

Emission Impacts of Connected and Automated Vehicle Deployment in California

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Background, Motivation and Scope

- Deployment of connected and automated vehicles (CAVs) likely to revolutionize travel demand patterns through changing:
  - Road capacity
  - Perceived safety and comfort
  - Attractiveness of “driving” a vehicle and value of travel time
  - Mode choice
  - Activity patterns and travel schedule
  - Residential location
  - Household interactions and destination choices
- Motivation and scope of the project:
  - Improve the understanding of the potential impacts of the introduction and rapid adoption of ***connected and automated vehicles*** (passenger vehicles with Level 5 automation)
  - Explore ranges of impacts of CAV deployment on passenger travel demand and greenhouse gas (GHG) and criteria pollutant emissions in California by 2050

Modeling the Impacts of CAV Deployment

Potential ranges of impacts of the introduction of vehicle automation for passenger travel on vehicle miles traveled (VMT), energy consumption and criteria pollutant emissions

Technological	Behavioral	Policy	Market
• Level of autonomation • Market penetration • Fuel type • …	• Value of travel time (VOTT) • Activity patterns • Trip generation • Mode choice • …	• Privately-owned vs. fleet-owned • Pooling • Pricing	• Market penetration • Business model • Cost for consumer • Consumer acceptance

Our Contribution

- Literature Review – guidelines on how to model uncertainties and potential impacts associated with CAV deployment *(not included in presentation today)*
- Expert Workshop – state of the art of CAV-related modeling studies *(not included in presentation today)*
- **Modeling – range of impacts on passenger travel demand, trip patterns, VMT and traffic congestion in future scenarios with CAVs**
- **Emissions – range of GHG and criteria pollutant emissions associated with the scenarios**

CAV Modeling Expert Workshop, UC Davis, April 2019

Modeling CAV Impacts with the California Statewide Travel Demand Model

- We make use of the official California Statewide Travel Demand Model (CSTDM v3)
- Activity-based model that can be applied to large-scale study area: entire state of California
- Include both short-distance and long-distance travel
- Include multiple modes – SOV, HOV, public transit, airplane, freight, walk/bike, etc.
- Model individual and household behavior changes and travel-related changes w.r.t. changes in travel times, costs and other impacts of new technologies
- Travel demand model outputs can be fed into emission model

General Assumptions

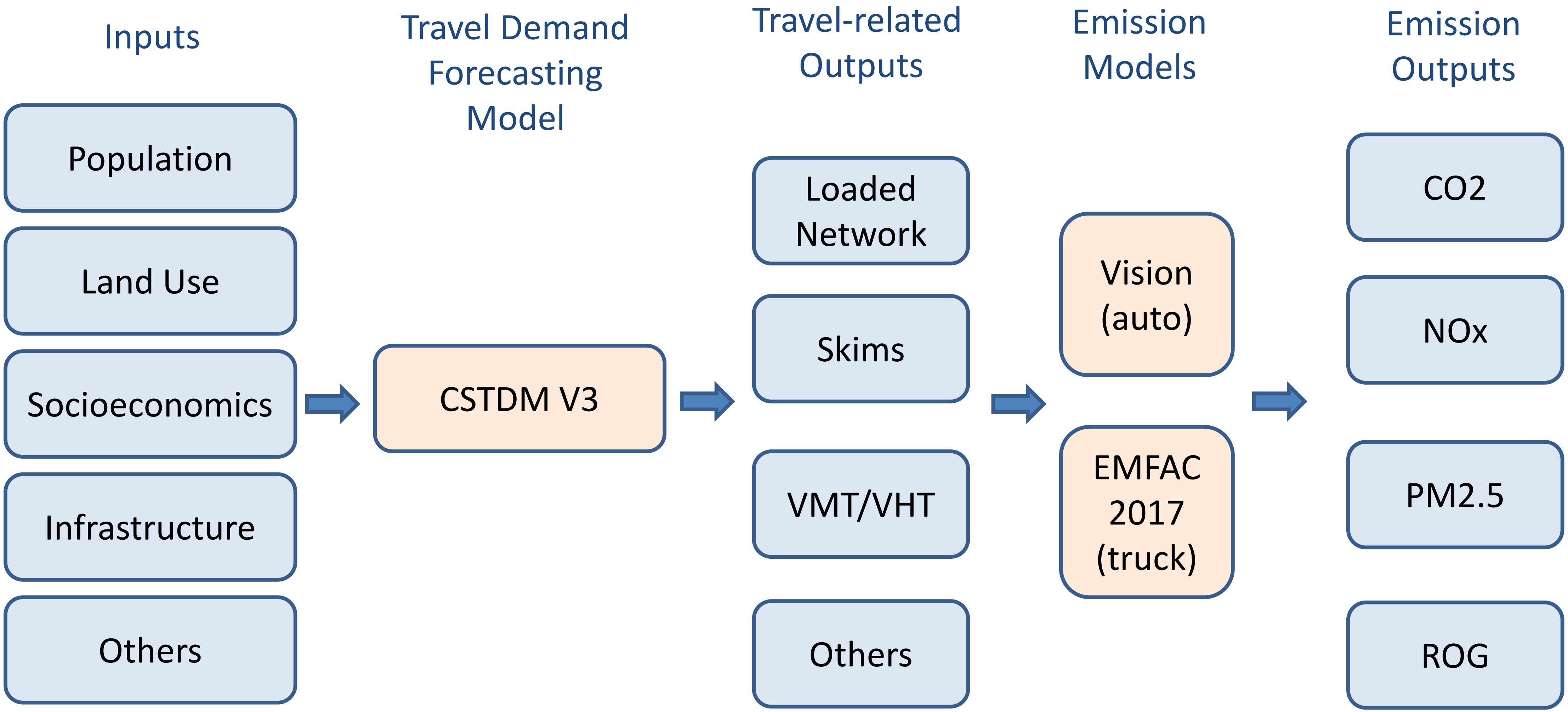
- Statewide activity-based model can capture the impacts of CAV through the changes in the travel behavior of the population.
- Our project focuses on the impacts of CAV w.r.t. passenger travel, with a primary focus on privately-owned vehicles (and limited information on freight).
- As the statewide travel demand model is not well-suited for modeling fleet-based mobility services, shared-fleet CAV deployment is accounted for with post-processing (outside of the main modeling framework).
- We build future transportation scenarios for year 2050, under assumptions of CAVs being widely available, and under different assumptions on fuel-type mix in the fleet.

