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Co-benefits and tradeoffs between safety, mobility, and environmental impacts for connected and automated vehicles

A large number of Connected and Automated Vehicle (CAV) applications are being designed, developed, and deployed in order to greatly improve our transportation systems in terms of safety, mobility, and reducing environmental impacts. These benefits can be quantified by a variety of performance measures that are often cited in the literature. However, most of these CAV applications are typically designed to improve transportation systems only in a particular dimension, usually focusing on either safety, mobility, or the environment. Very few research papers have considered a wider range or combination of performance measures across multiple dimensions, examining potential co-benefits or tradeoffs between these measures. For example, you can design a CAV application that greatly improves safety, but it might come at the cost of reducing traffic throughput. Further, the design of the CAV applications is often static and limited to specific traffic scenarios and conditions. CAVs that can adapt to different conditions, and be "tunable" for different societal needs will have much greater impact and versatility. In this presentation, we examine various co-benefits and tradeoffs of current CAV applications and consider how we can design these systems to have greater flexibility when it comes to deployment. We cite not only different CAV applications evaluated in simulation, but also real-world CAV deployments that operate on various testbeds, such as the Innovation Corridor located in Riverside, California. Based on this analysis, we can consider several new research directions for future CAV deployments.

Co-Benefits and Tradeoffs between Safety, Mobility, and Environmental Impacts for Connected and Automated Vehicles

IEEE Intelligent Transportation Systems Society
Workshop on Connected and Autonomous Vehicles
October 2022

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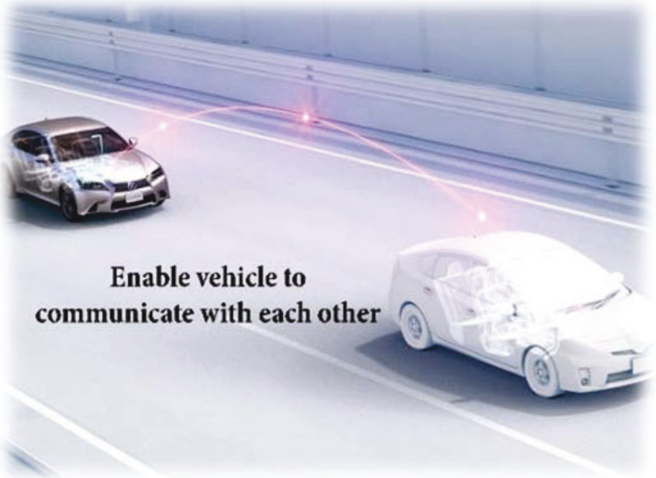
Many ways to classify CAV Applications



(Photos by Mohamed Zaki)

Vehicle-centric:

- ✓ Distributed/decentralized maneuvers
- ✓ Equipped vehicles that interacting with their surroundings,or vehicles' ego states

Infrastructure-centric:

- ✓ Centralized surveillance
- ✓ Intelligent Traffic Management Centers (TMC)
- ✓ Roadway infrastructure, e.g., inductive loop detectors, communication-capable roadside units

Traveler-centric:

- ✓ Pedestrians
- ✓ Bicycles
- ✓ Two-wheel wheelchairs

CAV Applications by Purpose

V2I Safety

Red Light Violation Warning
Curve Speed Warning
Stop Sign Gap Assist
Spot Weather Impact Warning
Reduced Speed/Work Zone Warning
Pedestrian in Signalized Crosswalk Warning (Transit)

V2V Safety

Emergency Electronic Brake Lights (EEBL)
Forward Collision Warning (FCW)
Intersection Movement Assist (IMA)
Left Turn Assist (LTA)
Blind Spot/Lane Change Warning (BSW/LCW)
Do Not Pass Warning (DNPW)
Vehicle Turning Right in Front of Bus Warning (Transit)

Agency Data

Probe-based Pavement Maintenance
Probe-enabled Traffic Monitoring
Vehicle Classification-based Traffic Studies
CV-enabled Turning Movement & Intersection Analysis
CV-enabled Origin-Destination Studies
Work Zone Traveler Information

Environment

Eco-Approach and Departure at Signalized Intersections
Eco-Traffic Signal Timing
Eco-Traffic Signal Priority
Connected Eco-Driving
Wireless Inductive/Resonance Charging
Eco-Lanes Management
Eco-Speed Harmonization
Eco-Cooperative Adaptive Cruise Control
Eco-Traveler Information
Eco-Ramp Metering
Low Emissions Zone Management
AFV Charging / Fueling Information
Eco-Smart Parking
Dynamic Eco-Routing (light vehicle, transit, freight)
Eco-ICM Decision Support System

Road Weather

Motorist Advisories and Warnings (MAW)
Enhanced MDSS
Vehicle Data Translator (VDT)
Weather Response Traffic Information (WxTINFO)

Mobility

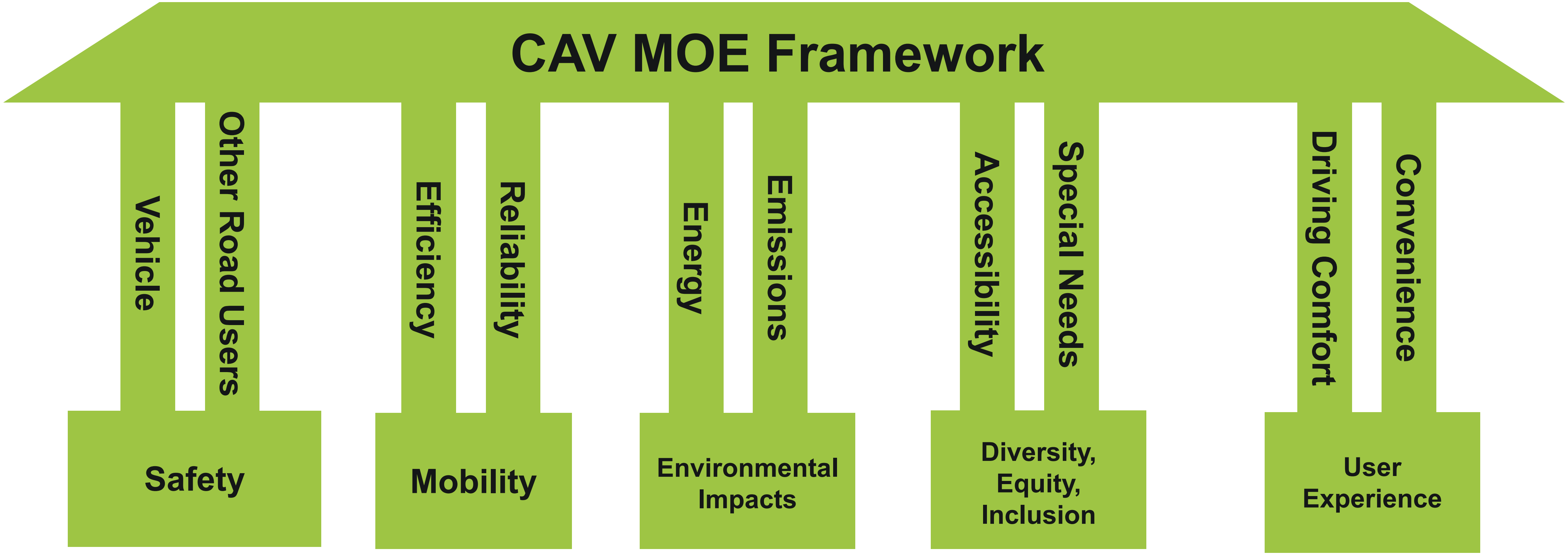
Advanced Traveler Information System
Intelligent Traffic Signal System (I-SIG)
Signal Priority (transit, freight)
Mobile Accessible Pedestrian Signal System (PED-SIG)
Emergency Vehicle Preemption (PREEMPT)
Dynamic Speed Harmonization (SPD-HARM)
Queue Warning (Q-WARN)
Cooperative Adaptive Cruise Control (CACC)
Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG)
Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE)
Emergency Communications and Evacuation (EVAC)
Connection Protection (T-CONNECT)
Dynamic Transit Operations (T-DISP)
Dynamic Ridesharing (D-RIDE)
Freight-Specific Dynamic Travel Planning and Performance
Drayage Optimization

Smart Roadside

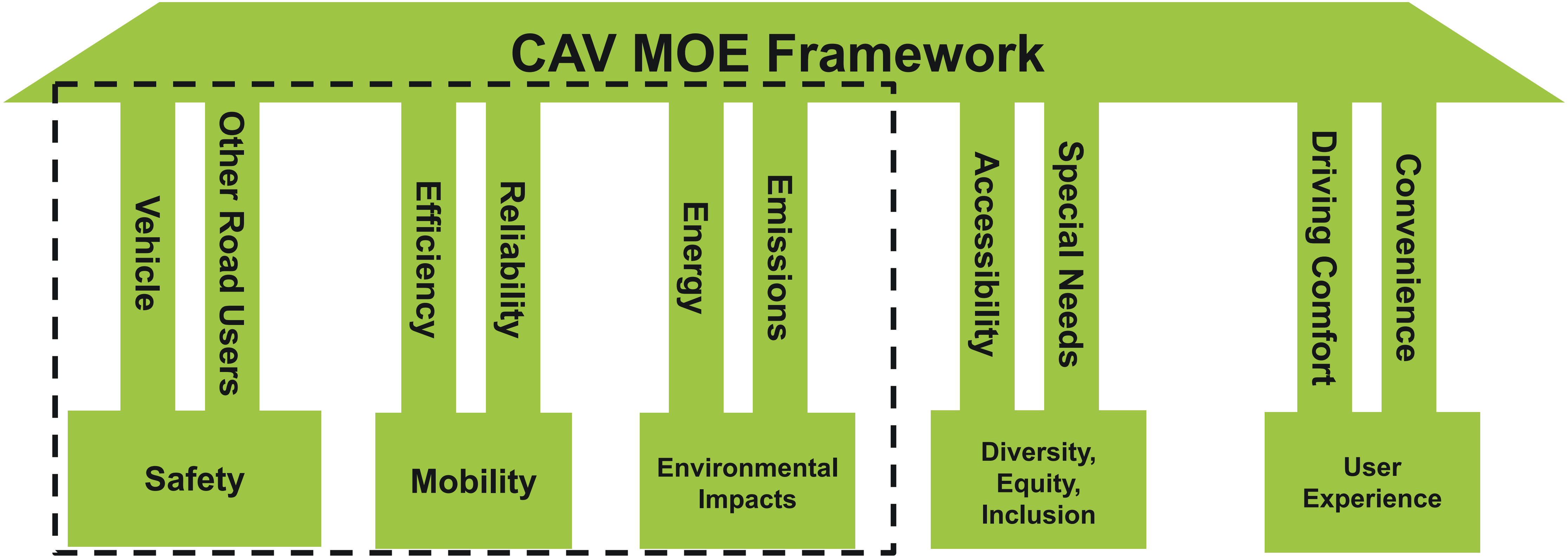
Wireless Inspection
Smart Truck Parking

- Most CAV applications are specifically designed to improve safety, mobility, and/or environment
- Many CAV applications require close to 100% penetration rate of connected vehicles

Key Measures of Effectiveness for CAVs



Key Measures of Effectiveness for CAVs



MOEs:
- Spacing
- Speed difference
- Time-to-collision
- Queue length
- Critical conflicts
- Non-critical conflicts
- Etc.

