ENERGY AND MOBILITY IMPACTS OF PRIVATELY OWNED FULLY AUTONOMOUS VEHICLES

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ABSTRACT

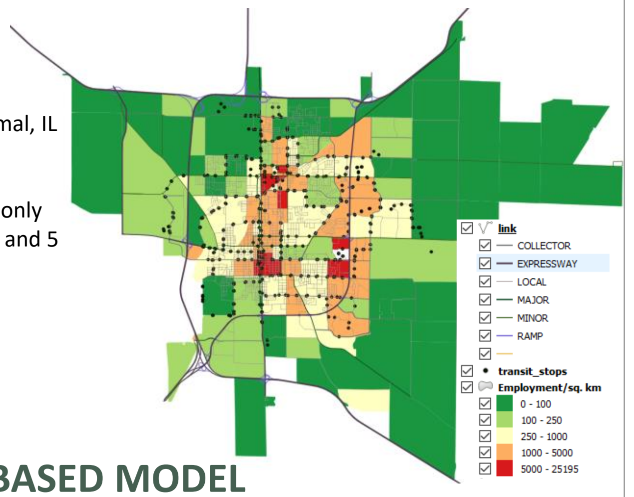
In this research, we explore the impact on mobility and energy use of wide-scale deployment of fully autonomous, privately owned vehicles. Such vehicles have a potential range of impacts in terms of traffic flow and transportation system performance, vehicle performance and energy use characteristics, and travel demand. We studied the combination of multiple effect of CAV deployment for a small metropolitan area over a variety of possible scenarios for baseline, near-term and long-term time-frames, demonstrating the range of possible impacts and exploring several potential mitigation strategies.

METHODOLOGY

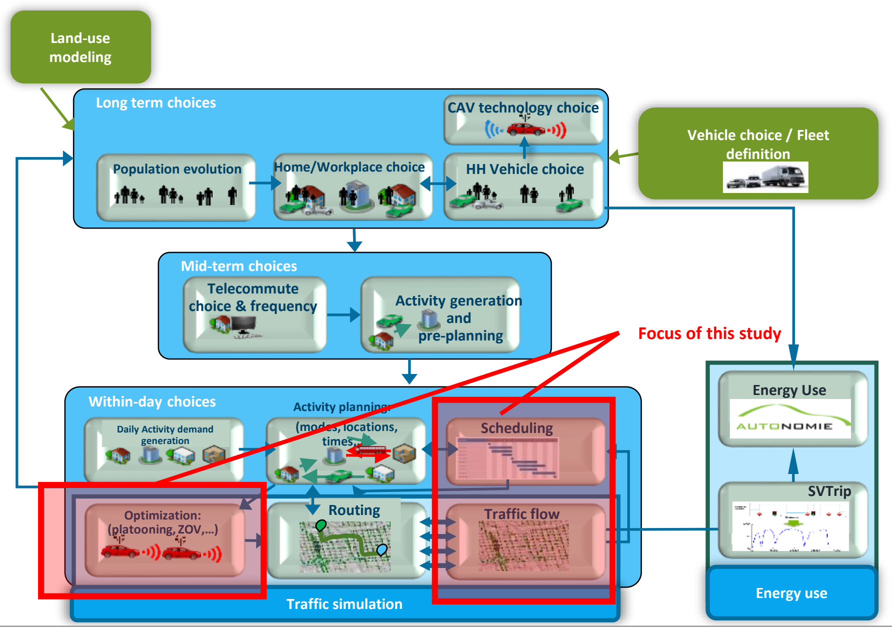
- POLARIS agent-based transportation simulator used to generate activities and traffic
  - Mesoscopic traffic simulator updated to account for link capacity improvements from empirical studies and microscopic traffic flow studies
  - Represent CAV impacts over a range of penetration levels under a variety of configurations (i.e. merging sections, on/off ramps, lane reductions, etc.).
- Optimization based intra-household vehicle sharing for CAV 5 assigns household's vehicles to household trips (for those with CAV 5, determined from vehicle choice model)
- POLARIS code generates and simulates dead-heading vehicle trips for CAV5 users
- Autonomie vehicle energy model used to estimate the energy consumption from CAVs