Some Limitations

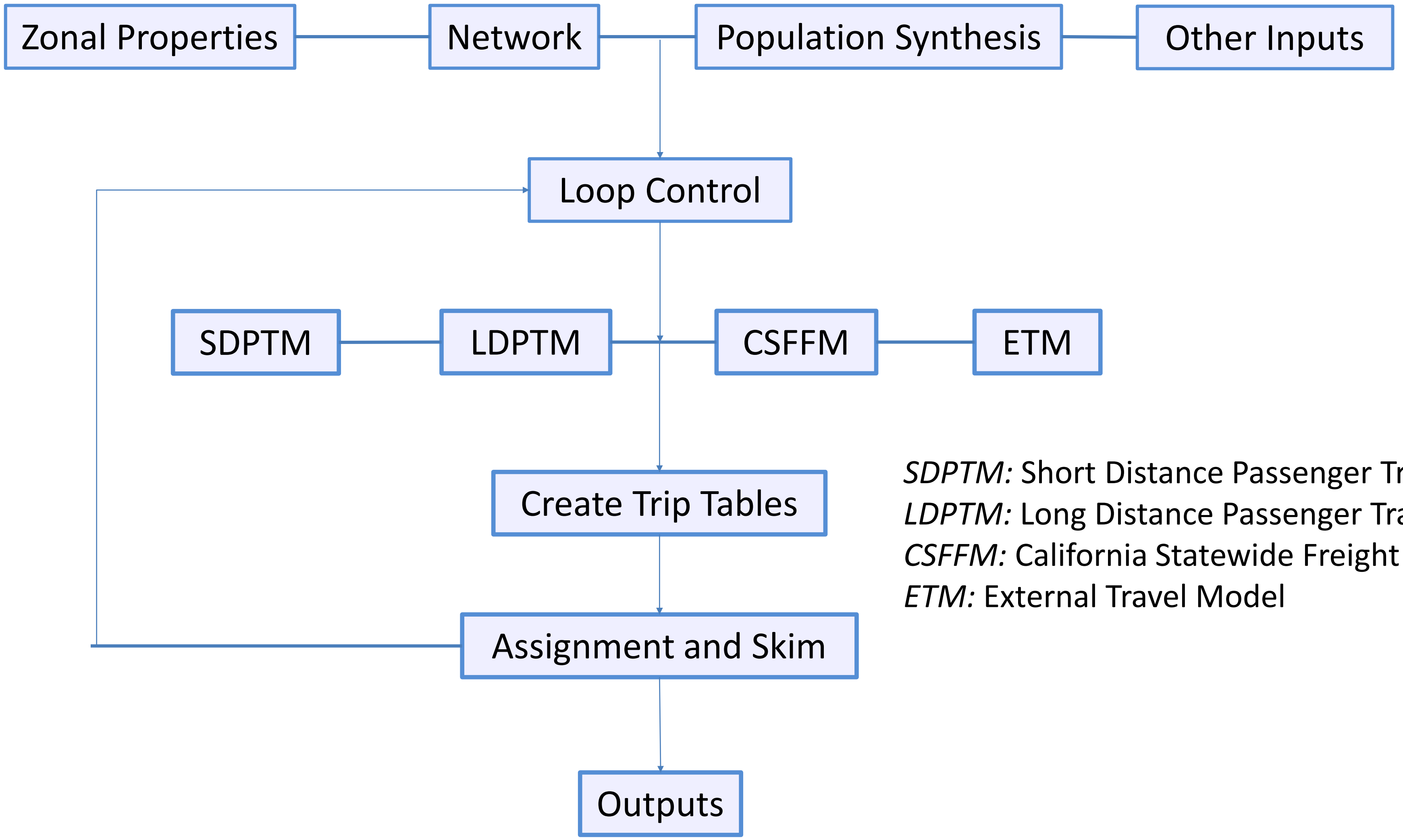
- Reliance on assumptions about activity-travel modeling from original model
- Original model estimated with data that did not include CAVs
  - Will assumptions hold in presence of a technology that will dramatically change society?
- Impacts of demographic information on CAV adoption are not accounted for
- Impacts of CAVs on activity patterns and trip generation do not seem to be well accounted for
- Land use is considered an exogenous input in the model and is not affected by the introduction of CAVs
  - Research suggests CAV deployment will likely affect land use!

Methodology – Overview

For each scenario, a set of inputs and assumptions is prepared and run in the CSTDM model

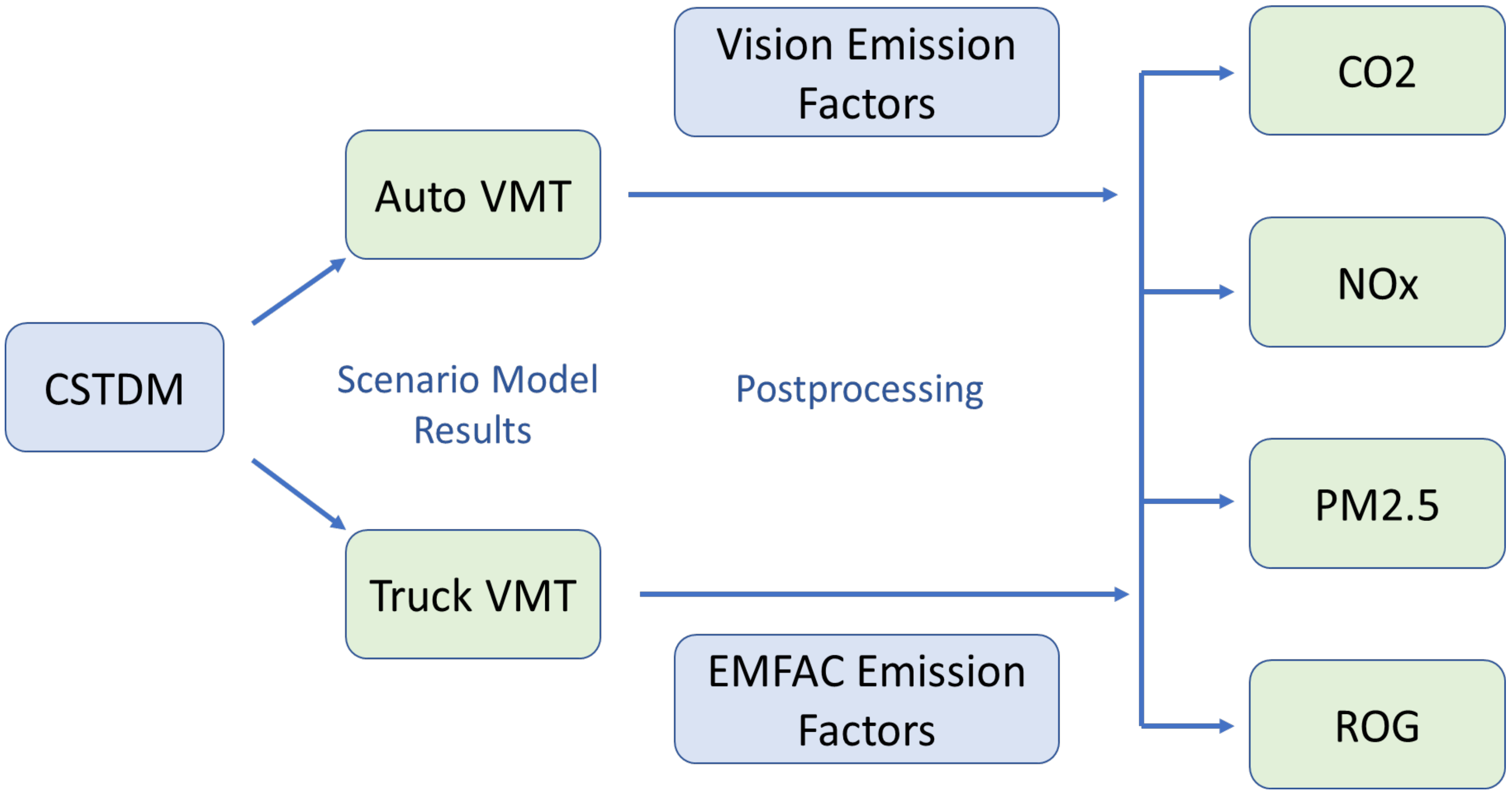


Application of California Statewide Travel Demand Model v3



SDPTM: Short Distance Passenger Travel Model
LDPTM: Long Distance Passenger Travel Model
CSFFM: California Statewide Freight Forecasting Model
ETM: External Travel Model

