the impact speed of those crashes by automatically applying the brakes.

March 17, 2016
AEB MOU Announcement

U.S. DOT and IIHS announce historic commitment of 20 automakers to make automatic emergency braking standard on new vehicles

Thursday, March 17, 2016
NHTSA contact: Gordon Trowbridge, 202-366-9550, Public.Affairs@dot.gov
IIHS contact: Russ Rader, 703-247-1530

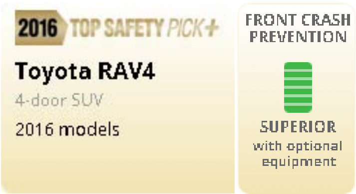
Additional Resources
» AEB Fact Sheet
» Administrator Rosekind's remarks

McLEAN, Va. - The U.S. Department of Transportation's National Highway Traffic Safety Administration and the Insurance Institute for Highway Safety announced today a historic commitment by 20 automakers representing more than 99 percent of the U.S. auto market to make automatic emergency braking a standard feature on virtually all new cars no later than NHTSA's 2022 reporting year, which begins Sept 1, 2022.

ADAS Performance Assessment

Several assessment programs are also accelerating deployment of on-board sensors for ADAS systems

IIHS HLDI



ConsumerReports

NHTSA
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

Year/Make/Model	Overall	Frontal Crash	Side Crash	Rollover	Recommended Technologies
2016 Toyota Highlander SUV FWD	★★★★★	★★★★☆	★★★★★	★★★★☆	
2016 Toyota Highlander SUV AWD	★★★★★	★★★★☆	★★★★★	★★★★☆	
2016 Toyota Highlander HV SUV AWD	★★★★★	★★★★☆	★★★★★	★★★★☆	

IIHS AEB: ADAC Target

NHTSA CIB/DBS: SSV

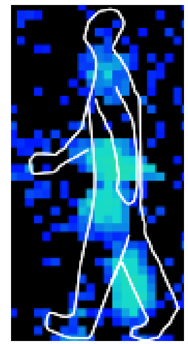
Future 3D Target

Target for ADAS Performance Confirmation

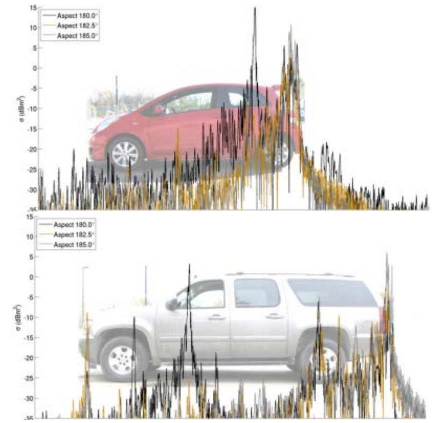
ADAS system performance is assessed against targets.

But, creation of good target is a real science

http://www.businessfinancenews.com/28331-toyota-motor-forefront-in-auto-safety-almost-all-toyota-cars-to-have-aeb-by/



Research into Evaluation Method for Pedestrian Pre-collision System



Radar Scanning for Development of Vehicle and Pedestrian Surrogate Targets for Vehicle Pre-Collision System (PCS) Testing, Rini Sherony, January 31st, 2013

http://www.4activesystems.at/en/

Target Road for ADAS Performance Confirmation?

How do we vehicle performance against roads?
(it would be nice to see a standard road…)

Traditional Approaches

- Camera
- Road Map
- Test Drive
- Experience

https://www.udot.utah.gov/main/f?p=100:pg:0:::1:T,V:3832,

http://www.nyc.gov/html/visionzero/pages/initiatives/street-design.shtml

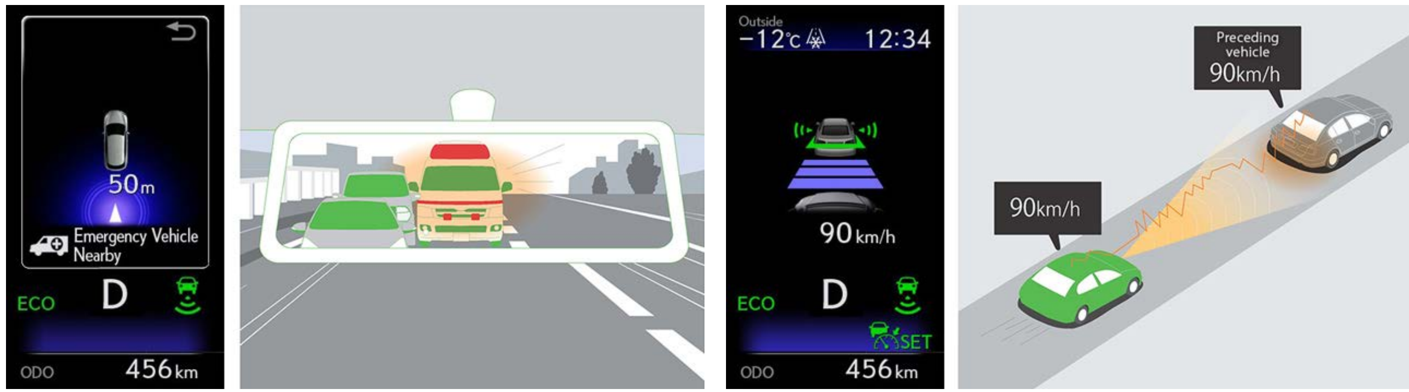
New Opportunities

- V2X
- 3D Map
- Data
- Levels

V2X as an Additional Sensor for Automated Driving Systems

V2X DSRC Technologies are also in the market

iTS CONNECT



Japanese: http://toyota.jp/technology/safety/itsconnect/
English: http://www.toyota-global.com/innovation/intelligent_transport_systems/infrastructure/

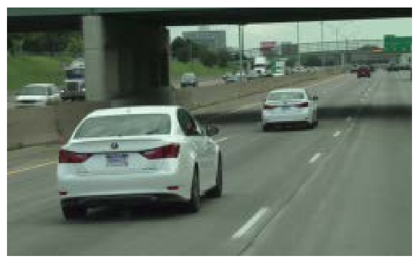
Automated Highway Driving Assist – 2014 Demonstration

Safety enhancement with driving automation technologies

Driver Assist:
On-Board Sensors

Lateral and Longitudinal Control

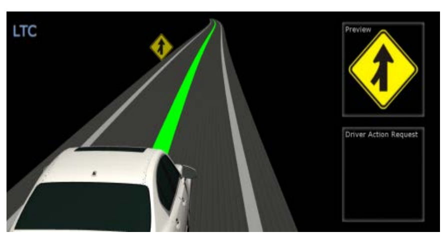
DRCC
Dynamic Radar Cruise Control



LTC
Lane Trace Control

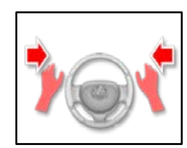
Two-Way Driver-Vehicle Interaction

Preview HMI



Driver Monitor HMI

Face Direction Detection



Steering Touch Sensor

Automated Highway Driving Assist – 2014 Demonstration

Infrastructure information for automation (map): an early alert about the road conditions where adequate support from the vehicle system may be limited.