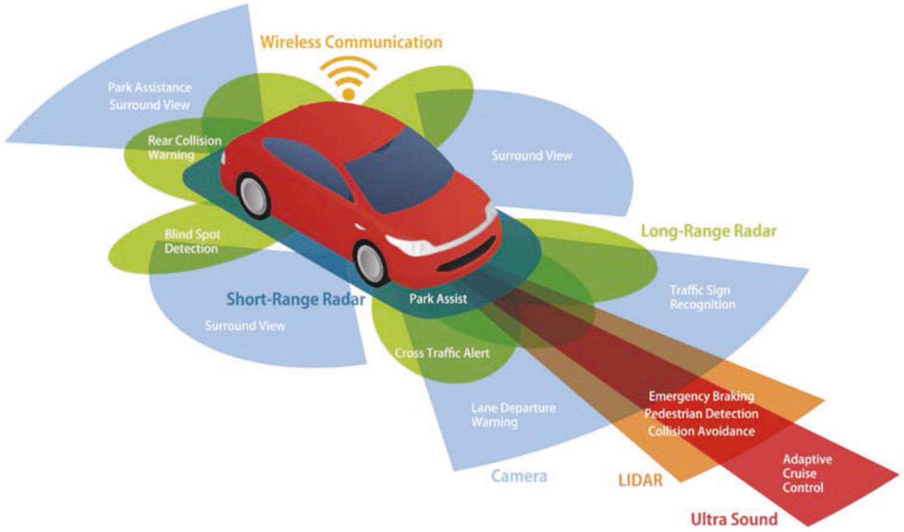
MOEs:
- Flow
- Queue length
- Avg travel time
- Avg speed
- VMT
- VHT
- Delay
- Number of stops
- LOS
- Etc.

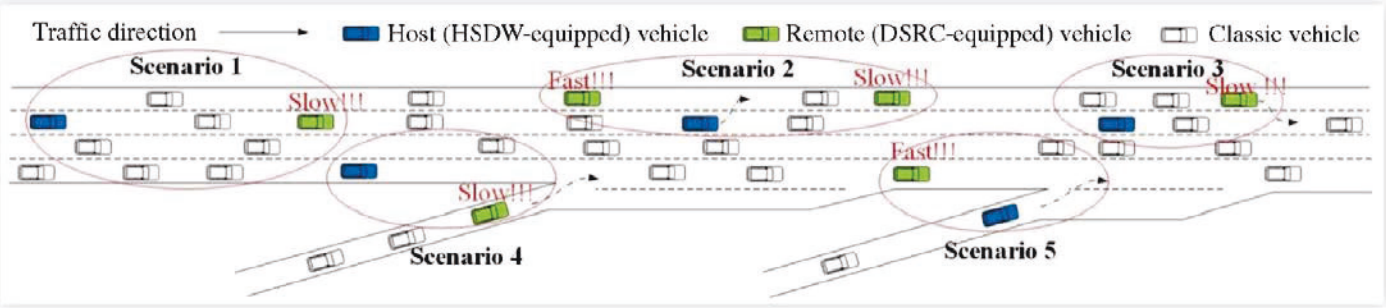
MOEs:
- Energy consumption
- Fuel consumption
- Pollutant emissions
- Noise
- Pavement
- Etc.

Connected Vehicle Safety Applications

TABLE 1 Safety applications.

	Application
V2I	Curve Speed Warning
	In-Vehicle Signage
	Oversize Vehicle Warning
	Pedestrian in Signalized Crosswalk Warning
	Railroad Crossing Violation Warning
	Red Light Violation Warning
	Reduced Speed Zone Warning
	Restricted Lane Warning
	Spot Weather Impact Warning
	Stop Sign Gap Assist
	Stop Sign Violation Warning
	Warnings about Hazards in Work Zone
	Warnings about Upcoming Work Zone
V2V	Automatic Lane Change [60]
	Control Loss Warning
	Do Not Pass Warning
	Emergency Electronic Brake Light [61]
	Emergency Vehicle Alert
	Forward Collision Warning [62]
	High Speed Differential Warning [12]
	Intersection Movement Assist [63]
	Lane Change Warning [64]
	Motorcycle Approaching Indication
	Pre-Crash Actions [62]
	Situational Awareness
	Slow Vehicle Warning
	Stationary Vehicle Warning
	Tailgating Advisory
	Vehicle Emergency Response

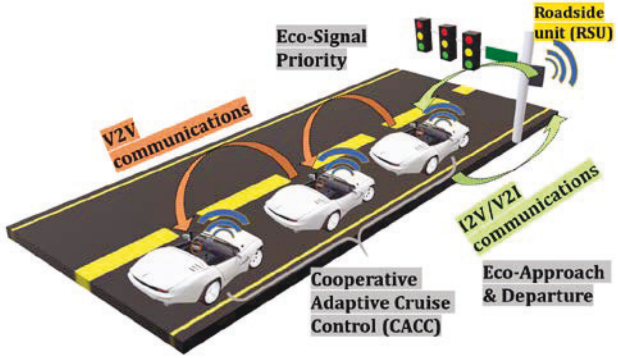




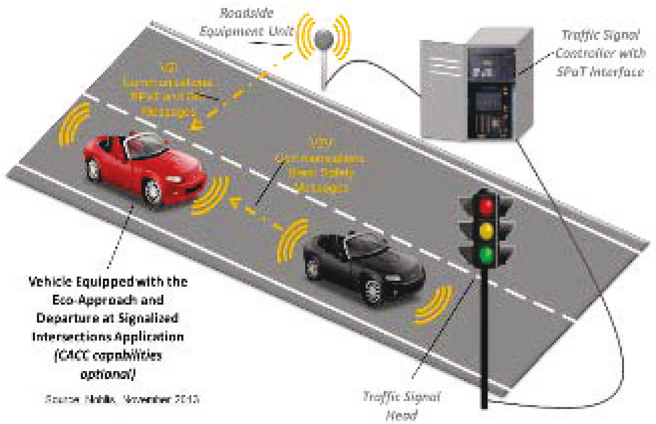
Connected Vehicle Mobility Applications

TABLE 2 Mobility applications.

Application
Cooperative Adaptive Cruise Control [65, 66]
Queue Warning [67]
Lane Speed Monitoring [68]
Speed Harmonization
Vehicle Data for Traffic Operations
Emergency Vehicle Preemption
Freight Signal Priority [69]
Intelligent Traffic Signal System
Pedestrian Mobility
Transit Signal Priority



Intelligent Roadway Management



Variations of Smart Intersection Management

Connected Vehicle Environmental Applications

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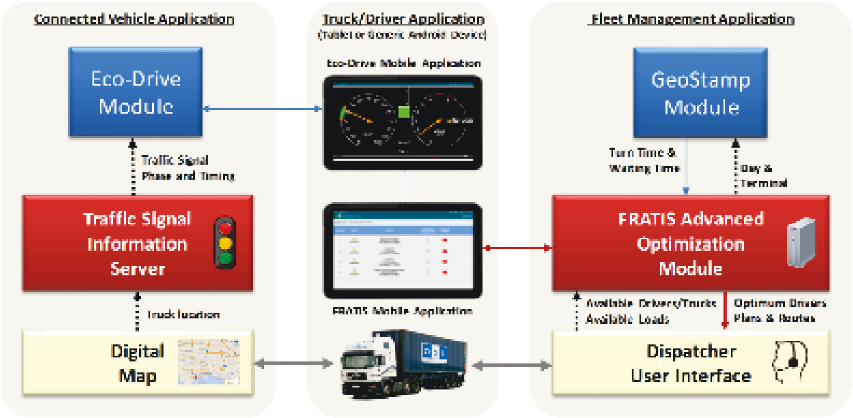
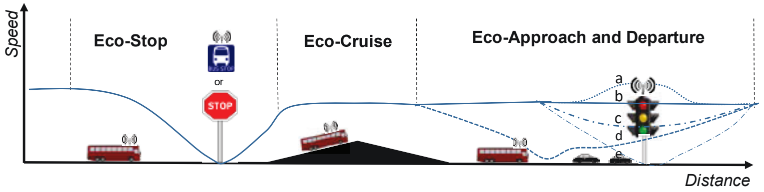
TABLE 3 Environmental applications.