Postprocessing: Emission Computation



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Scenario Design

Scenario	Private CAV	Shared Automated Vehicle (SAV)	Pricing	Zero Emission Vehicle (ZEV)
0: Business as usual (BAU); no CAVs				
1: Private CAV	√			
2: Private CAV + Pricing	√		√	
3: Private CAV + ZEV	√			√
4: Shared CAV		√		
5: Shared CAV + Pricing		√	√	
6: Shared CAV + ZEV		√		√

- For each scenario, we design upper and lower bounds
- Shared CAV scenarios are obtained through post-processing of trip generation and mode choice steps (before trip assignment)
- ZEV scenarios are obtained through postprocessing of the travel model outcomes

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Assumptions: Scenarios 1, 2, and 3

Scenario	Assumptions in Travel Demand Model	Adjustment (Off-model Processing)	Zero-Emission Miles
1a. Private CAV LB	1. Operating cost -25%; 2. Capacity +50% (-20%); 3. Parking cost - 25%; 4. Driver's license relax age to 12; 5. Auto (SOV,HOV2,HOV3+) VOT -50%.	None	Natural fleet population
1b. Private CAV UB	Same as 1a	1. +15% induced trip demand for all modes for SD and LD; 2. SD deadheading trips +20% SOV, +15% HOV2, +15% HOV3+.	Same as 1a
2a. Private CAV + Pricing LB	1. Operating cost +50%; 2. Capacity +50% (-20%); 3. Parking cost - 25%; 4. Driver's license relax age to 12; 5. Auto (SOV,HOV2,HOV3+) VOT -50%.	None	Same as 1a
2b. Private CAV + Pricing UB	Same as 2a	Same as 1b	Same as 1a
3a. Private CAV + ZEV LB	Same as 1a	None	91%
3b. Private CAV + ZEV UB	Same as 1a	Same as 1b	91%

Assumptions: Scenarios 4, 5, and 6

Scenario	Assumptions in Travel Demand Model	Adjustment (Off-model Processing)	Zero-Emission Miles
4a. Shared CAV LB	1. Operating cost -25%; 2. Capacity +50% (-20%); 3. Parking cost - 25%; 4. Driver's license relax age to 12; 5. Auto (SOV,HOV2,HOV3+) VOT -50%.	1. For SD TAZ level OD, Move 10% of SOV trips to HOV2 (get 60%), and HOV3+ (get 40%); Move 40% of PT trips to HOV2 (get 70%), and HOV3+ (get 30%) 2. SD deadheading +10% HOV2, +10% HOV3+	Natural fleet population
4b. Shared CAV UB	Same as 4a	1. TAZ level OD trips +15% induced demand for all modes for SD and LD; 2. For SD TAZ level OD, Move 10% of SOV trips to HOV2 (get 60%), and HOV3+ (get 40%); Move 40% of PT trips to HOV2 (get 70%), HOV3+ (get 30%); 3. SD deadheading +20% SOV, +20% HOV2, +20% HOV3.	Same as 4a
5a. Shared CAV + Pricing LB	1. Operating cost +50%; 2. Capacity +50% (-20%); 3. Parking cost - 25%; 4. Driver's license relax age to 12; 5. Auto (SOV,HOV2,HOV3+) VOT -50%.	Same as 4a	Same as 4a
5b. Shared CAV + Pricing UB	Same as 5a	Same as 4b	Same as 4a
6a. Shared CAV + ZEV LB	Same as 4a	Same as 4a	91%
6b. Shared CAV + ZEV UB	Same as 4a	Same as 4b	91%

Findings: Trips and VMT for Scenarios 1 and 2

Scenario	BAU 2050	1a. Private CAV LB	1a % change vs. BAU	1b. Private CAV UB	1b % change vs. BAU	2a. Private CAV + Pricing LB	2a % change vs. BAU	2b. Private CAV + Pricing UB	2b % change vs. BAU
Total Person Trips	208,484,087	211,988,016	1.7%	283,140,473	35.8%	211,921,665	1.6%	282,031,638	35.3%
Auto Person Trips	181,925,683	190,009,673	4.4%	257,865,378	41.7%	185,507,411	2.0%	251,655,246	38.3%
Short Distance Transit Trips	7,322,712	4,953,980	-32.3%	5,697,077	-22.2%	6,005,806	-18.0%	6,906,677	-5.7%
Long Distance Rail Trips (CVR + HSR)	82,079	34,397	-58.1%	39,557	-51.8%	48,231	-41.2%	55,466	-32.4%
In-state Air Trips	21,127	6,432	-69.6%	7,397	-65.0%	10,056	-52.4%	11,564	-45.3%
Walk/Bike Trips	17,627,299	16,255,805	-7.8%	18,694,176	6.1%	19,590,124	11.1%	22,528,643	27.8%
School Bus Trips	1,505,187	727,729	-51.7%	836,888	-44.4%	760,037	-49.5%	874,043	-41.9%
Trips per Person	3.9	4.0	1.7%	5.3	35.8%	4.0	1.6%	5.3	35.3%
Trips per Household	10.5	10.7	1.7%	14.2	35.8%	10.6	1.6%	14.2	35.3%
VMT Autos	1,140,235,200	1,196,268,400	4.90%	1,616,268,400	41.70%	906,346,100	-20.50%	1,217,167,900	6.70%
Auto VMT per Person	21	22	5.20%	30	42.30%	17	-20.20%	23	7.00%
Auto VMT per Household	57	60	4.90%	81	41.70%	46	-20.60%	61	6.80%

Findings: Mode Share for Scenarios 1 and 2

Scenario	BAU 2050	1a. Private CAV LB	1a vs BAU Absolute Difference	1a % change vs. BAU	1b. Private CAV UB	1b vs BAU Absolute Difference	1b % change vs. BAU	2a. Private CAV + Pricing LB	2a vs BAU Absolute Difference	2a % change vs. BAU	2b. Private CAV + Pricing UB	2b vs BAU Absolute Difference	2b % change vs. BAU
SOV	48.42%	54.79%	6.37 p.p.	13.16%	56.60%	8.18 p.p.	16.89%	52.63%	4.21 p.p.	8.70%	54.57%	6.15 p.p.	12.69%
HOV2	22.71%	20.51%	-2.21 p.p.	-9.71%	20.29%	-2.42 p.p.	- 10.65%	20.68%	-2.04 p.p.	-8.97%	20.54%	-2.18 p.p.	-9.58%
HOV3+	16.13%	14.33%	-1.80 p.p.	-11.14%	14.18%	-1.95 p.p.	-12.07%	14.23%	-1.90 p.p.	-11.80%	14.13%	-2.00 p.p.	-12.41%
Short Distance Transit	3.51%	2.34%	-1.18 p.p.	-33.47%	2.01%	-1.50 p.p.	-42.71%	2.83%	-0.68 p.p.	-19.31%	2.45%	-1.06 p.p.	-30.28%
Long Distance Rail	0.04%	0.02%	-0.02 p.p.	-58.79%	0.01%	-0.03 p.p.	-64.51%	0.02%	-0.02 p.p.	-42.19%	0.02%	-0.02 p.p.	-50.05%
In-state Air	0.01%	0.00%	-0.01 p.p.	-70.06%	0.00%	-0.01 p.p.	-74.22%	0.00%	-0.01 p.p.	-53.17%	0.00%	-0.01 p.p.	-59.54%
Walk/Bike	8.45%	7.67%	-0.79 p.p.	-9.30%	6.60%	-1.85 p.p.	-21.91%	9.24%	0.79 p.p.	9.33%	7.99%	-0.47 p.p.	-5.52%
School Bus	0.72%	0.34%	-0.38 p.p.	-52.45%	0.30%	-0.43 p.p.	-59.06%	0.36%	-0.36 p.p.	-50.32%	0.31%	-0.41 p.p.	-57.07%