A: Left Merge Preview

An uncommon merge from left is ahead

B: Exit Only Lane Preview

The AHDA vehicle needs to exit the highway if remains in this lane

C: Unsupported Scene Preview

Difficult to see lane markings by camera.

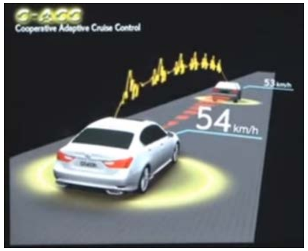
D: End of Highway Preview

The current highway ends.

Connected and Automated

Information from & about the road, traffic and other vehicles will enhance capabilities & performance of automated vehicle control systems.

V2X Communication

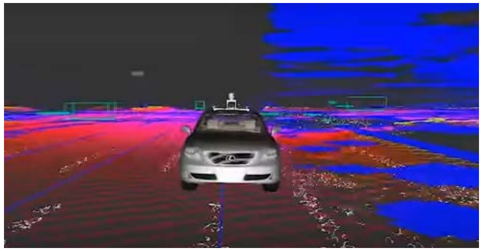


Automated Driving

Advanced Sensing

Digital Map

Data



Better Driving Experience

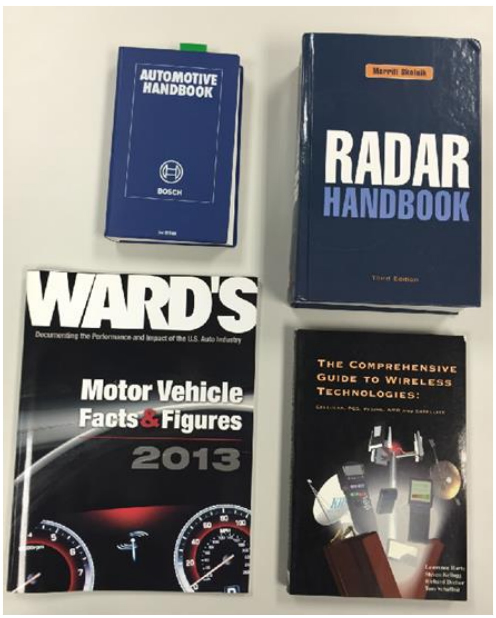
Toyota to Display New Map Generation System at CES 2016
http://corporatenews.pressroom.toyota.com/releases/toyota+map+generation+ces+2016.htm

Toward More Cooperative Driving: Road & Vehicles

Our goals are the same. We need each other.

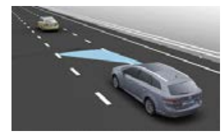
But… are we working together?

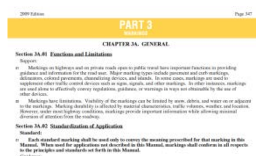
<u>We have two sets of materials.</u>



Vehicle Design

How should we set requirements for lane marker detection?





It is in Part 3 of MUTCD (90 pages). They are guidelines.

There are many faded lane markings. (“ fix the road “)

It is maintained based on our standards. (“make cars better”)

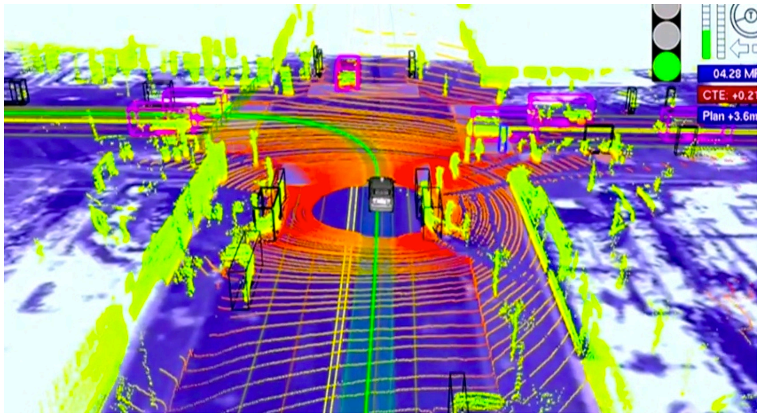
Road Design

<u>It is a good time for us to work together.</u>

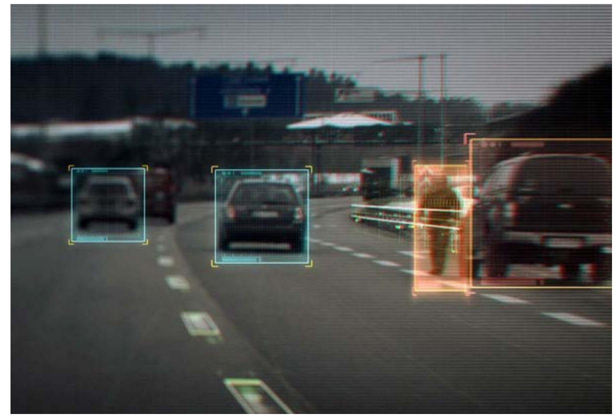
What Vehicles can “See”

Sensing technologies have been improving significantly.

(sample images found through Google search “sensor image on-board car ”)



http://spectrum.ieee.org/automaton/robotics/artificial-intelligence/how-google-self-driving-car-works



http://www.4erevolution.com/volvo-drive-me/

http://autonomos-labs.com/research/

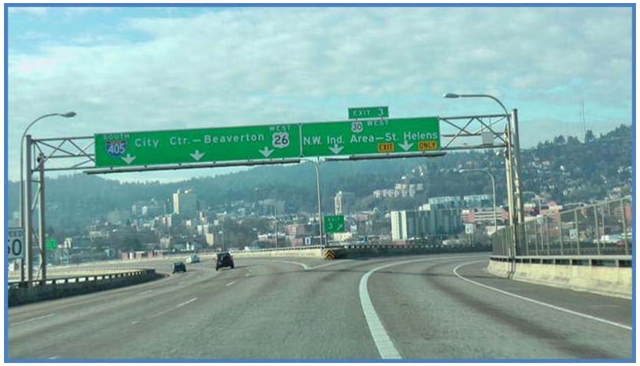
http://www.linleygroup.com/mpr/article.php?id=11437

http://wccftech.com/tesla-autopilot-story-in-depth-technology/4/

What Vehicles may not be able to “See” sometimes

There are still areas for improvements.