CASE STUDY

- Location: Bloomington-Normal, IL
- Timeframe:
  - base year (2015)
  - short-term (2025 – CAV4 only
  - long-term (2040) – CAV 4 and 5
- 65,000 households
- 156,000 people
- 222 TAZs
- 2,833 activity locations
- 3,947 links
- 470 transit stops

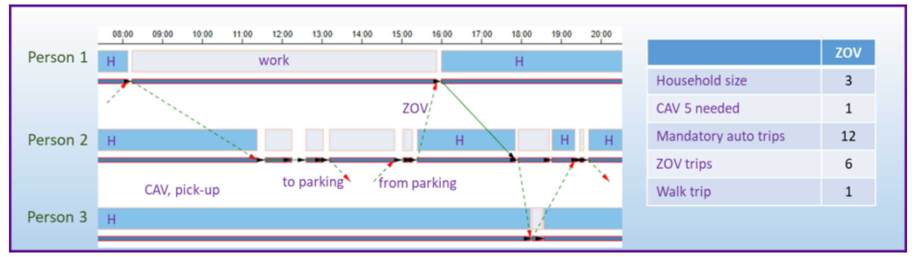


POLARIS, AGENT-BASED MODEL



INTRA-HOUSEHOLD VEHICLE/RIDE SHARING BEHAVIOR MODEL

- Finds the optimum utilization of vehicles for household who own level 5 Avs:
  - Assigns AVs to household trips, while minimizing the cost
  - Included costs: energy, taxi, vehicle ownership, parking, value of time, ZOV charge
  - Considers vehicle sharing as well as ride sharing
  - Considers flexibility in start and duration of activities to modify schedules
  - Allows vehicles to go home for parking when parking at activity location is costly
  - Modes: auto, taxi, others(walk and transit if predetermined)
  - Vehicles could travel to home for parking, if parking at activity location is expensive.
  - Feasibility of travels in terms of time, between activity locations is considered



$$\sum^{i}\sum^{a}\left(|\boldsymbol{\sigma}_{i,a}-s_{i,a}|+|\boldsymbol{\delta}_{i,a}-d_{i,a}|\right)*Cost_{Time}+$$ *Changes to schedule*

$$\sum_{v=0}^{V}\sum^{i}\sum^{a}\sum^{j}\sum^{b}\sum^{m}{}^{A_{j,b,e}}_{A_{i,a,s}}T_v*\left(Cost_{Fuel}*{}^{A_{j,b,e}}_{A_{i,a,s}}R_v\right)+$$ *fuel cost for trips between activities*

$$\sum_{v=1}^{V}\sum^{i}\sum^{a}{}^{A_{i,a,e}}_{Home}T_v*\left(Cost_{CAV}+(Cost_{Fuel}+Cost_{ZOV-Tax})*{}^{A_{i,a,e}}_{Home}R_v\right)+$$ *Vehicle ownership, fuel, ZOV tax: First trip of each vehicle (from home to an act),*

$$\sum_{v=1}^{V}\sum^{i}\sum^{a}{}^{Home}_{A_{i,a,s}}T_v*(Cost_{Fuel}+Cost_{ZOV-Tax})*{}^{Home}_{A_{i,a,s}}R_v+$$ *Fuel and ZOV tax: for last trip of each vehicle (from an act to home)*

$$\sum_{v=1}^{V}\sum^{i}\sum^{a}\sum^{j}\sum^{b}{}^{A_{i,a,e}}_{Prk_{j,b,s}}T_v*(Cost_{Fuel}+Cost_{ZOV-Tax})*{}^{A_{i,a,e}}_{Prk_{j,b,s}}R_v+$$ *Fuel and ZOV tax: for trips from parking to an act*

$$\sum_{v=1}^{V}\sum^{i}\sum^{a}{}^{Prk}_{A_{i,a,s}}T_v*(Cost_{Fuel}+Cost_{ZOV-Tax})*{}^{Prk}_{A_{i,a,s}}R_v+$$ *Fuel and ZOV tax: Trips from an act to parking*

$$\sum_{v=1}^{V}\sum^{i}\sum^{a}\sum^{j}\sum^{b}{}^{A_{j,b,e}}_{A_{i,a,s}}Z_v*\left(Cost_{ZOV-Tax}*{}^{A_{j,b,e}}_{A_{i,a,s}}R_v\right)$$ *Tax: ZOV trips between two activities*