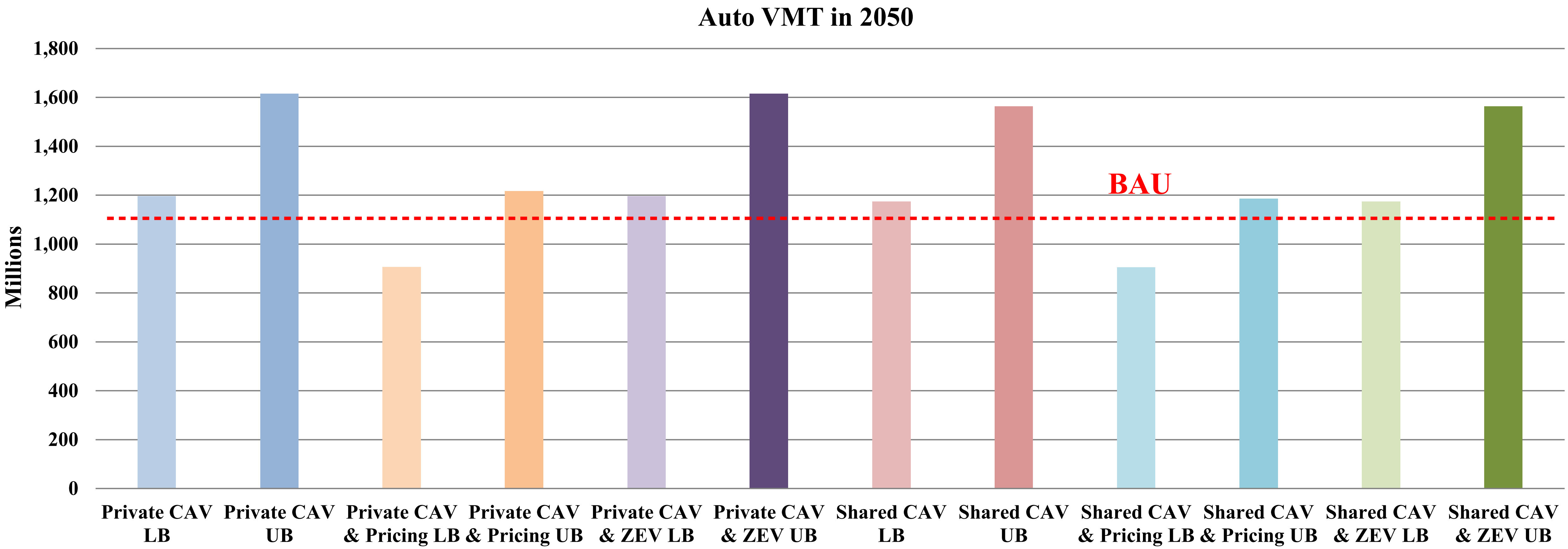
Findings: Trips and VMT for Scenario 4 and 5

Scenario	BAU 2050	4a. Shared CAV LB	4a % change vs. BAU	4b. Shared CAV UB	4b % change vs. BAU	5a Shared CAV + Pricing LB	5a % change vs. BAU	5b Shared CAV + Pricing UB	5b % change vs. BAU
Total Person Trips	208,484,087	220,696,172	5.90%	287,824,869	38.10%	220,720,887	5.90%	286,820,613	37.60%
Auto Person Trips	181,925,683	200,699,421	10.30%	264,828,606	45.60%	196,700,212	8.10%	259,206,892	42.50%
Short Distance Transit Trips	7,322,712	2,972,388	-59.40%	3,418,246	-53.30%	3,603,484	-50.80%	4,144,006	-43.40%
Long Distance Rail Trips (CVR + HSR)	82,079	34,397	-58.10%	39,557	-51.80%	55,466	-32.40%	55,466	-32.40%
In-state Air Trips	21,127	6,432	-69.60%	7,397	-65.00%	11,564	-45.30%	11,564	-45.30%
Walk/Bike Trips	17,627,299	16,255,805	-7.80%	18,694,176	6.10%	19,590,124	11.10%	22,528,643	27.80%
School Bus Trips	1,505,187	727,729	-51.70%	836,888	-44.40%	760,037	-49.50%	874,043	-41.90%
Trips per Person	3.9	4.1	5.90%	5.4	38.10%	4.1	5.90%	5.4	37.60%
Trips per Household	10.5	11.1	5.90%	14.5	38.10%	11.1	5.90%	14.4	37.60%
VMT Autos	1,140,235,200	1,174,326,900	3.00%	1,563,847,600	37.20%	904,886,900	-20.60%	1,185,310,300	4.00%
Auto VMT per Person	21	22	3.30%	29	37.60%	17	-20.70%	22	4.20%
Auto VMT per Household	57	59	3.00%	79	37.20%	46	-20.60%	60	4.00%

Findings: Mode Share for Scenario 4 and 5

Scenario	BAU 2050	4a. Shared CAV LB	4a vs BAU Absolute Difference	4a % change vs. BAU	4b. Shared CAV UB	4b vs BAU Absolute Difference	4b % change vs. BAU	5a Shared CAV + Pricing LB	5a vs BAU Absolute Difference	5a % change vs. BAU	5b Shared CAV + Pricing UB	5b vs BAU Absolute Difference	5b % change vs. BAU
SOV	48.42%	47.38%	-1.04 p.p.	-2.16%	50.12%	1.69 p.p.	3.50%	45.50%	-0.03 p.p.	-6.0%	48.29%	0.00 p.p.	-0.30%
HOV2	22.71%	25.82%	3.11 p.p.	13.68%	24.83%	2.12 p.p.	9.32%	26.01%	0.03 p.p.	14.50%	25.09%	0.02 p.p.	10.50%
HOV3+	16.13%	17.74%	1.61 p.p.	10.01%	17.07%	0.94 p.p.	5.81%	17.61%	0.01 p.p.	9.20%	16.98%	0.01 p.p.	5.30%
Short Distance Transit	3.51%	1.35%	-2.17 p.p.	-61.65%	1.19%	-2.32 p.p.	-66.19%	1.63%	-0.02 p.p.	-53.5%	1.44%	-0.02 p.p.	-58.9%
Long Distance Rail	0.04%	0.02%	-0.02 p.p.	-60.41%	0.01%	-0.03 p.p.	-65.09%	0.03%	0.00 p.p.	-36.20%	0.02%	0.00 p.p.	-50.90%
In-state Air	0.01%	0.00%	-0.01 p.p.	-71.24%	0.00%	-0.01 p.p.	-74.64%	0.01%	0.00 p.p.	-48.30%	0.00%	0.00 p.p.	-60.20%
Walk/Bike	8.45%	7.37%	-1.09 p.p.	-12.88%	6.49%	-1.96 p.p.	-23.18%	8.88%	0.00 p.p.	5.00%	7.85%	-0.01 p.p.	-7.1%
School Bus	0.72%	0.33%	-0.39 p.p.	-54.33%	0.29%	-0.43 p.p.	-59.73%	0.34%	0.00 p.p.	-52.30%	0.30%	0.00 p.p.	-57.80%