It cannot see it if it is not there.



https://www.fhwa.dot.gov/publications/research/safety/13048/004.cfm

It may not see everything

https://www.transportation.gov/fastlane/new-york-city-florida-pilot-overnight-truck-deliveries

It may not see it if it is hard to see.

http://www.mlive.com/news/detroit/index.ssf/2015/02/schools_close_spin-out_crashes.html

It may see something even it is not there.

And, also it is very dynamic…

Lane Detection and Tracking (https://www.youtube.com/watch?v=BadCBN48ztY), Smartmicro 3DHD Automotive Radar (https://www.youtube.com/watch?v=ON97Bm-IKgE&list=PL52C8001562502C7D), Delphi Automotive Radar provided by AutonomouStuff (https://www.youtube.com/watch?v=OovcjSbbdBM)

Potential Areas for Collaborative Work

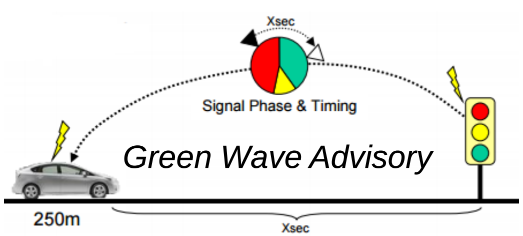
Personal thoughts…

Identify crash prevention countermeasures through crash causation and crash history studies?

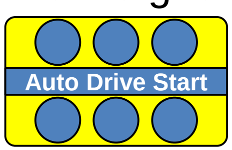
Designate "auto drive capable" roads?

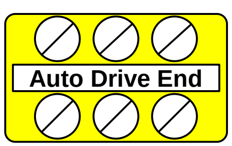
http://www.ops.fhwa.dot.gov/publications/fhwahop14022/chapter5.htm

Avoid Smart Road – Smart Car Conflict

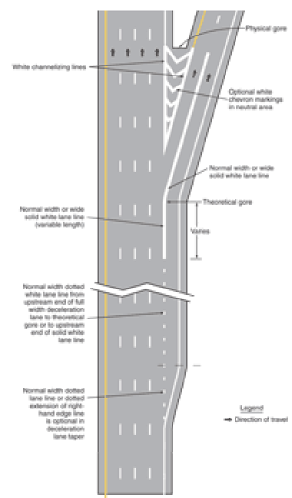


New Signs?

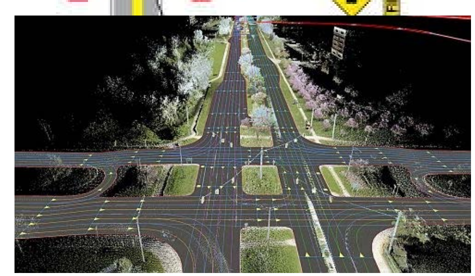




Joint Review of MUTCD?



Mapping Convention of Signs?



http://www.car-engineer.com/here-provider-of-real-time-digital-maps/

Better Roads and Better Vehicles = Better Driving

Connected and automated driving brings good driving experience.

On-Board Sensor | ***DSRC*** | ***Map, Data, and Other Technology Improvement***

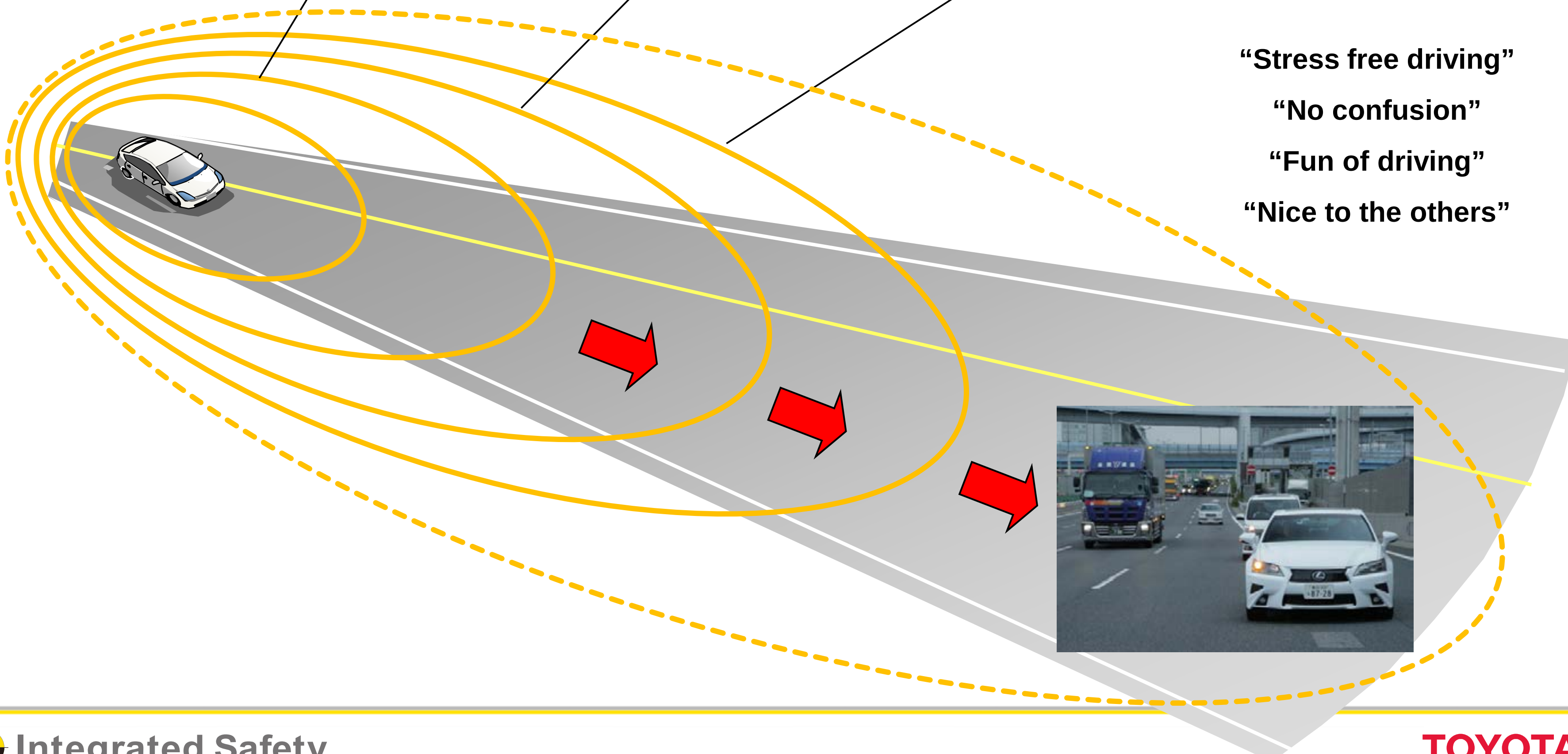
Collision Mitigation → **Collision Avoidance** → **Risk Mitigation** → **Risk Avoidance** → **Guarded Driving**

"Stress free driving"

"No confusion"

"Fun of driving"

"Nice to the others"



Summary

Vehicle Technology:

- Improvement of ADAS system availability and performance enables enhancement of Advanced Driving Support Systems (ADAS) toward automated driving.
- V2X and data/map will serve as additional sensors.