A_i All activities belong to person $i \in P$
$A_{i,a}$ Activity a, belong to person $i \in P, a \in A_i$
$A_{i,a,s}$ Start of Activity a, belong to person $i \in P, a \in A_i$
$A_{i,a,e}$ End of Activity a, belong to person $i \in P, a \in A_i$
$s_{i,a}$: **planned** start time of activity $a, a \in A_i, i \in P$
$d_{i,a}$: **planned** duration of activity $a, a \in A_i, i \in P$
$e_{i,a} = s_{i,a} + d_{i,a}$: **planned** end time of activity $a, a \in A_i$
$S_{i,a}$: start time **threshold** of activity $a, a \in A_i, i \in P$
$D_{i,a}$: Duration **threshold** of activity $a, a \in A_i, i \in P$
$H_{i,a}$: Binary, 1 if activity a is a Home activity $a, a \in A_i$
V: Maximum number of vehicles in a household
${}^{A_{i,a,e}}_{Home}R_v$ Travel time from home to $A_{i,a,e}$ at time $e_{i,a}$ by vehicle v
${}^{A_{j,b,n}}_{A_{i,a,m}}R_v$ Travel time from $A_{i,a,m}$ to $A_{j,b,n}$ by vehicle v at time t; $m, n \in \{s, e\}$, where $(m = s \rightarrow t = s_{i,a}, m = e \rightarrow t = e_{i,a})$
${}^{Prk}_{A_{i,a,s}}R_v$ Travel time from $A_{i,a,s}$ to parking at time $s_{i,a}$ by vehicle v (after dropping off person i)
${}^{A_{j,b,e}}_{Prk_{A_{i,a,s}}}R_v$ Travel Time from Parking to $A_{j,b,e}$ at time $e_{j,b}$ by vehicle v (where vehicle v had gone to parking from $A_{i,a,s}$

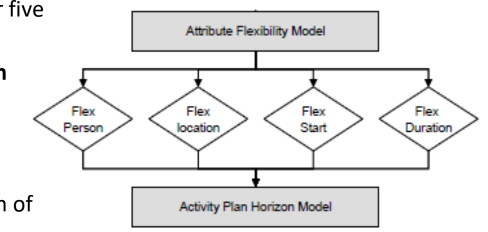
Decision Variables:
Linear:
$\boldsymbol{\sigma}_{i,a}$: **optimal** start time of activity $a, a \in A_i, i \in P$
$\boldsymbol{\delta}_{i,a}$: **optimal** duration of activity $a, a \in A_i, i \in P$
$\boldsymbol{\varepsilon}_{i,a} = \boldsymbol{\sigma}_{i,a} + \boldsymbol{\delta}_{i,a}$: **optimal** end of activity $a, a \in A_i, i \in P$
Binaries:
v=0 is reserved for taxi trips and also used for bike/walk/transit mode that have been scheduled in advance.
${}^{A_{j,b,n}}_{A_{i,a,m}}T_v$: Travel from $A_{i,a,m}$ to $A_{j,b,n}$ by vehicle v

INTRA-HOUSEHOLD VEHICLE/RIDE SHARING MODEL IMPLEMENTATION

- Mixed Integer Programming (MIP) Optimization Model: Solved using Gurobi Optimization
- Coded in POLARIS in C++: household-level agent event for schedule optimization
- Runs for every household (with CAV5) in POLARIS:
  - Uses time dependent travel times to check for feasibility of optimized schedules
  - Uses Activity Attribute Flexibility Model, to determine perceived flexibility start time and duration)
  - Generates new travel episodes for the ZOV trips between locations and to/from parking
  - Replaces pre-planned SOV trips with shared AV trips as needed