CAVs Could Lead to Substantial Increase in Statewide VMT



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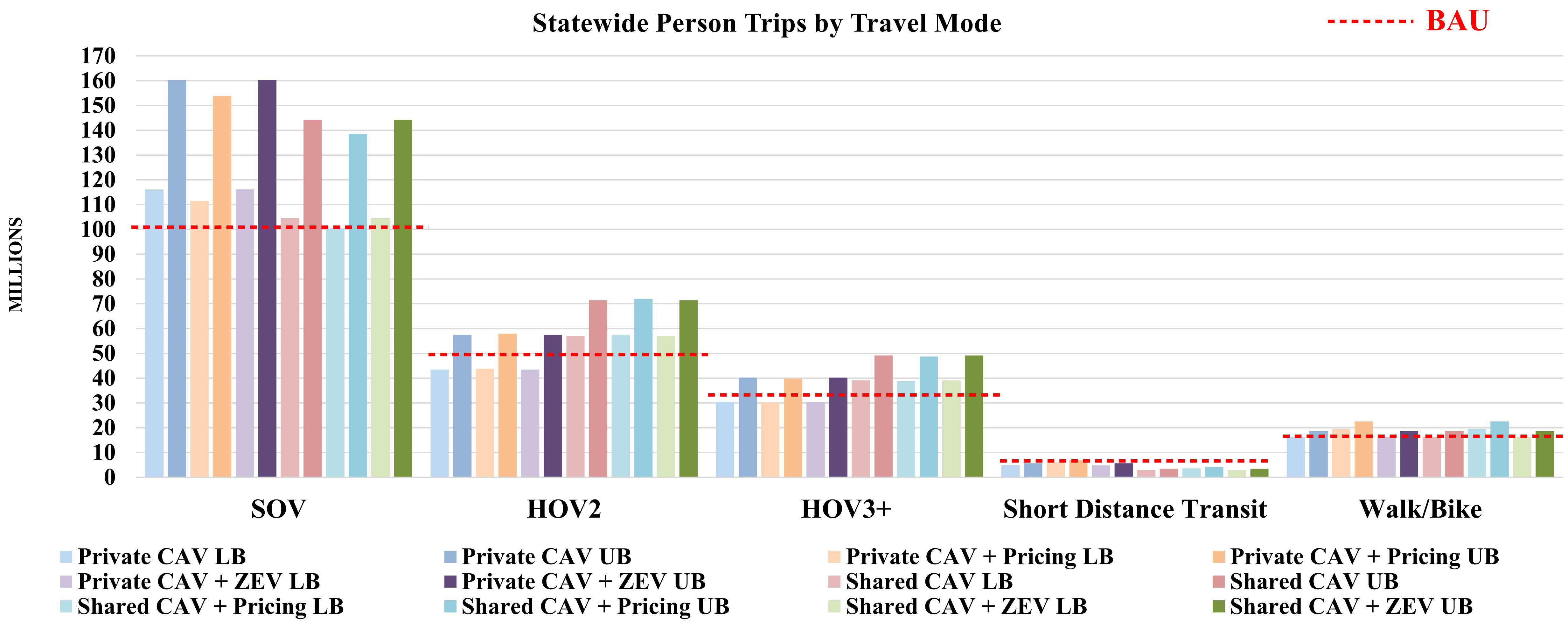
Pricing and Sharing Could Lead to Similar Number of Person Trips but with Lower VMT in 2050



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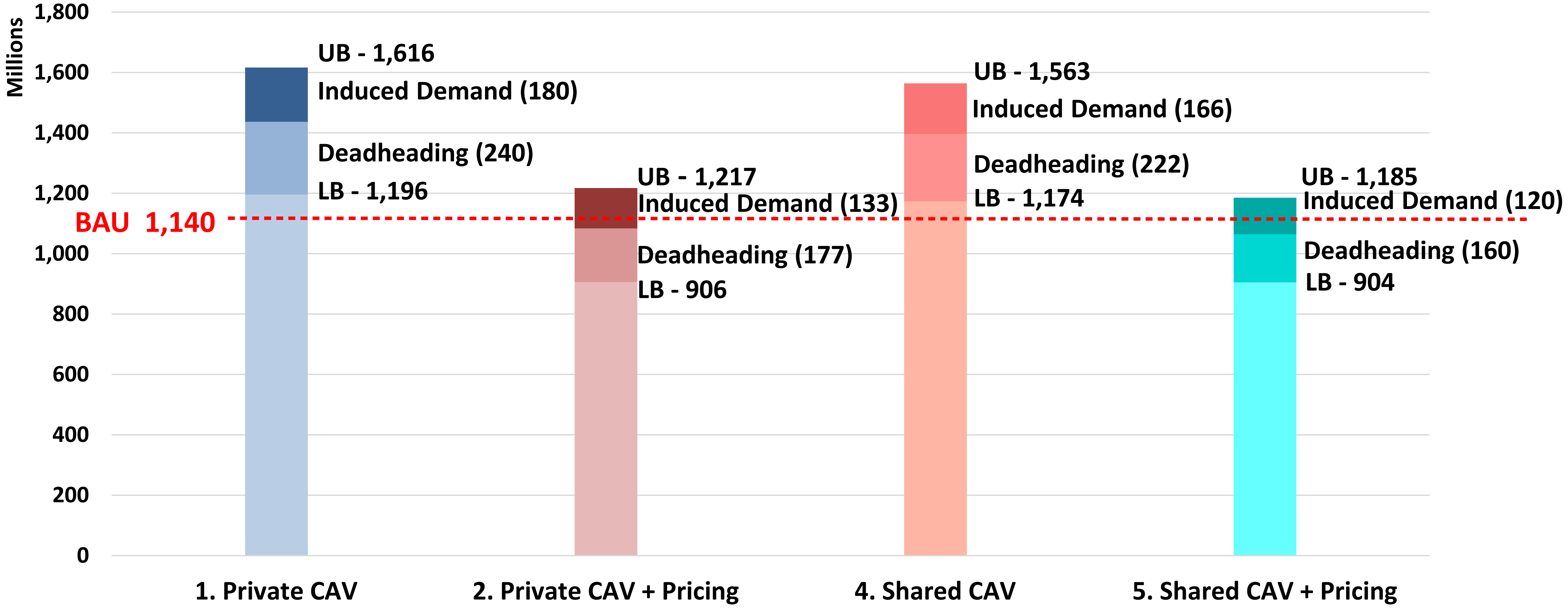
Range of 2050 Auto VMT for Modeled Scenarios