Road-Vehicle Interaction:

- Inter-industry dialogue is essential for:
  - Ensuring good performance of vehicle systems on public highways
  - Avoiding potential conflict between smart cars and smart roads.
  - Setting roadmaps toward deployment of new technologies.
  - Sharing know-hows for improving traffic safety
- Talk between industry associations may be most efficient.
  - Than all OEMs trying to talk to all states separately.

AVS 2016
BREAKOUT SESSION #20

Dynamic Map Development in SIP-adus

Cross-Ministerial Strategic Innovation Promotion Program
Innovation of Automated Driving for Universal Services

July 20, 2016

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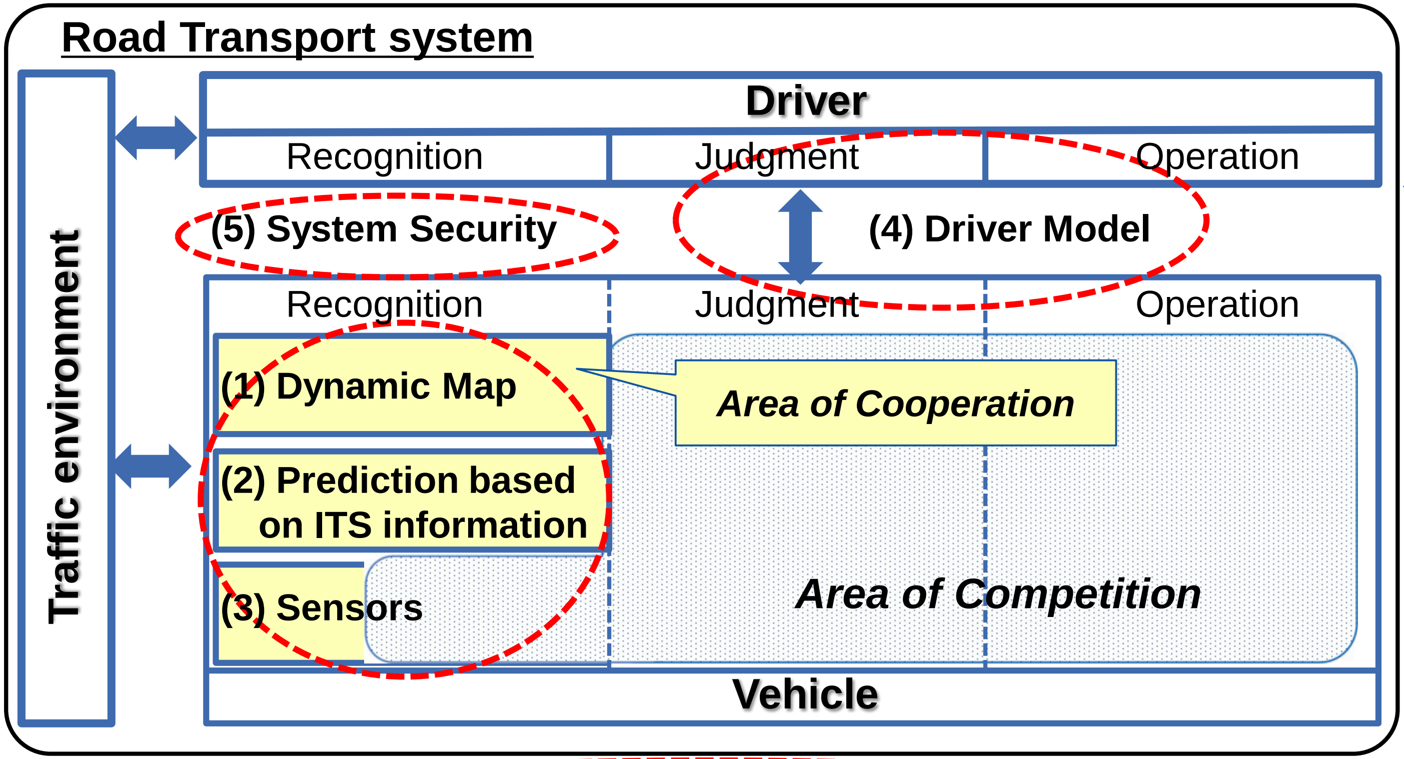
（Nissan Motor Company）