Application
Connected Eco-Driving [70]
Dynamic Eco-Routing [1]
Eco-Approach and Departure at Signalized Intersections [71]
Eco-Integrated Corridor Management Decision Support System
Eco-Lanes Management
Eco-Multimodal Real-Time Traveler Information
Eco-Ramp Metering
Eco-Smart Parking
Electric Charging Stations Management



Variations of Dynamic Eco-Driving Techniques



Dynamic Powertrain Management

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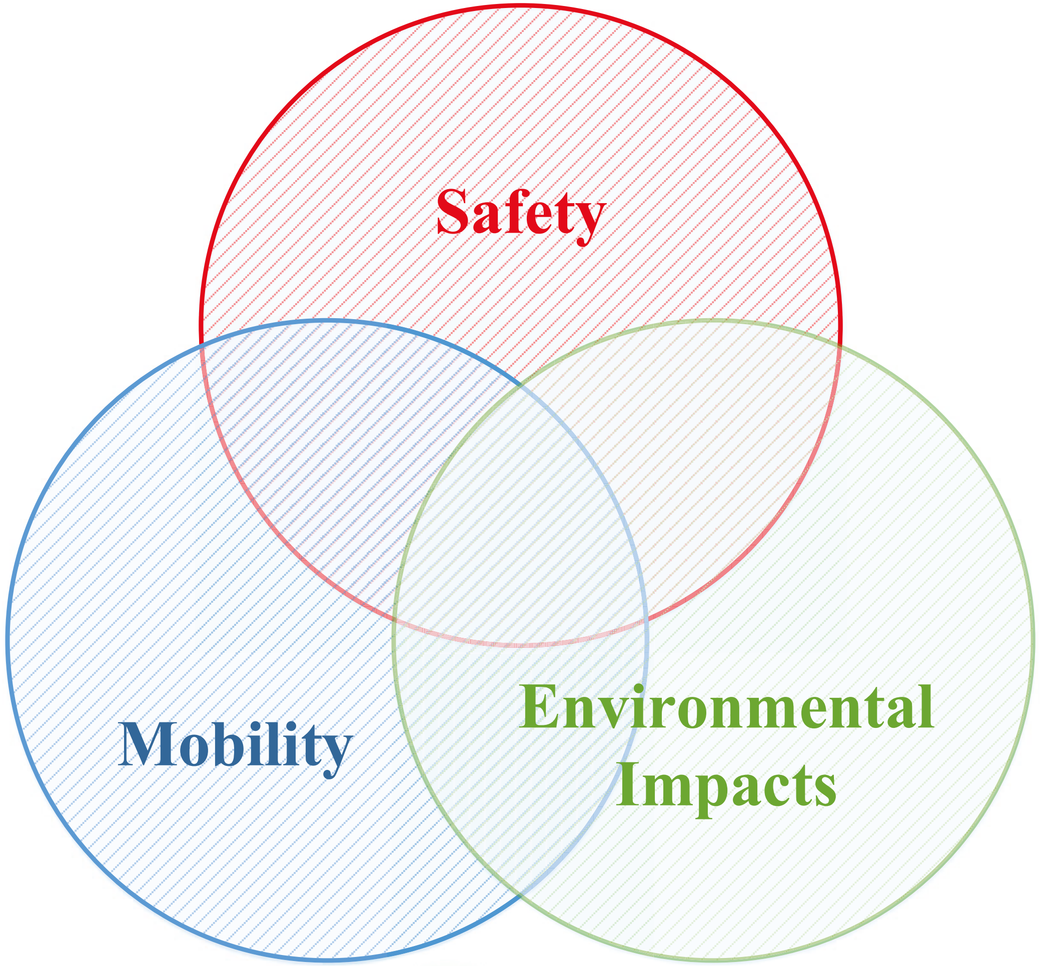

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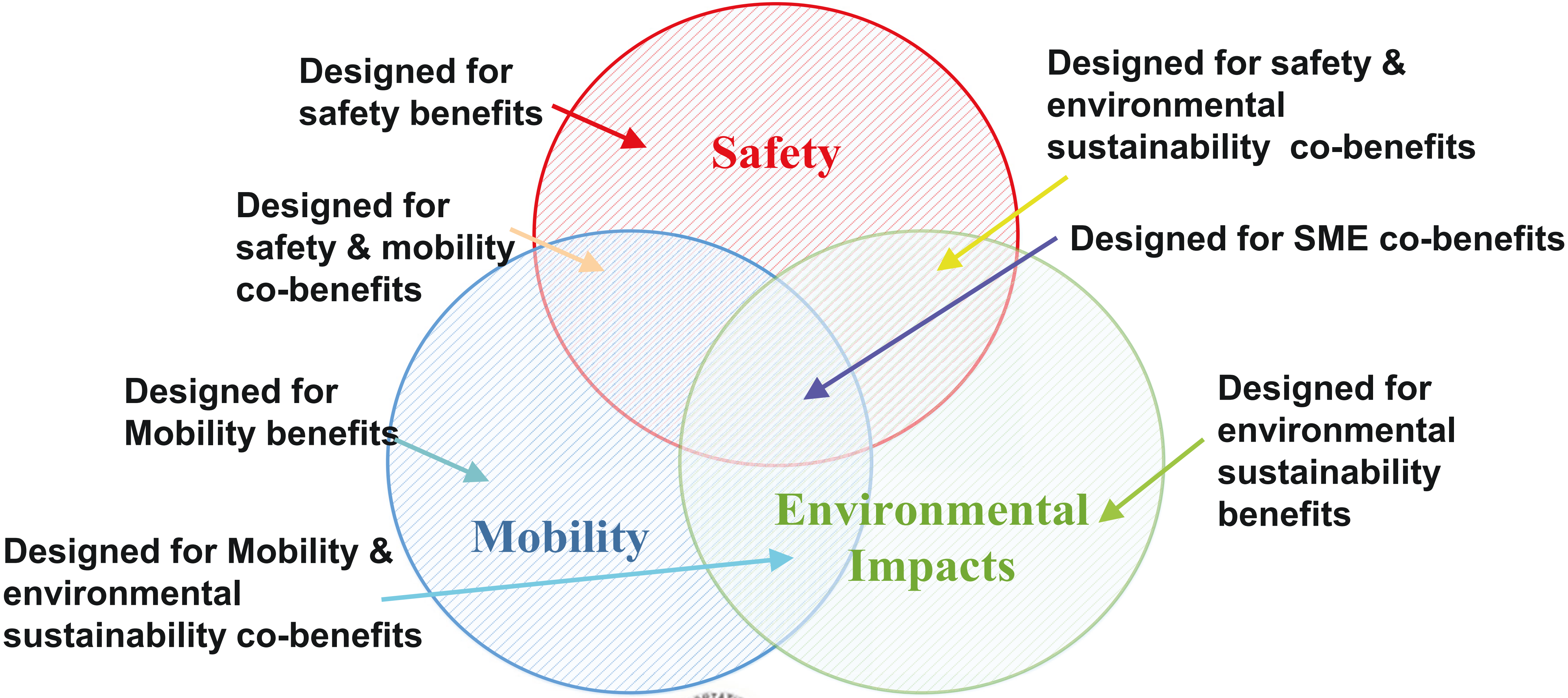

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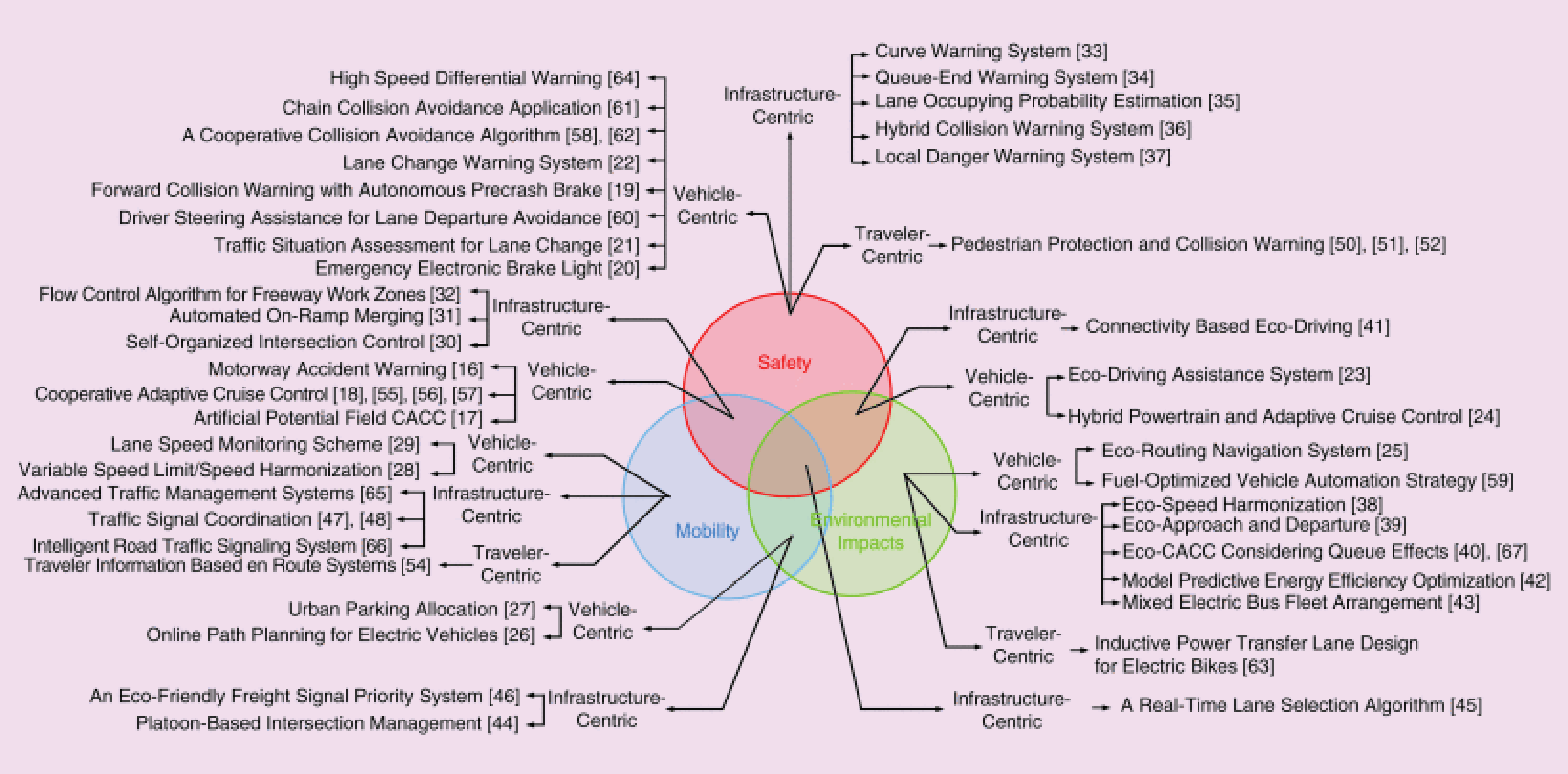
Literature Survey