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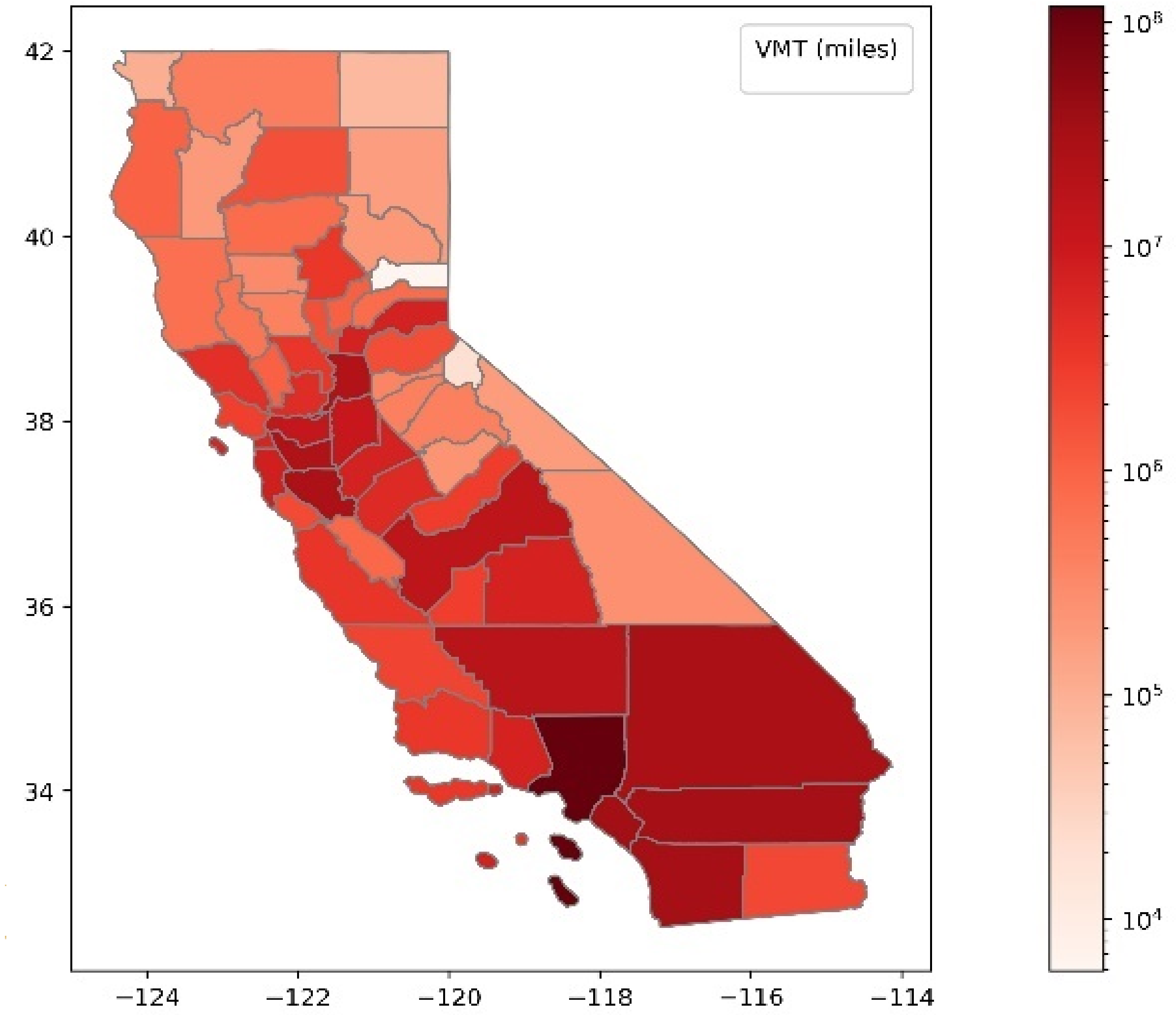
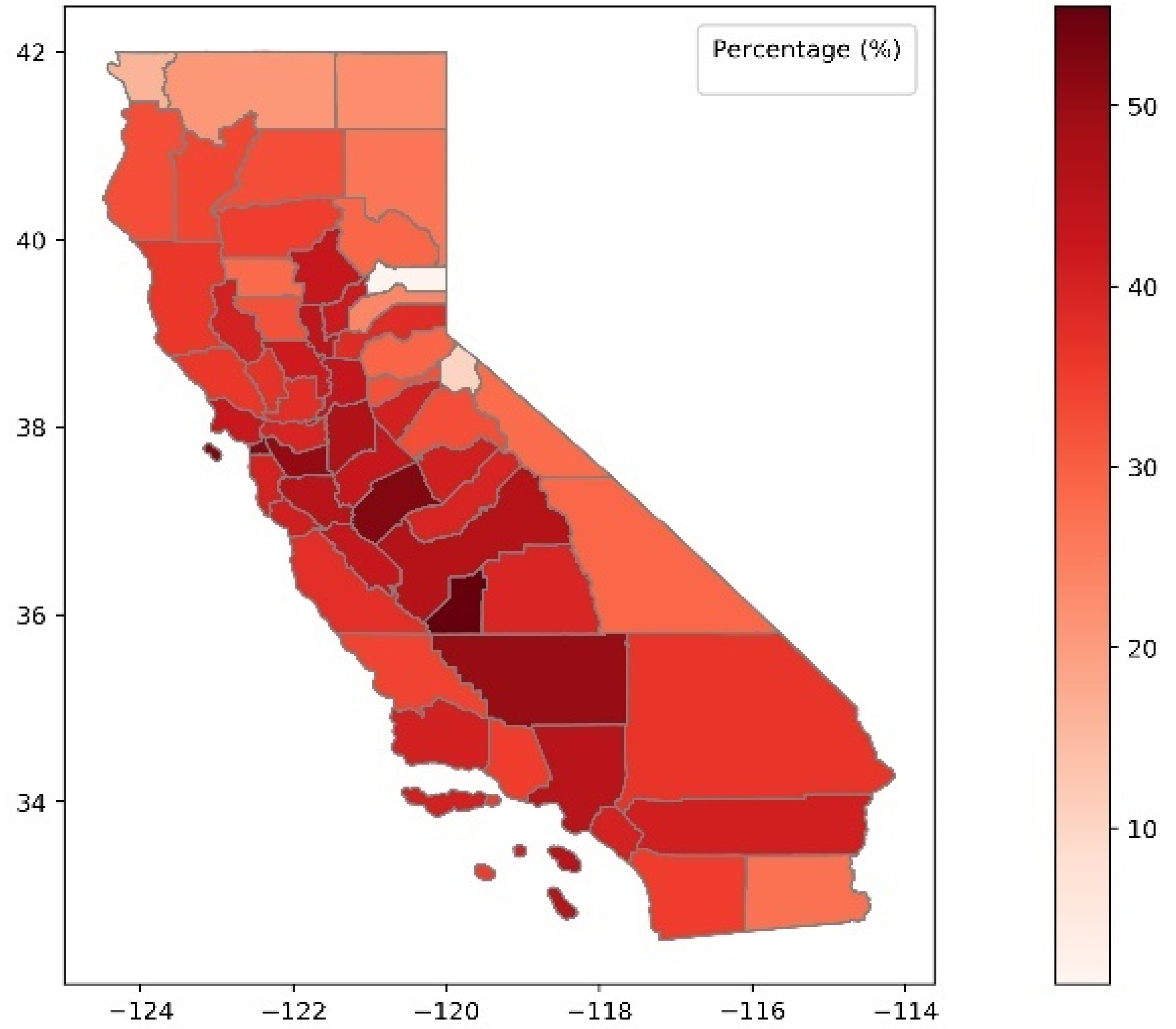
Findings: Auto VMT 2050 – Private CAV (Scenario 1b)