Scope of SIP-adus

(I) Development and verification of automated driving system



(III) International cooperation

(1) Open research facility
(2) Social acceptance
(3) Technology transfer

(1) Enhanced local traffic management
(2) Next generation transport system

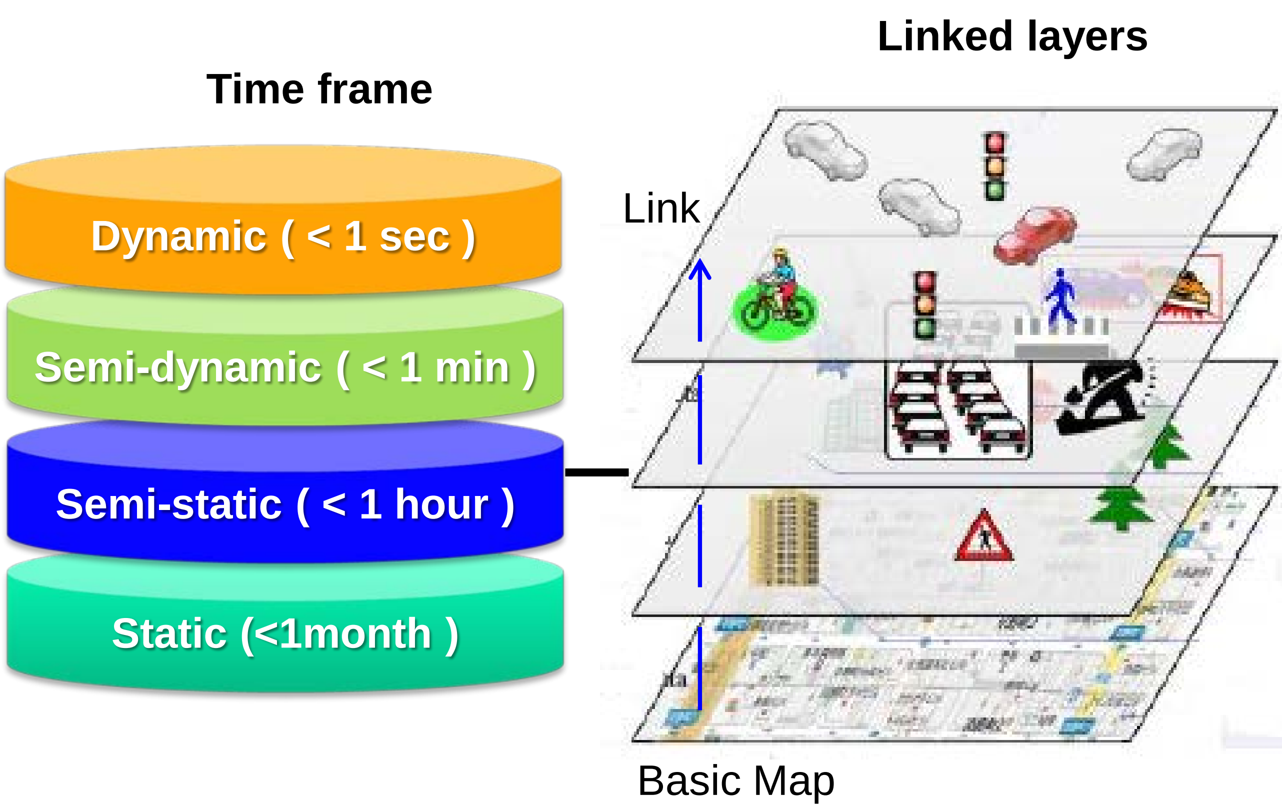
(IV) Development for next generation urban transport

(1) Traffic fatality reduction effect estimation method & national shared database
(2) Macro and micro data analysis and simulation technology
(3) Local traffic CO_2 emission visualization technology

(II) Basic technologies to reduce traffic fatalities and congestion

Dynamic Map

Hierarchical structure of digital ‘Map’ layered by time frame



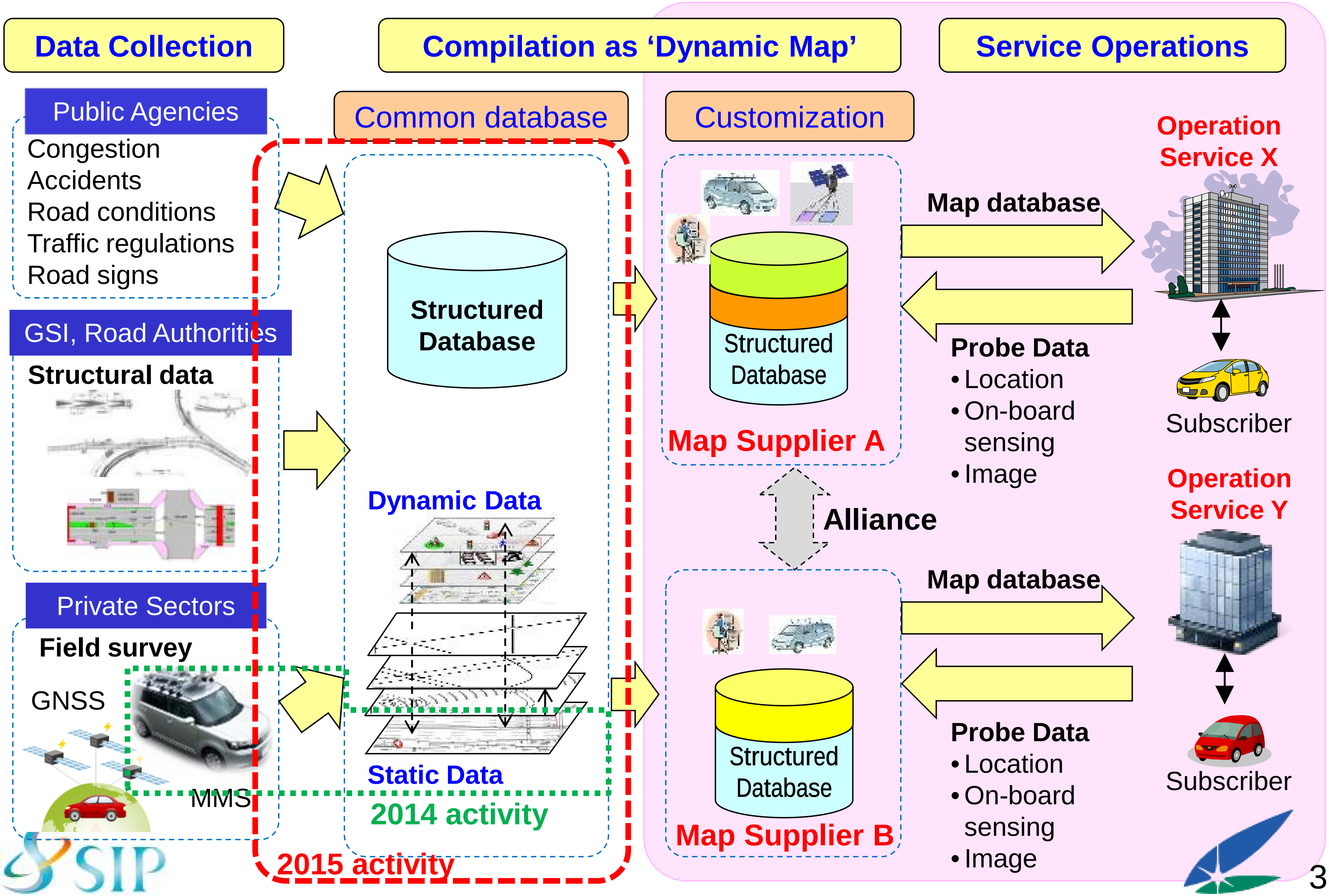
Information through V to X
- surrounding vehicles
- pedestrians
- timing of traffic signals

Traffic Information
- accidents
- congestion
- local weather

Planned and forecast
- traffic regulations
- road works
- weather forecast

Basic Map Database
- Digital cartographic data
- Topological data with unique
- Road Facilities