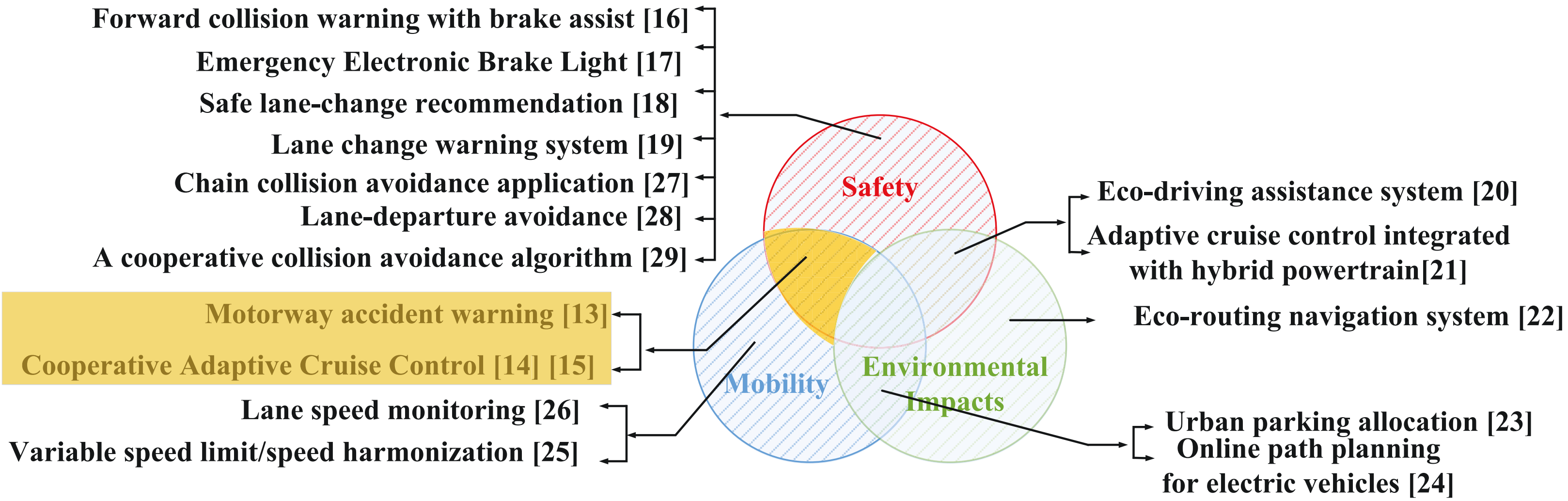


Danyang Tian, Guoyuan Wu, Kanok Boriboonsomsin, and Matthew J. Barth, "Performance measurement evaluation framework and co-benefit/: tradeoff analysis for Connected and Automated Vehicles (CAV) applications: a survey," *IEEE Intelligent Transportation Systems Magazine*, vol. 10, no. 3, pp. 110-122.

The survey includes but not limit to:

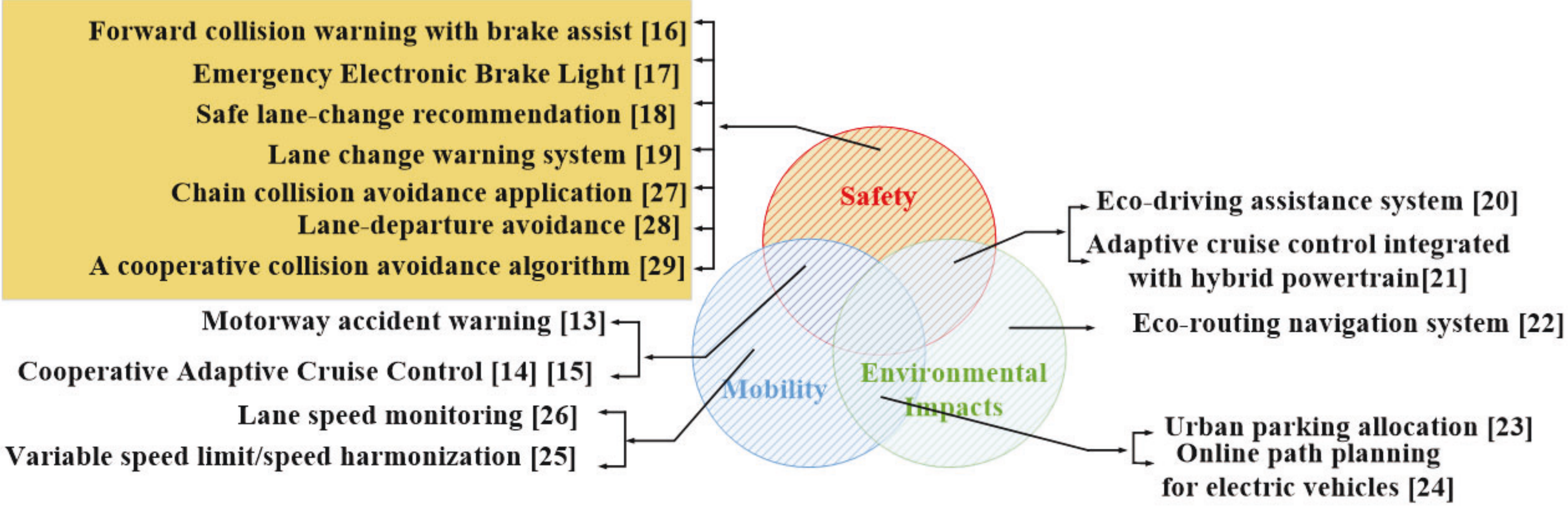
- ✓ Forward collision warning
- ✓ Lane-change warning
- ✓ Curve warning system
- ✓ Emergency Electric Brake Light warning
- ✓ Adaptive Cruise Control
- ✓ Cooperative Adaptive Cruise Control
- ✓ Eco-routing navigation system
- ✓ Urban parking management
- ✓ Lane speed monitoring
- ✓ Queue-end warning
- ✓ Local danger warning
- ✓ Pedestrian protection system

Example 1: Safety-Mobility CAV Applications



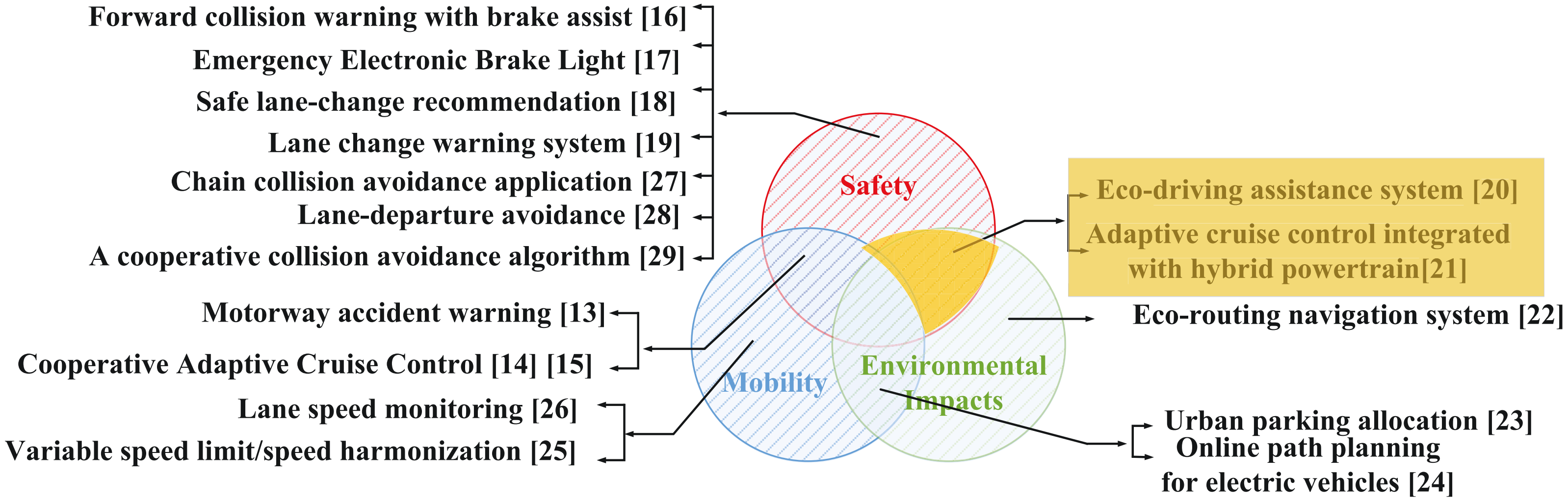
Application	Safety Improvement	Mobility Improvement	Environment Impacts Improvement
A lane closure alert	Potential rear-end reduction	Relief of bottlenecks congestion	Unknown
Cooperative Adaptive Cruise Control (CACC)	Harmonizing the speed of platoons in a safe manner	Increasing the traffic capacity under high penetration rates	

Example 2: Safety CAV Applications



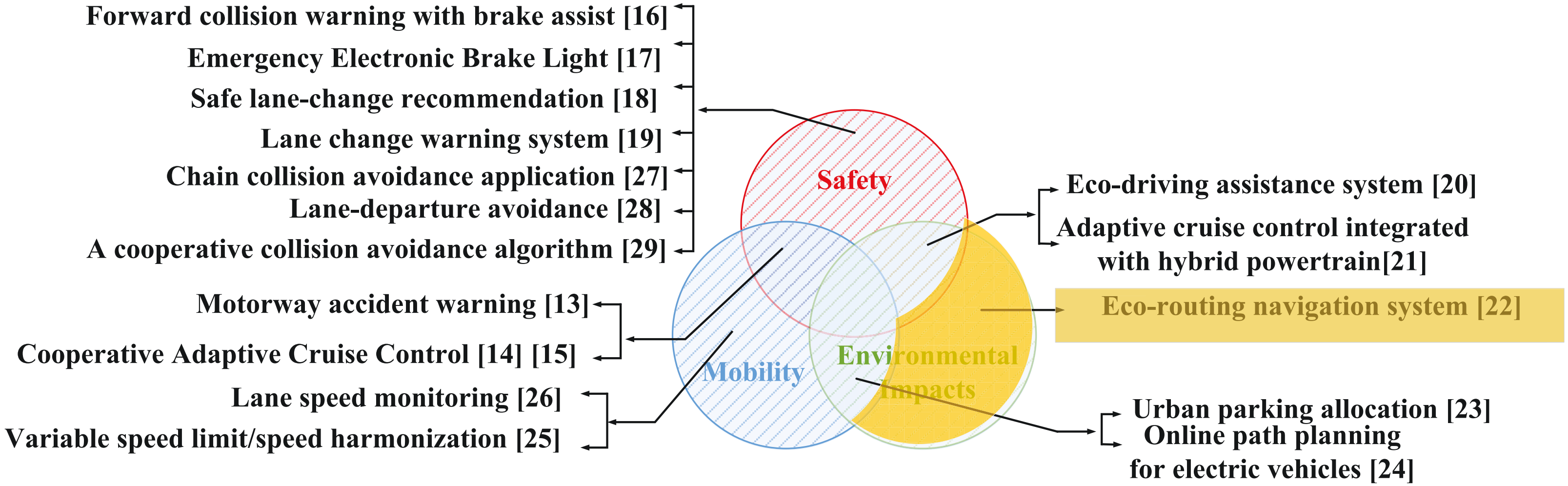
Application	Safety Improvement	Mobility Improvement	Environment Impacts Improvement
Pre-collision system	Time-to-Collision as surrogate collision risk evaluation	Increased stop-and-go behaviors	Safety enhancement probably achieved at the cost of larger GHG emissions
Emergency Electronics Brake Light (EEBL)	Collision number reduction		
Lane change warning system	Real-time minimum safe distance	Unknown	