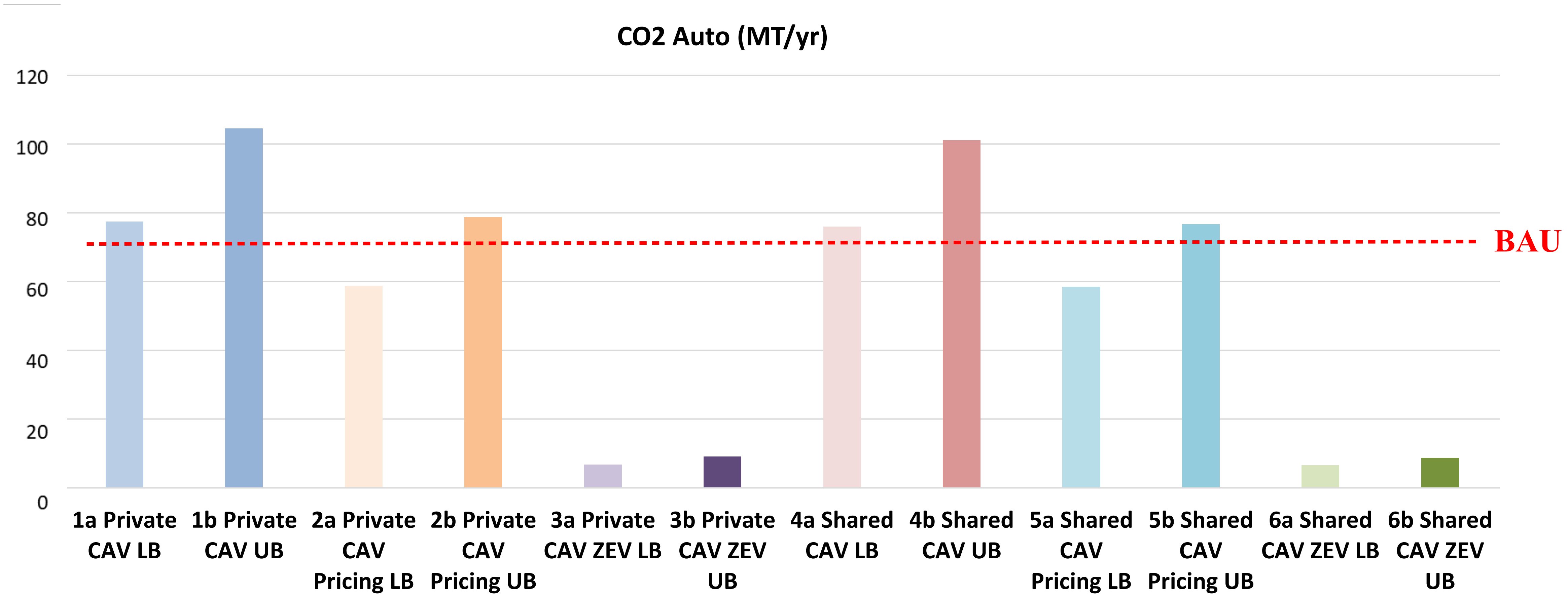
Absolute Change in VMT between Scenario 1b (Private CAV UB) and BAU



Change (%) in VMT between Scenario 1b (Private CAV UB) and BAU



Findings: CO_2 Emissions in 2050



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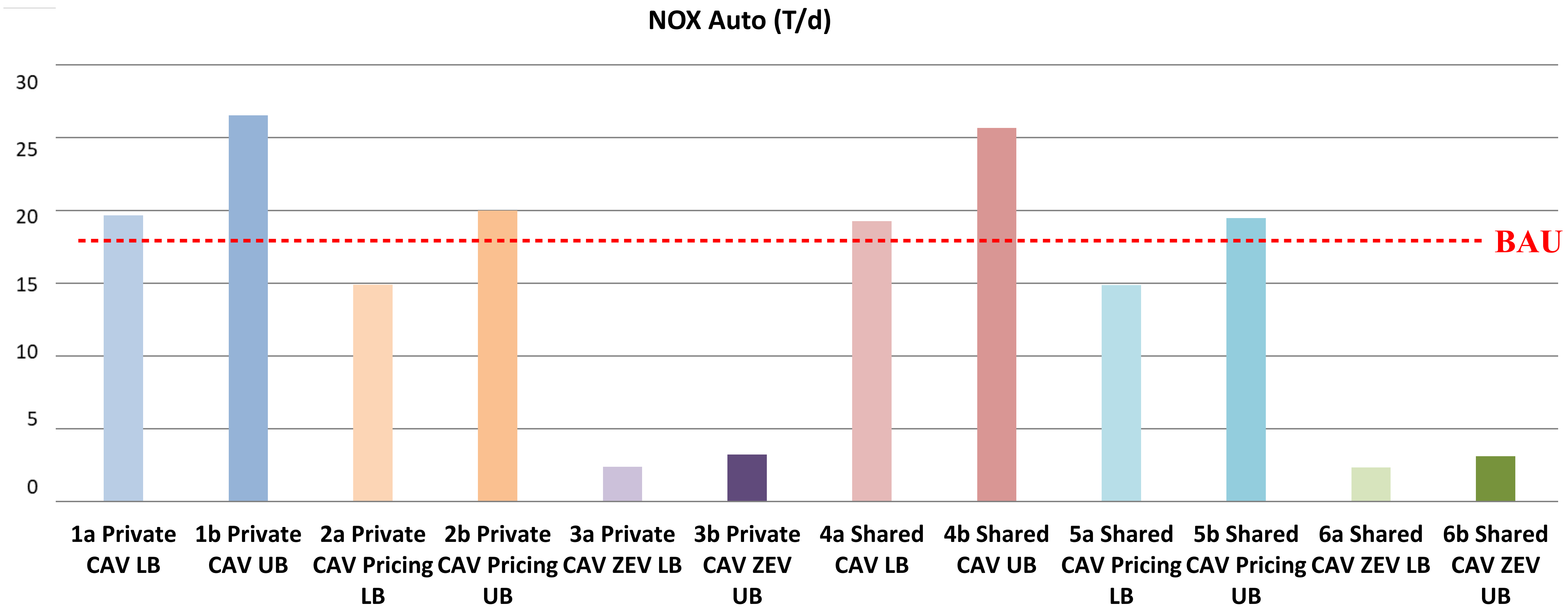
Findings: NOX Emissions in 2050



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Some Implications for Policy Making

- The study highlights the potential for CAV deployment to considerably increase VMT and considerably reduce mode share for public transportation, long-distance rail and in-state air travel.
- According to the model results, the relative increase in VMT will affect the central San Joaquin Valley to a great extent than other regions in the state.
- Pricing strategies that discourage car travel coupled with policies that promote shared deployment of CAV could mitigate at least in part the increase in travel demand associated with CAVs.
- The study highlights the importance of early deployment of ZEVs, as they can considerably offset the tailpipe GHG and criteria pollutant emissions from CAVs.
- Importance of coordination among various policies: if deployed in isolation, ZEVs will cut emissions, but other negative externalities from increase in car travel and traffic congestion will remain.