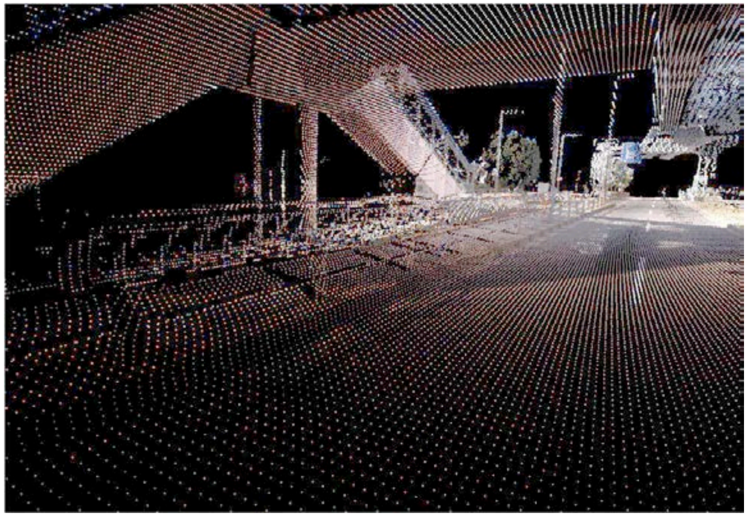
Framework for Dynamic Map



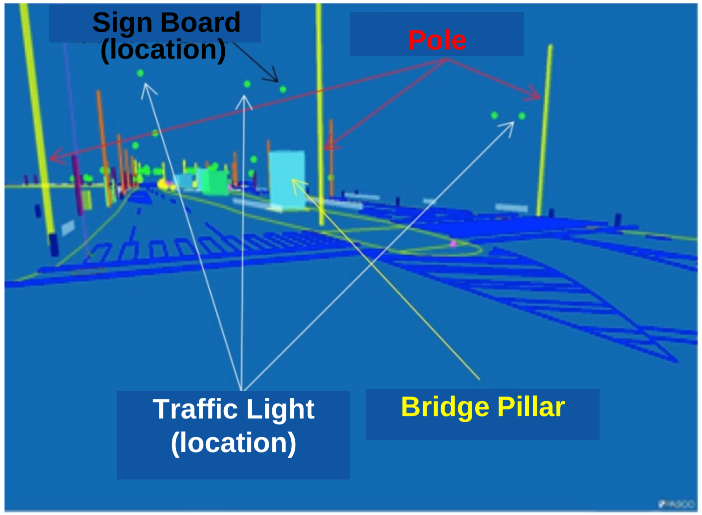
Prototyping HD Static Map (2014)