Example 3: Safety-Environmental CAV Applications



Application	Safety Improvement	Mobility Improvement	Environment Impacts Improvement
Eco-Driving application	Integration of various information sources (not validate)	Steady-speed, smooth-deceleration traffic but with longer travel time	Eco-friendly speed
Intelligent Environment-Friendly Vehicles	Adaptive Cruise Control (ACC)	Unknown	Hybrid powertrain

Example 4: Environmental CAV Application



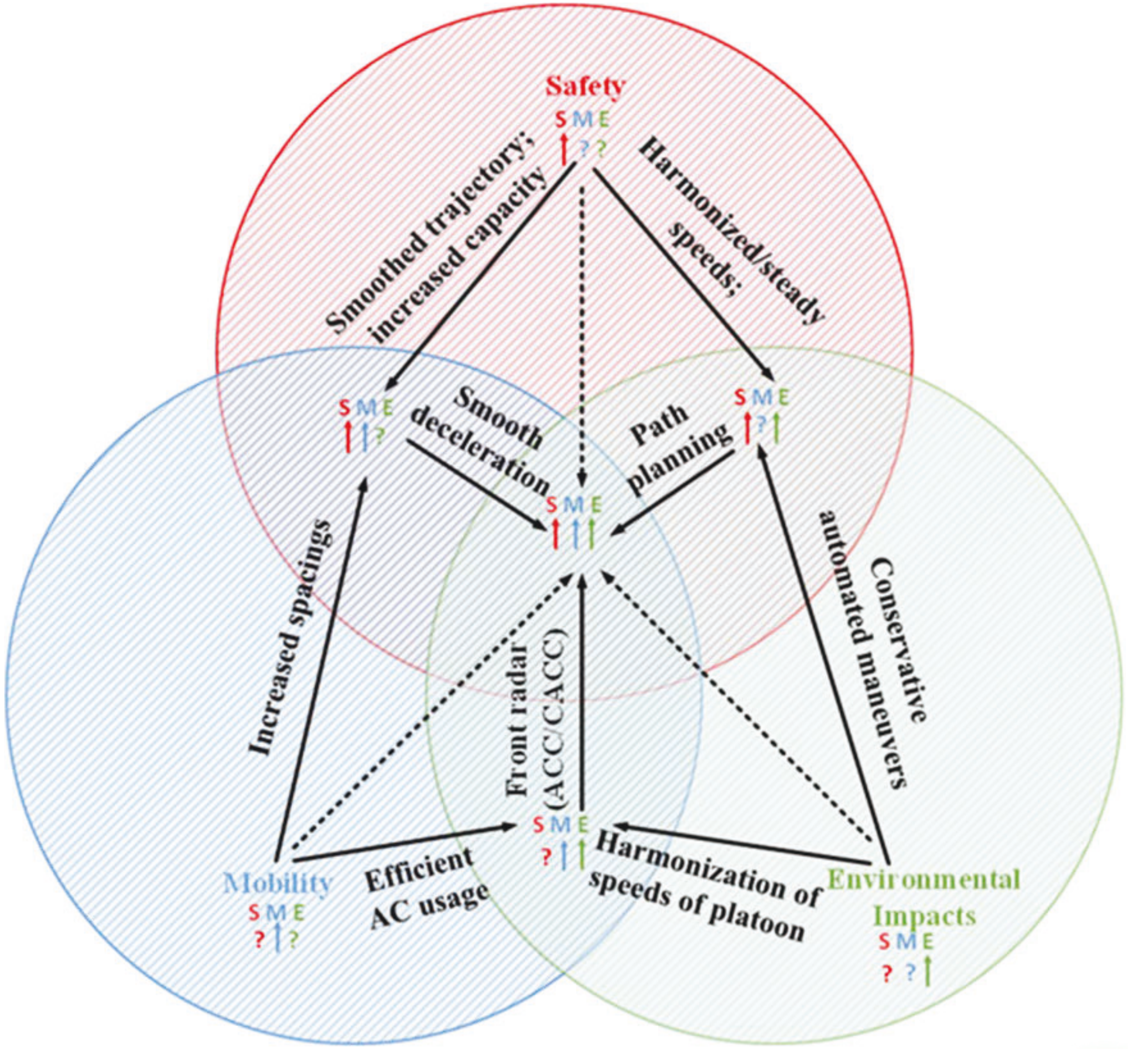
Application	Safety Improvement	Mobility Improvement	Environment Impacts Improvement
Eco-routing navigation system	Unknown	Travel time increase	Eco-routes are generally not the fastest route

Summary of CAV Application Categories

Safety focused (25)	S M E ↑ ? ?	S M E ↑ ↑ ?	S M E ↑ ? ↑	S M E ↑ ↑ ↑
	15 out of 25 (60%)	6 out of 25 (24%)	3 out of 25 (12%)	1 out of 25 (4%)
Mobility focused (18)	S M E ? ↑ ?	S M E ↑ ↑ ?	S M E ? ↑ ↑	S M E ↑ ↑ ↑
	7 out of 18 (39%)	6 out of 18 (33%)	4 out of 18 (22%)	1 out of 18 (6%)
Environmental impacts focused (15)	S M E ? ? ↑	S M E ↑ ? ↑	S M E ? ↑ ↑	S M E ↑ ↑ ↑
	7 out of 15 (47%)	3 out of 15 (20%)	4 out of 15 (27%)	1 out of 15 (7%)

- **Most of the applications listed are safety-oriented**
- **Very few studies that evaluate all three MOEs**
- **Most of the current CAV applications are not designed to be capable of achieving the three aims at the same time**

Observations



- There are many intrinsic and extrinsic factors that affect CAV system performance; static calibration leads to poor performance
- Many CAV deployments could have multiple co-benefits *by combining* several different-MOE-focused applications
- CAV penetration rate is one important dimension that should be taken into account when the performance is measured

Variations on CAV Applications:

We want to effectively designing new versions (variations) of CAV applications that are *dynamically adjustable* to improve multiple MOEs

- Lane Speed Monitoring and Optimal Lane Selection
- Routing Vehicles based on Real-Time System Conditions
- Co-Optimizing Signal Timing and Vehicle Trajectories at Intersections

Lane Speed Monitoring and Optimal Lane Selection:

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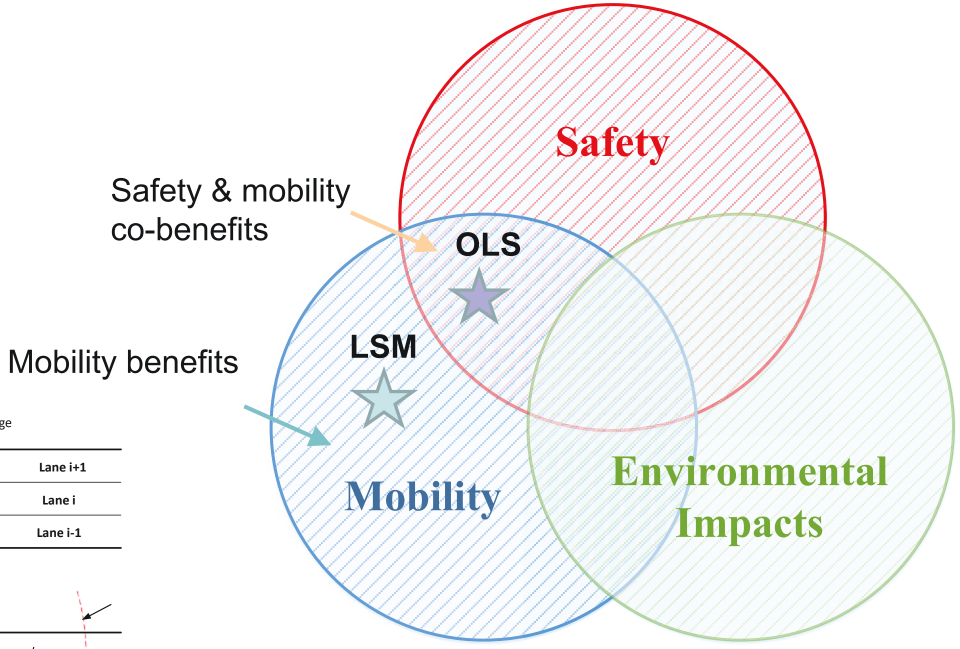
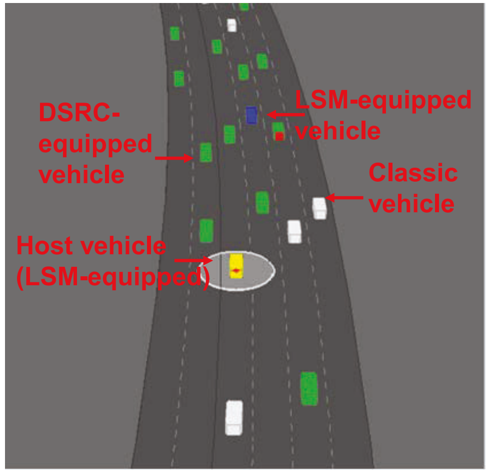
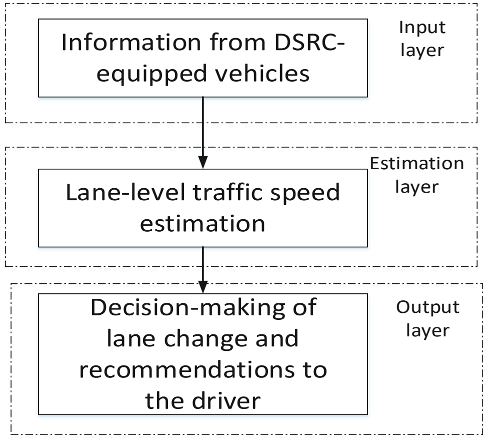
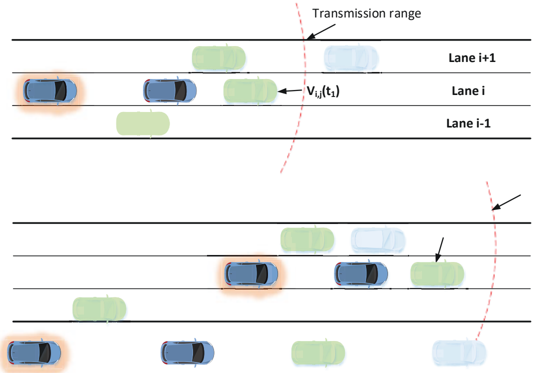
Lane Speed Monitoring (data informed) ⟷ **Short-range vs long-range connectivity** ⟷ **Optimal Lane Selection** (data driven)