Some Implications for Policy Making (2)

Additional policy recommendations include:

- Make sure that CAV are deployed as shared use vehicles, rather than privately owned;
- Ensure widespread carpooling;
- Deploy CAV with zero tailpipe emissions;
- Take advantage of opportunities to introduce pricing strategies;
- Increase line-haul transit use and coordinate its services with other modes of travel, rather than replacing it;
- Ensure CAV are not larger or more energy consumptive; and
- Program vehicle behavior to improve livability, safety and comfort on surface streets.

CAVs can improve mobility for individuals with mobility impairments:

- Consider incentive programs to promote shared (electric) CAV projects targeted at elderly / physically-impaired individuals to reduce mobility barriers and efficiently allocate recourses.

Uncertainties and Limitations

Limitations of activity-based models in general:

1. Whether and how CAVs will become accessible to the various segments of the population and in the large span of spatial locations is still an open research question;
2. It is still unclear how people will perceive CAVs and how they will adjust their activity and travel choices;
3. We use models that are estimated, calibrated and validated using survey data from the past, with many uncertainties about the future (changes in lifestyle, technology, urban form, policy, etc.);
4. The introduction of an “unknown” brand-new CAV travel mode might have largely unknown impacts on travel demand and push current models outside of their range of application.

Additional limitations specific to this project:

1. CAV deployment might lead to modifications in land use that are not accounted for in this study;
2. CSTDM seems to be rather sensitive to changes in travel cost, but less so to travel time;
3. The model is rather sensitive to changes in the inputs affecting mode choice, but not so much in the trip generation step.

The limitations above suggest that even the Upper Bound (UB) scenarios in this project might ***underestimate*** the future travel demand impacts of CAV deployment.

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Previous Experience in the Transportation Literature

Author	*Location*	*Method*	*Travel Effects*	*AV*	*Scenario Parameters*	*Mode Choice*	*Total VMT*	*Travel Time*	*Land Use/Parking*
Thakur et al. 2016	Melbourne, Australia	Travel & land use model calibrated to regional forecasts	Home location, destination, mode & SA route choice	100% Personal	50% VOT	+3 PP Car; -3 PP Transit	+30%	+24% Avg. VTT	Suburb pop.: +2% outer; -1% middle; -4% inner
Childres S et al. 2014	Seattle, WA (US)	MPO regional activity-based travel model	Destination, mode & SA route choice	100% Personal	+30% road capacity +30% road capacity; 65% high income VOT +30% road capacity; 65% VOT; -50% parking cost	0 PP -1 PP Car +1 PP Car; -2 PP Walk	+3.6% +5% +19.6%	-17.6 Avg. Delay -14.3 Avg. Delay +17.3 Avg. Delay	Outlying & some core high access & VMT increase
Gucwa 2014	San Francisco CA (US)	MPO regional activity-based travel model	Destination, mode & SA route choice	100% Personal	+100% road capacity		+2%		
					+100% road capacity; 50% VOT	-	+7.9%	-	
Auld et al. 2017	Ann Arbor, MI (US)	Activity & agent-based travel model (POLARIS) with data from MPO (survey & network)	Trip, destination, mode & DTA route choice	100% Personal	+12% to +77% road capacity		+0.4% to +2%	-1.8% to -4.5% Avg. VTT	
				20% Personal	25% to 75% VOT		+1.3% to +5%	+1.8% to +7.1% Avg. VTT	
				75% Personal	25% to 75% VOT		+5.7% to +18.6%	+8% to +30% Avg. VTT	
				20% Personal	25% to 75% VOT; +3% road capacity		+1.6% to +5.3%	+1.6% to +7.1% Avg. VTT	
				75% Personal	25% to 75% VOT; +12% road capacity		+4.3% to +12.7%	+3.2% to +15.9% Avg. VTT	
				100% Personal	25% to 75% VOT; +77% road capacity; AV Int.		+10% to +28.2%	+4.5% to +30.1% Avg. VTT	
Levin & Boyles 2015	Downto wn Austin, TX (US)	Modified 4 Step Model & MPO travel data	Destination, mode & SA route choice (parking & repositioning)	100% Personal	Reduced following distance & jam densities	-63% transit trips;+274.5 vehicle trips	-	-9% Avg. Link Speed (weighted by length)	Increased parking disutility
Azevedo et al. 2016	CBD Singapore	Activity & agent travel model (SimMobility) with travel survey, network & taxi data	Trip, destination, time of day, mode & DTA route choice	Shared Taxi	No private vehicles; areas only accessed by transit; service cost 40% current taxi	+3% PP transit; +29% PP shared taxi; +1% PP taxi, +1% PP walk		-	

Source: Rodier et al. 2019

Previous Experience in the Transportation Literature (2)

Percentage change in trips by mode for peak and off-peak periods for the automated vehicle scenarios

Scenario	*Time of Day*	*Drive Alone*	*Shared Ride*	*Transit*	*Walk and Bike*
Base Case	Peak	6,269,541	4,955,338	791,508	1,346,109
	Off-Peak	5,350,847	3,836,884	384,401	1,279,525
	Total	11,620,388	8,792,222	1,175,909	2,625,634
Increase Roadway	Peak	1%	0%	1%	-3%
Capacity (100%)	Off-Peak	0%	0%	0%	-2%
	Total	0%	0%	1%	-2%
Reduce Value of Drive	Peak	1%	1%	-5%	-4%
Time (25%)	Off-Peak	1%	1%	-5%	-4%
	Total	1%	1%	-5%	-4%
Reduce Operating	Peak	1%	1%	-4%	-5%
Vehicle Costs ($0.04)	Off-Peak	1%	1%	-4%	-4%
	Total	1%	1%	-4%	-4%
New Drivers	Peak	7%	-6%	-11%	-5%
	Off-Peak	5%	-3%	-13%	-3%
	Total	6%	-5%	-12%	-4%
Combined Effects	Peak	11%	-3%	-19%	-13%
	Off-Peak	6%	-2%	-23%	-11%
	Total	9%	-3%	-20%	-12%
Road Pricing and	Peak	4%	-11%	10%	23%
Combined Effects	Off-Peak	-1%	-8%	-1%	20%
	Total	2%	-10%	6%	22%

Percentage change in vehicle miles traveled (VMT), vehicle volumes (VOL), and vehicle hours of delay (VHD) for peak and off-peak periods for the automated vehicle scenarios

Time of Day	*VMT*	*VOL*	*VHD*
Peak	86,883,585	176,476,827	334,246
Off-Peak	99,744,968	204,064,211	527,911
Total	207,969,628	378,077,830	2,566,657
Peak	6%	0%	-70%
Off-Peak	1%	0%	-83%
Total	4%	0%	-78%
Peak	4%	0%	18%
Off-Peak	2%	0%	1%
Total	3%	0%	7%
Peak	3%	3%	14%
Off-Peak	3%	2%	-1%
Total	3%	2%	5%
Peak	3%	0%	11%
Off-Peak	1%	0%	-4%
Total	2%	0%	1%
Peak	15%	10%	-56%
Off-Peak	6%	6%	-79%
Total	11%	8%	-70%
Peak	-6%	-10%	-80%
Off-Peak	-7%	-8%	-86%
Total	-7%	-9%	-84%