Road Environment

Target Area

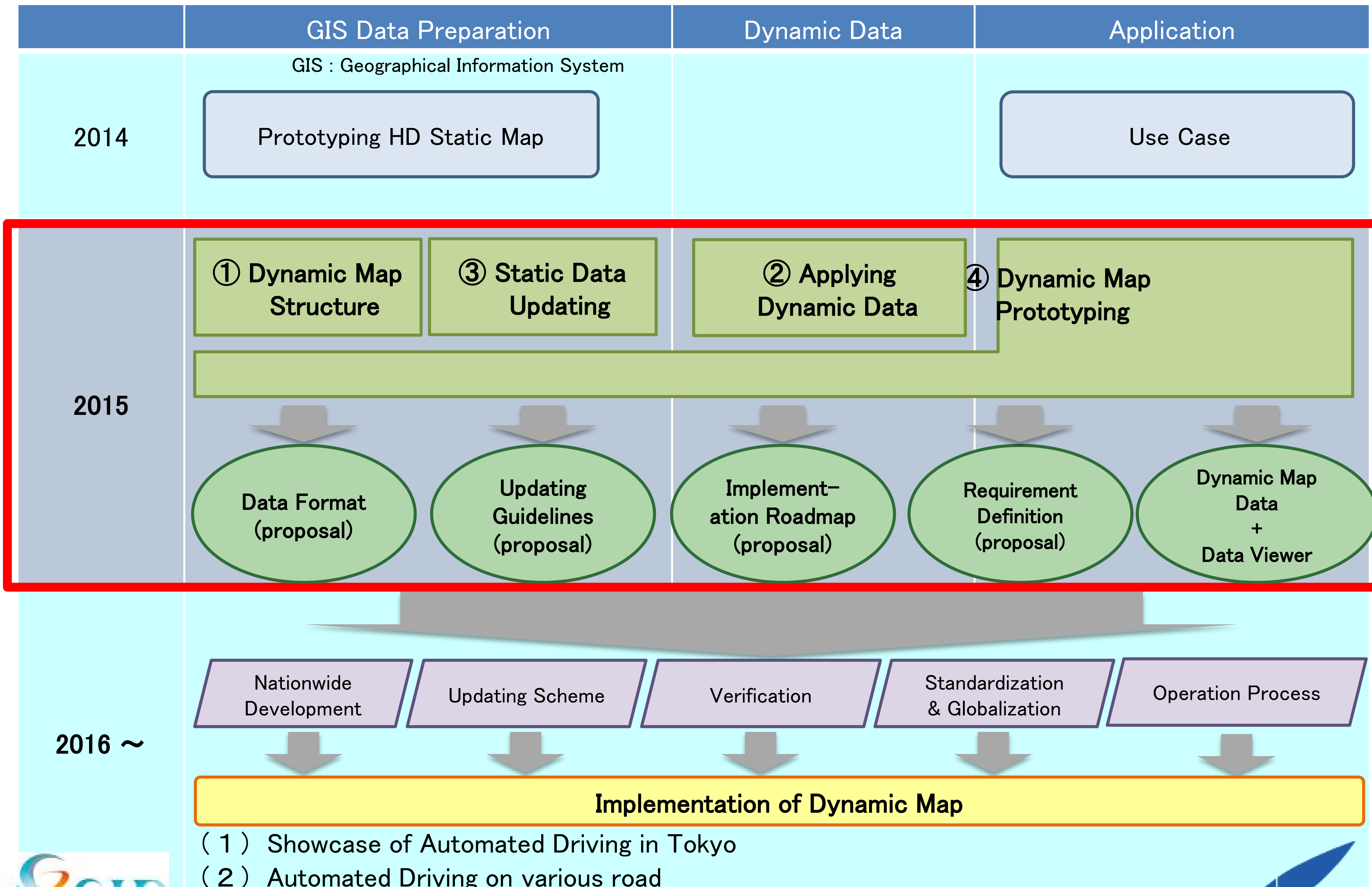


3D Measurement



Linked Objects

Static + Dynamic Data Structuring

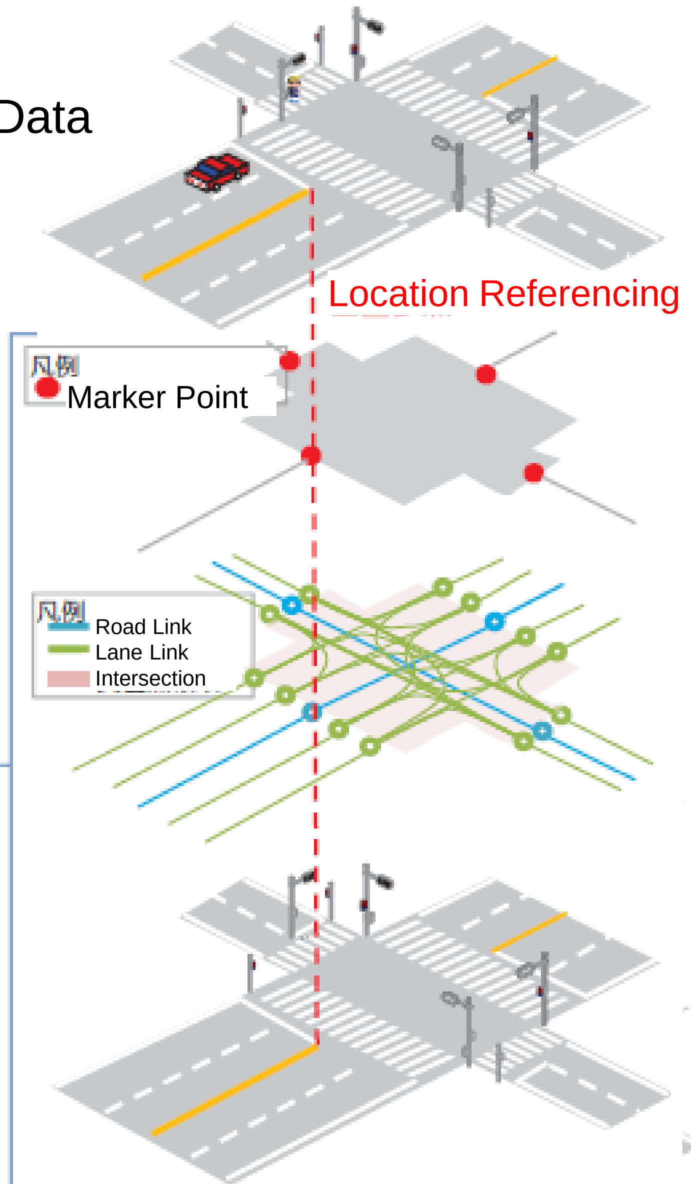


Dynamic Map Structure

Dynamic Data

Static Data

±25cm Relative accuracy



Dynamic Data
Vehicle, Pedestrian, Traffic light : Point data
Traffic jam, Traffic control info. : Line data

Location Reference Layer
Section ID, Marker Point, Longitude & Latitude

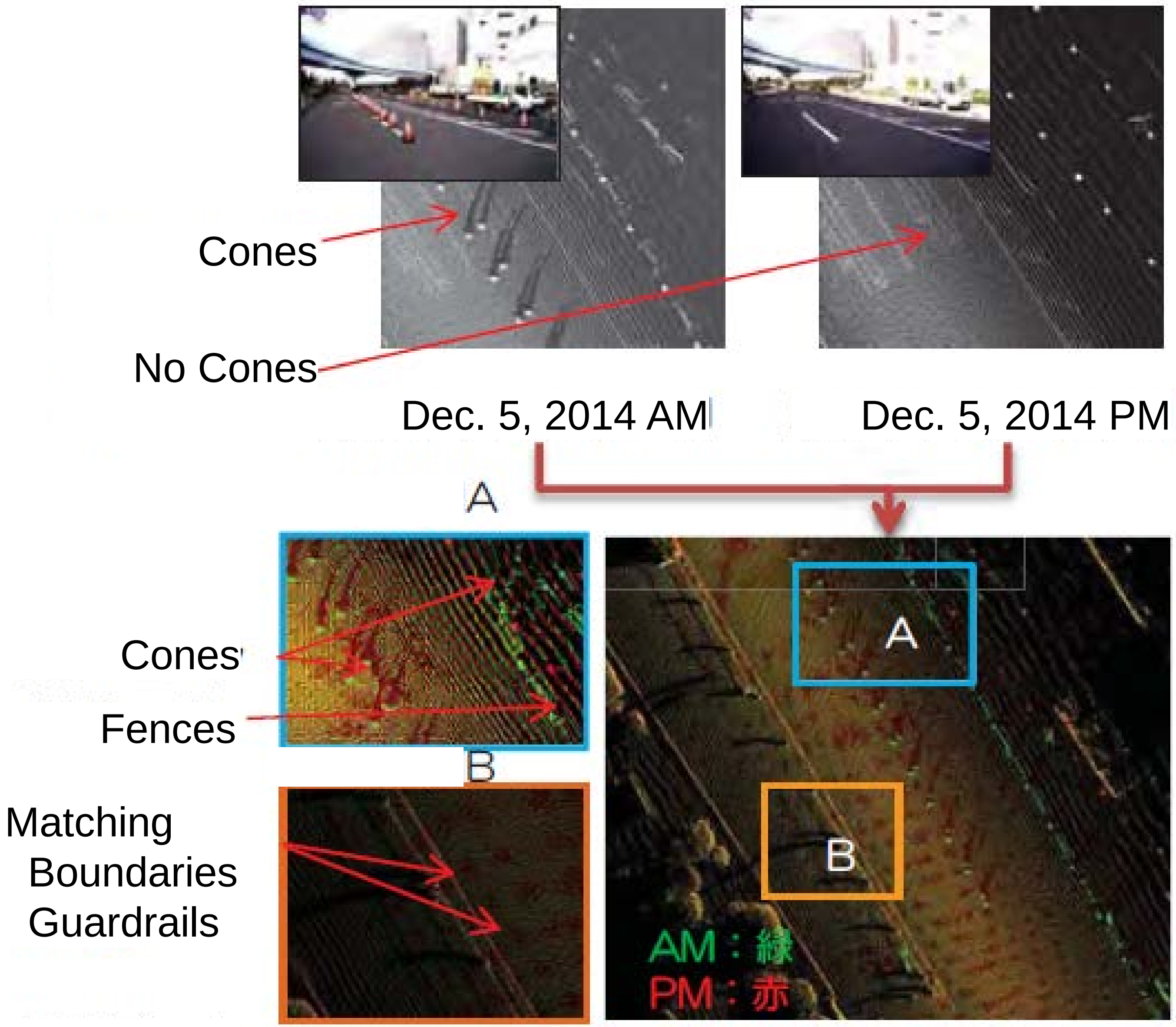
Digital Roadmap, Lane-level map

Virtual Features
Road link, Lane link, Intersection area

Mapping from MMS data

Real Features
Lanemark, Shoulder, Stopline, Crossing, etc.