LSM-equipped vehicles versus unequipped vehicles:

- **Up to 11% increase of average speed;**
- **Up to 50% increase of relative conflict frequency (but no crashes);**
- **Slight increase (3%) of fuel consumption**
- **Additional lane change behaviors emerge**

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Danyang Tian, Weixia Li, Guoyuan Wu, Kanok Boriboonsomsin, Matthew Barth, Samer Rajab and Sue Bai, "Evaluating the effectiveness of V2V-based lane speed monitoring application: a simulation study," in Proc. 19th IEEE Intelligent Transportation Systems, Rio, Brazil, Nov. 2016, pp. 1592-1597

ITSS Intelligent Transportation Systems Society IEEE

VT College of Engineering Mechanical Engineering Virginia Tech

Lane Speed Monitoring and Optimal Lane Selection:

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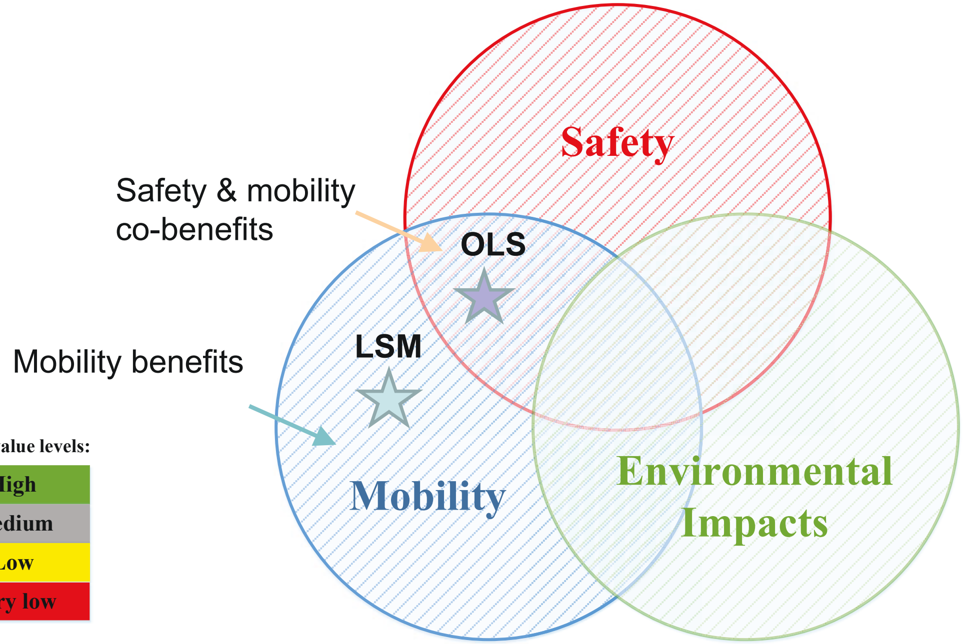
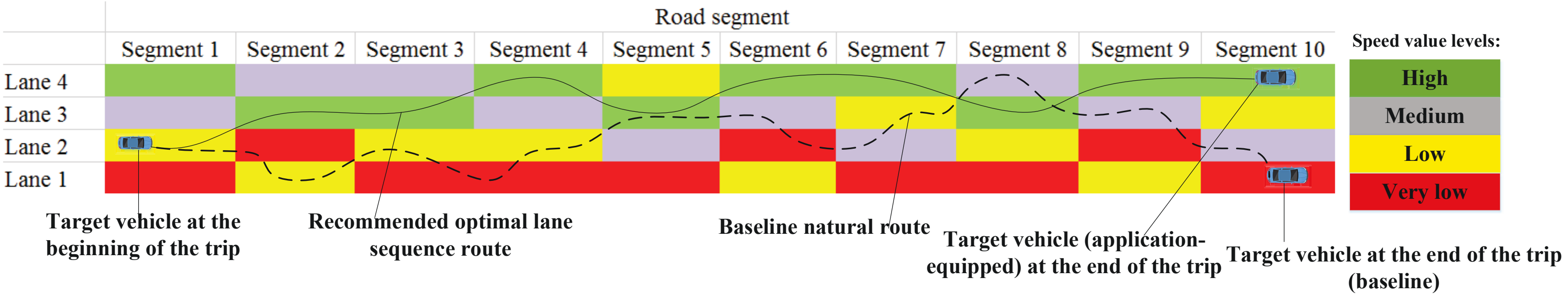
Lane Speed Monitoring (data informed)

Short-range vs long-range connectivity

Optimal Lane Selection (data driven)





The Optimal Lane Selection (OLS) application assists with lane selection, i.e., finding the optimal lane-level micro-routing in terms of maximizing the sum of average speed based on predicted lane-level traffic states

- **Travel times of OLS application-equipped vehicles can be reduced by up to 8%;**
- **The potential conflict risk of application-equipped vehicles is reduced as well**
- **Users turn on the LSM mode when mobility benefits are required, while they can switch to the OLS mode when they pay more attention to safety than usual (e.g., under rainy days).**

Danyang Tian, Guoyuan Wu, Kanok Boriboonsomsin, Matthew J. Barth, Samer Rajab and Sue Bai, "Connected vehicle-enabled cooperative smart lane selection," Transportation Research Board (TRB) 98th Annual Meeting, Washington, DC, USA, Jan. 2019.

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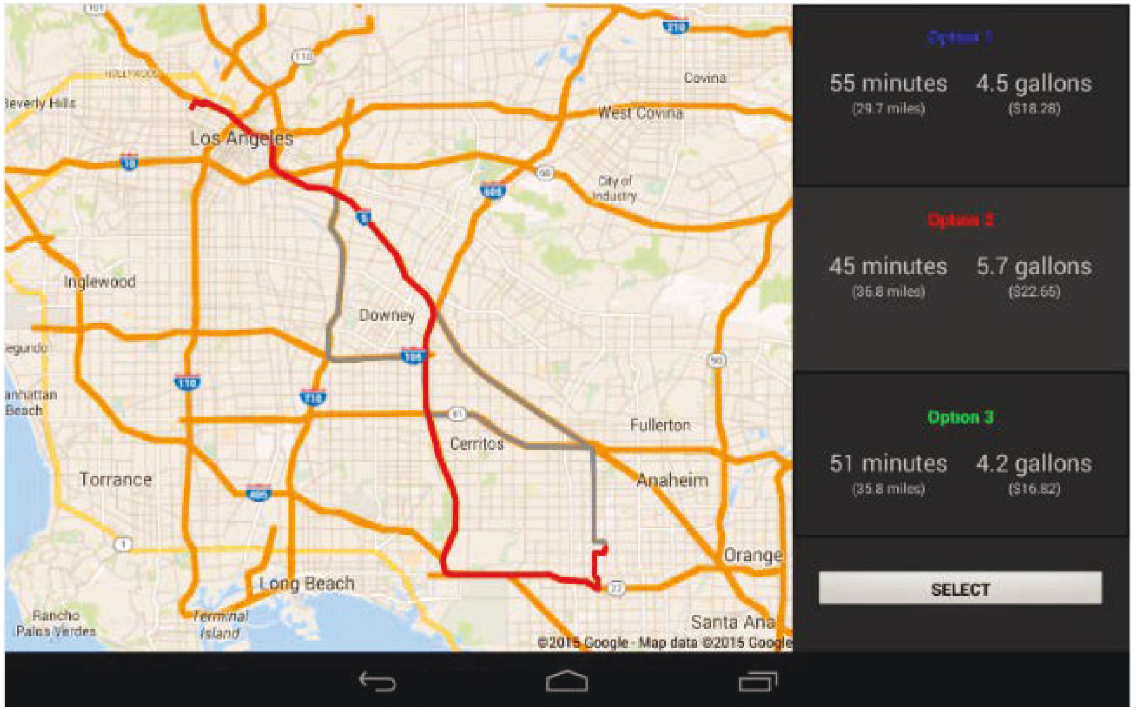
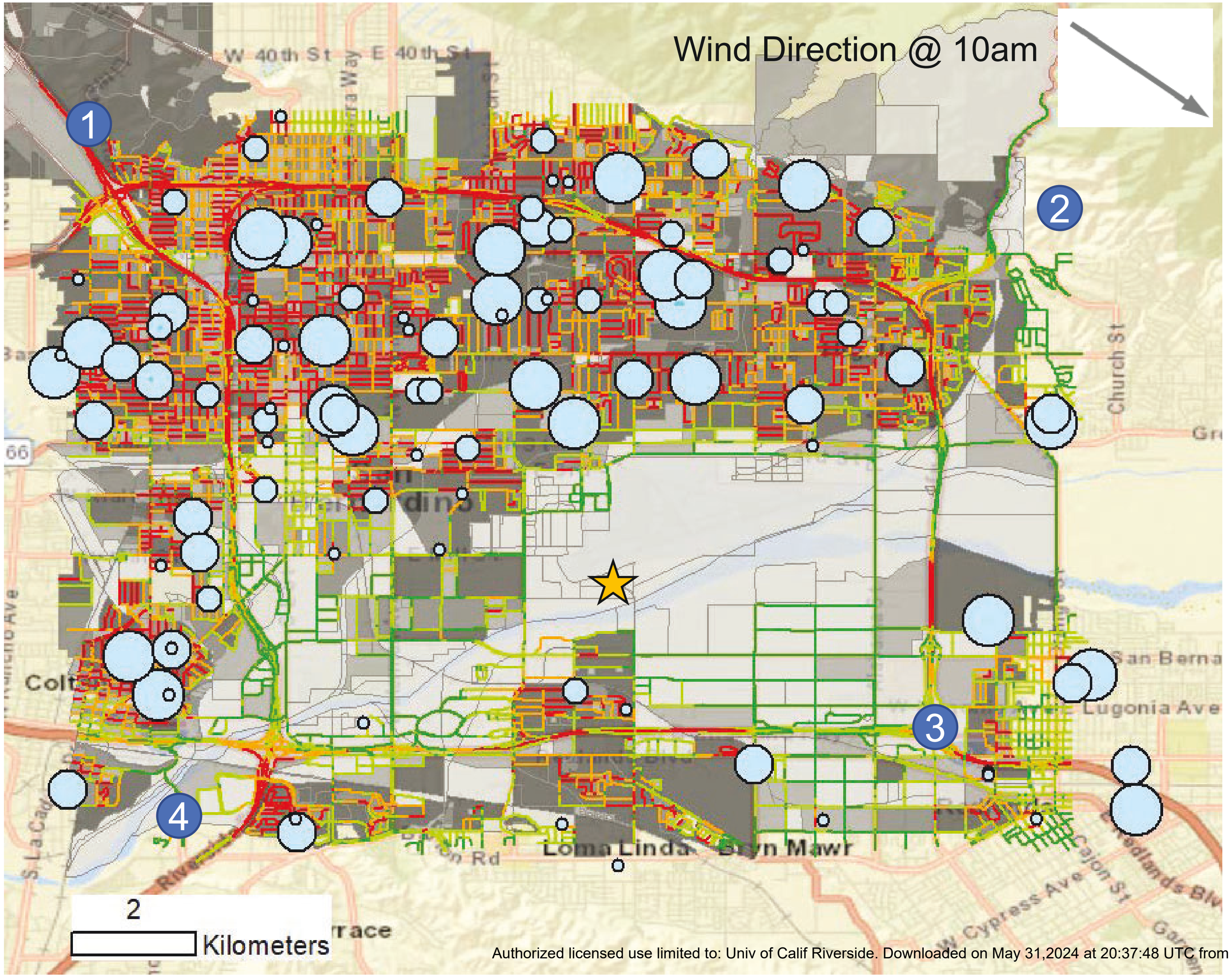
Variable Routing Methodologies

- **Shortest distance** route (rudimentary navigation)
- **Fastest route** (requires traffic information)
- **Eco-routes** can be chosen that reduce fuel consumption (or emissions), typically with a small travel time penalty
- ***Low-exposure routes*** can be chosen that reduce exposure of pollutants to local residents



San Bernardino Airport at 10am of a typical weekday



Facility Population

- 70 - 283
- 284 - 512
- 513 - 664
- 665 - 2732

Sensitive receptors (schools, assist. living, etc.)

Census Block 2018 Population

Working Hour

- 1
- 2 - 28
- 29 - 57
- 58 - 3505

General population density

Road Network PM2.5

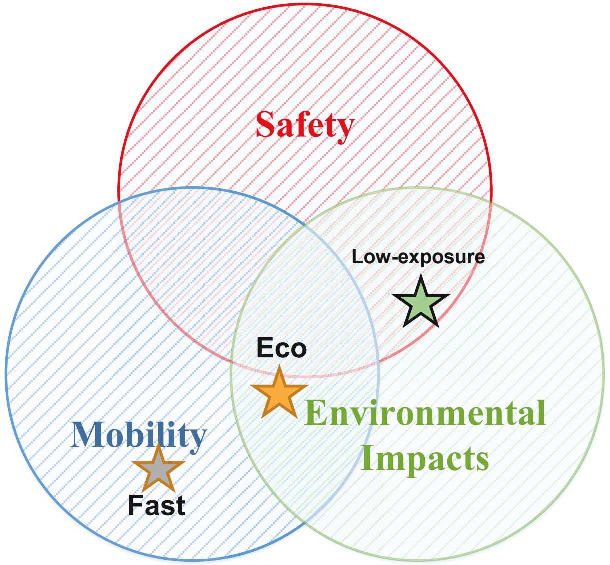
IM of total population (µg/kg mass)

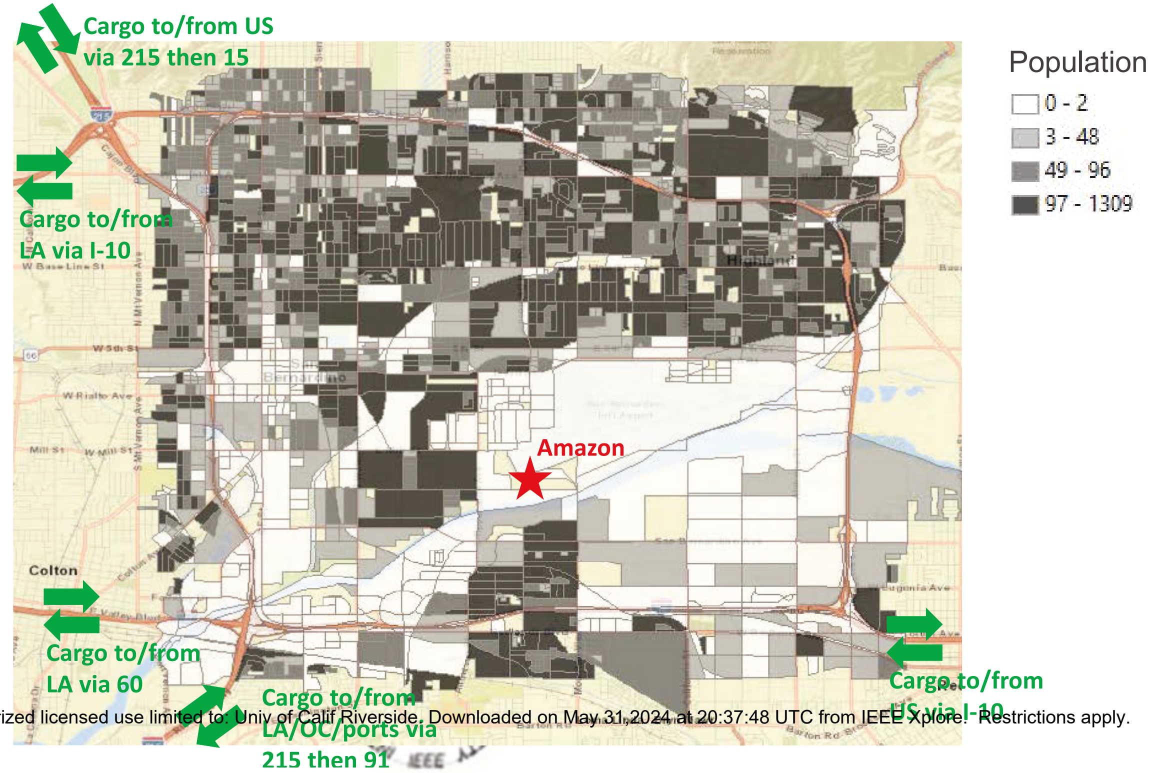
- 0.000
- 0.001 - 0.003
- 0.004 - 0.009
- 0.010 - 5.277

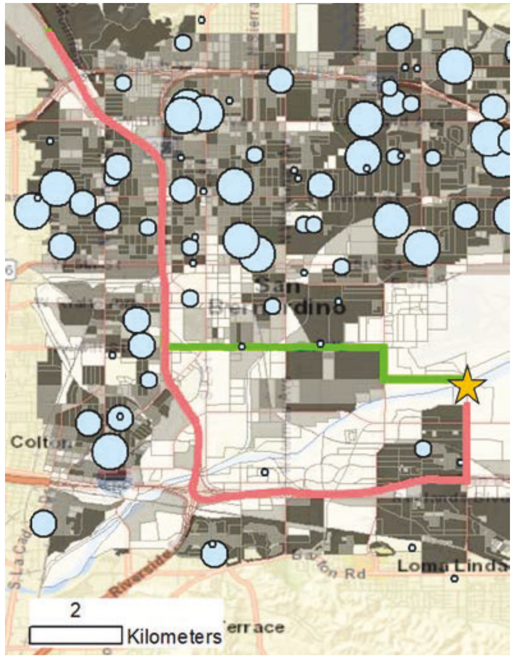
Roadway exposure rating

Condition-Based Routing

- Use fastest routing when meeting critical time deadlines (e.g., just-in-time deliveries for nighttime flights)
- Use eco-routing when time is not critical (reduces costs)
- Use low-exposure routing during sensitive air quality scenarios (kids walking to/from school, bad air quality days, etc.)