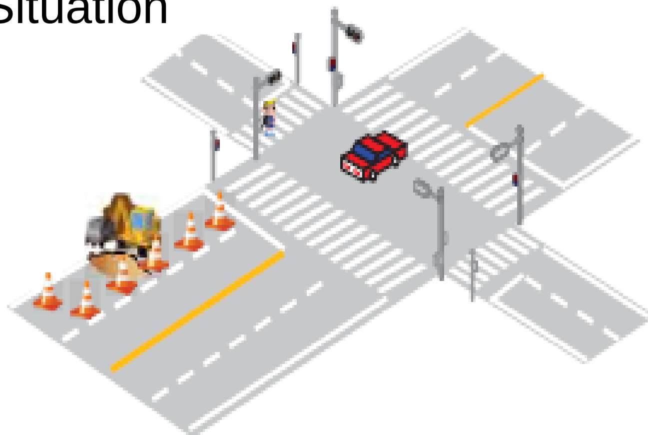
Static Data Updating



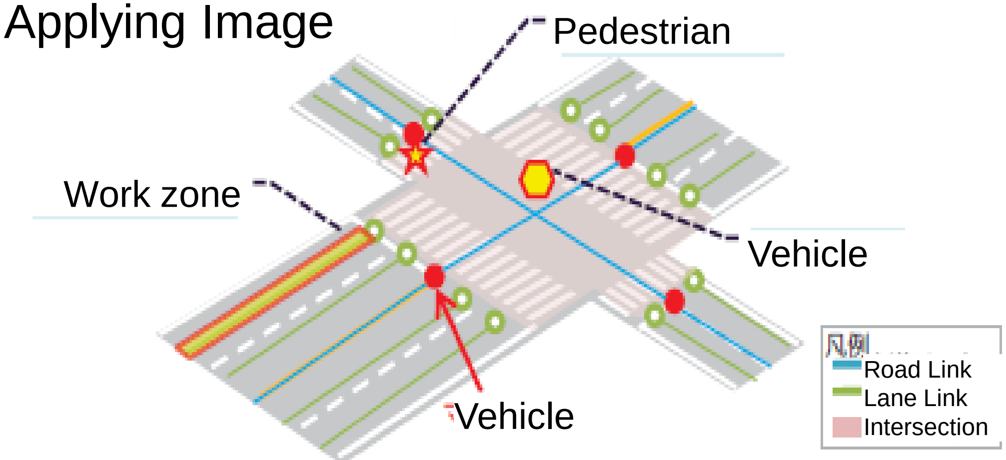
Matching 2 layers

Applying Dynamic Data

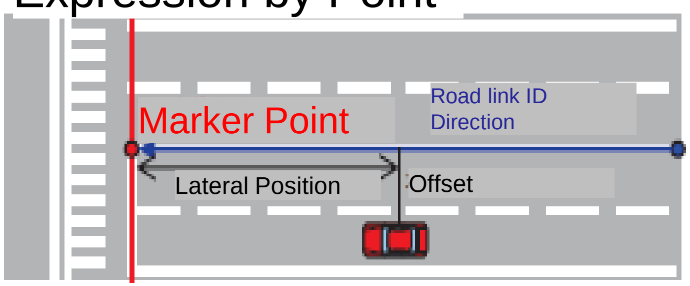
Actual Situation



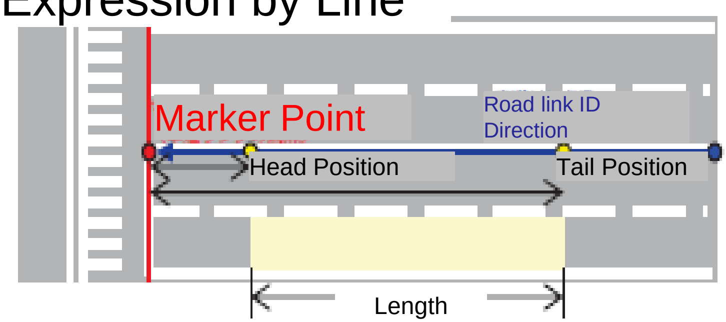
Applying Image



Expression by Point



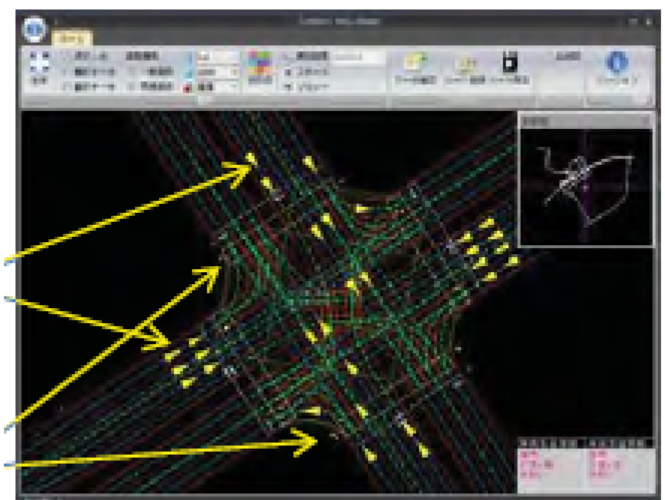
Expression by Line



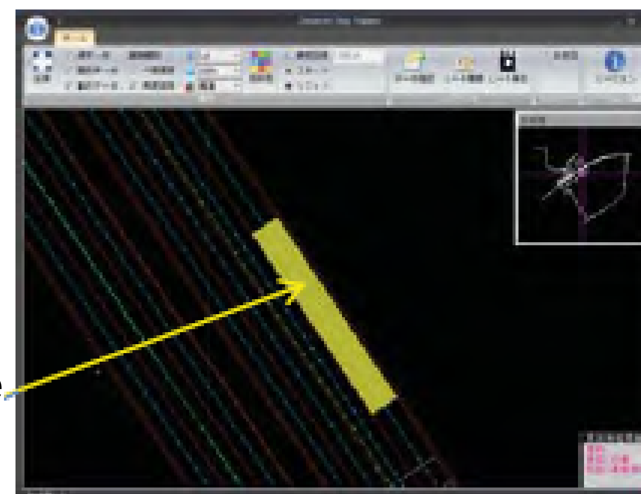
Dynamic Map Prototyping - Viewer

Vehicle

Pedestrian



Work zone



Next Steps

- **Applying Real Dynamic Data to Dynamic Map Structure**
- **Evaluation in Large Area**
- **International Standardization**

Thank you for your attention !