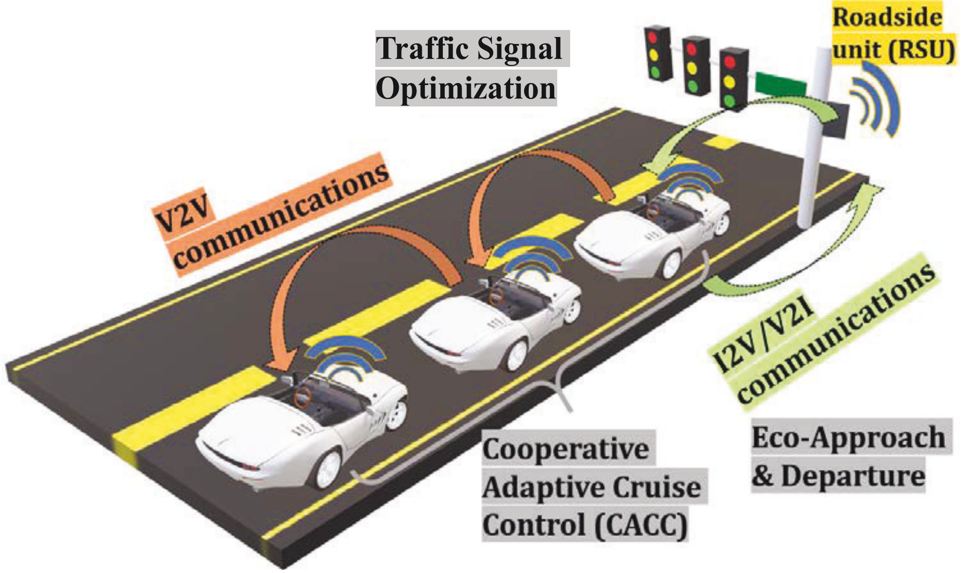


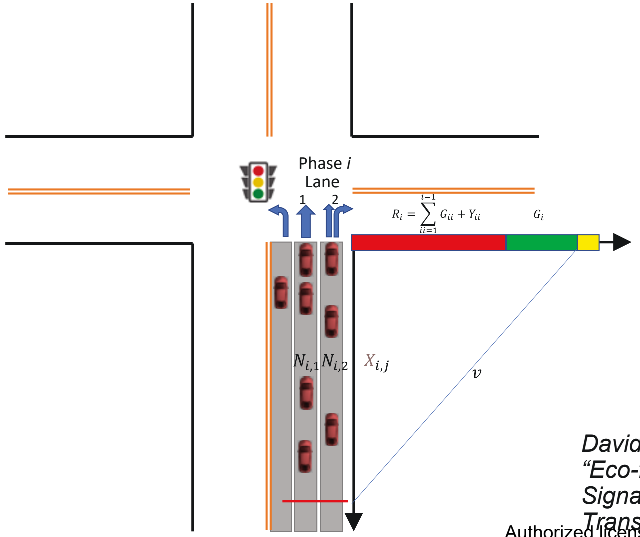


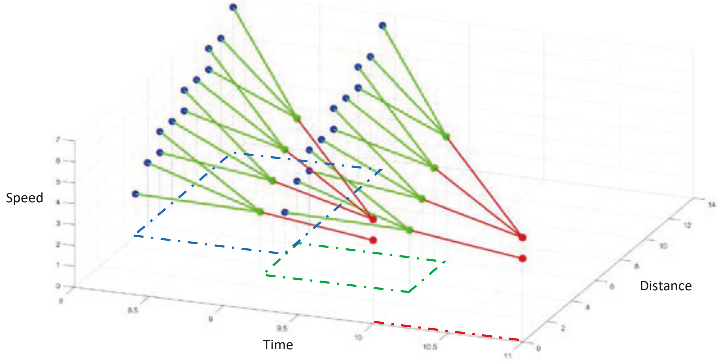


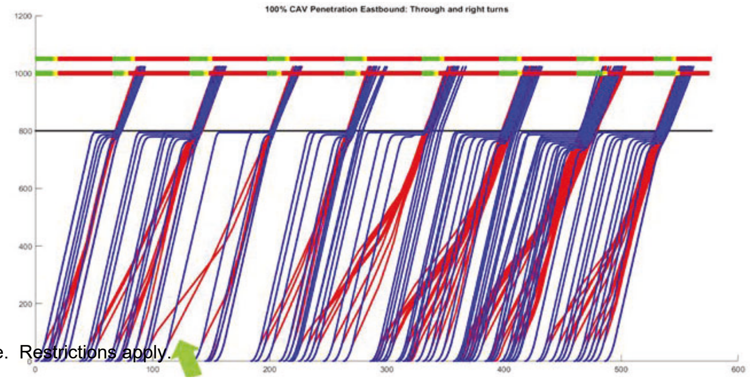
Eco-friendly Cooperative Traffic Optimization at Signalized Intersections (ECoTOp)

- **Co-optimizes connected vehicle trajectories AND signal timing**
- **Some inherent conflict when pursuing their own optimality in operation**

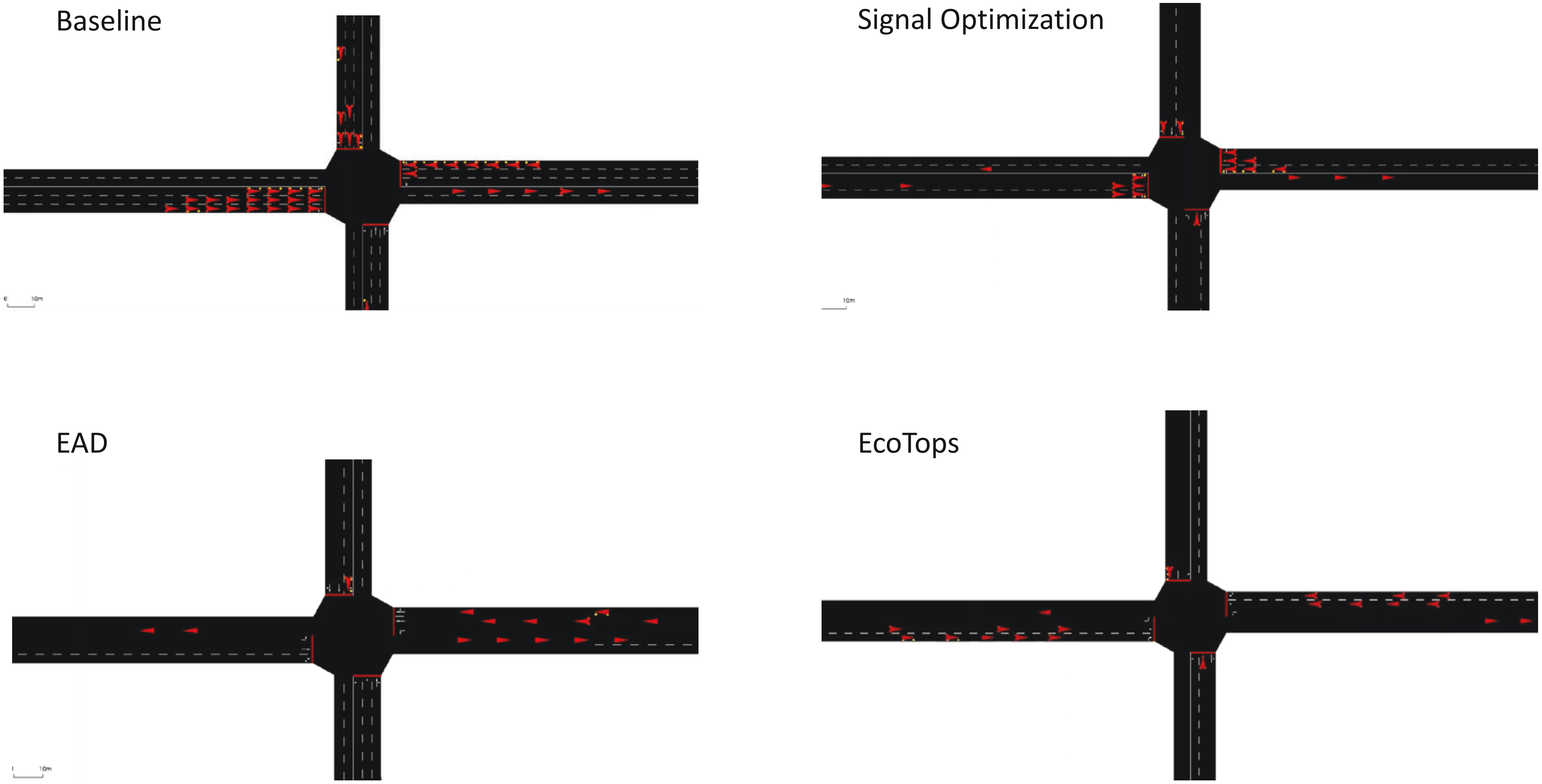




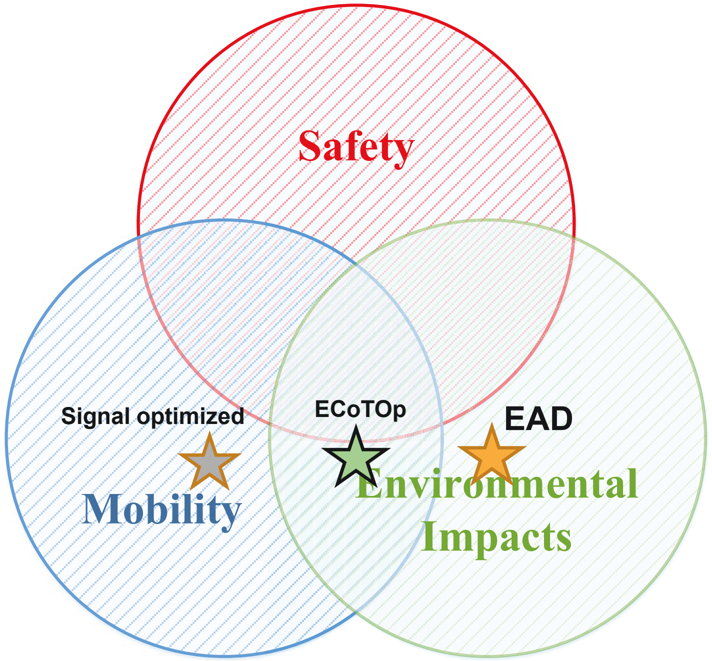




David Oswald, Peng Hao, Guoyuan Wu, and Matthew Barth, "Eco-friendly Cooperative Traffic Optimization (EcoTOp) at Signalized Intersections with Mixed Connected Traffic", Transportation Research Board Annual Meeting, Washington, DC, January 2023.


Baseline
Signal Optimization
EAD
EcoTops

	No Optimization	Signal Optimization
No EAD	Emissions (CO_2) 432.38 g/mile; Mobility 1899.42 veh/hr	435.6 g/mile +0.7%; 2093.02 veh/hr +10.2%
EAD	387.15 g/mile -10.4%; 1977.7 veh/hr +4.12%	381.4 g/mile -11.8%; 2046.8 veh/hr +7.75%



- Performance metrics are for all vehicles in entire intersection (750m radius)
- V/C ratio is 0.8
- CAV penetration rate is 80%
- 100% LDVs (no trucks)

Conclusions

- **Automated Vehicles should be connected and designed for system-wide benefits (not just individual benefits)**
- **CAV application designs should:**
  - **Have flexible programming, responding to system inputs**
  - **Should consider multiple MOEs, and where possible combine compatible applications**
  - **Allow for dynamic re-programming based on societal conditions**
- **Promising CAV Concept Operations should evaluated in simulation <u>AND</u> in real-world conditions, or a combination (using hardware in the loop, digital-twins, etc.)**

Matt Barth

- Low exposure routing
- Condition-based routing
- Also showed signal examples with multiple objectives

Discussion

- Chumin: what do you think would be the killer application for CAV?
  - Lane control. Ramp control. Intersections. Cooperative perception in roundabouts. Basically a combination
- For the automaker, they have to focus on something
  - Camp: CACC. Auto approach and departure
  - Brian: saving fuel (because it means something to consumers). A holistic approach, not vehicles by itself
- Robo fleet (AASHTO).
- Equity
  - Especially in areas where there are warehouses and trucks
- Some agreement that all these measures are related (e.g., the emission is also a safety problem)
- Azim: who is going to be coordinating the control? (answers: google, Waze). But they are tools, not really coordinating/controlling

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