ACTIVITY ATTRIBUTE FLEXIBILITY AND OTHER BEHAVIORAL CONSTRAINTS

- Determines perceived flexibility (flexible, inflexible) for five primary activity attributes
  - mode, who with, location, **start time** and **duration**
  - Used to relax constraints in optimization model
- Developed for 5 activity purposes: work, personal, household needs, discretionary, and shopping
- Uses socio-demographic and travel pattern information of individuals
- Included in POLARIS behavioral modeling simulator



SCENARIO ANALYSIS

Demand (Year X CAV price)	CAV Tech.	None		Level 4[6]		Level 5[7]
	Year	Base	2040	2025	2040	2040
	2015-base	x				
	2025-base					
	2025-cav-low[1]			x		
	2025-cav-high[2]			x		
	2040-base		x			
	2040-cav-low[3]				x	x
	2040-cav-high[4]				x	x
	2040-cav-low-charge[3,5]					x
	2040-cav-high-charge[4,5]					x

1. 2025 Low CAV scenario, price = $7,500
2. 2025 High CAV scenario, price = $2,500
3. 2040 Low CAV scenario, price = $2,500
4. 2040 High CAV scenario, price = $0
5. High road pricing tax - $0.10 per mile for ZOV miles
6. Not fully autonomous, no ZOV, VOTT = 0.5
7. Fully autonomous, ZOV allowed, VOTT = 0.25 [lower VOTT here to represent the full automation]

Assumptions for Case Study

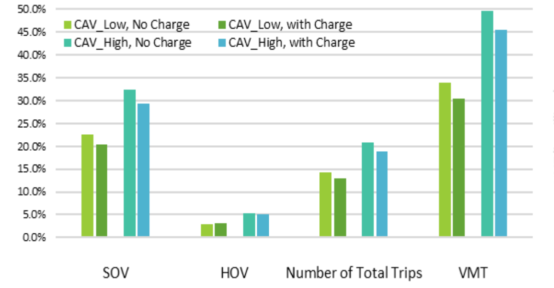
Description	Cost
Parking	$0/hr
Vehicle Ownership	$20/veh
Energy	$0.13/mile
Taxi	$3 + $0.8/mile
Value of Time	$10/hr

Flexibility Model Assumptions

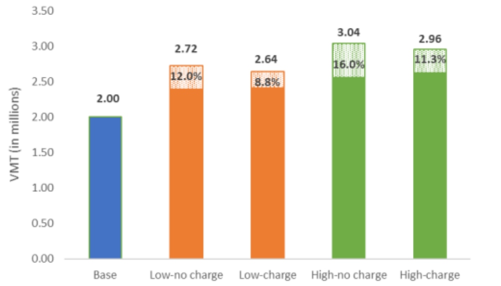
Start time flexibility	Low	60 min
	Moderate	15 min
	High	5 min
Duration flexibility	Low	60 min
	Moderate	15 min
	High	5 min

MOBILITY IMPLICATIONS OF HH SHARED-AV

- Under CAV5, **SOV** trips **significantly increase** due to ZOV trips for
- **VMT increases** at a higher rate: ZOV trips plus induced demand



Δ total, SOV and HOV trips and Total VMT



Total VMT and ZOV fraction for each scenario

COMPARISON TO BASELINE FOR LEVEL 4 AND 5 CAV SCENARIOS

- VMT and VHT significantly increase when CAV5s replace CAV4s, as penetration rate increases
- Improvements in vehicle powertrain technology (high tech: EV penetration, advanced powertrains, etc.) help
- Regulating ZOVs (pricing) adjusts the impact to some degrees

	Impacts of population growth				Fuel use (gallon)	
	Total trips	VMT	VHT	Avg. Speed (mph)	Tech-low	Tech-high
2015-base	475,149	1,646,450	67,730	24.3	64,428	
2025_base	10.2%	11.0%	2.3%	8.5%	-25.1%	-46.4%
2040_base	18.5%	21.4%	15.7%	5.3%	-51.1%	-82.5%

	Impacts of level 4 CAV				Fuel use (gallon)	
	trips	VMT	VHT	Avg. Speed (mph)	Tech-low	Tech-high
2025_base	524,054	1,841,289	69,029	26.7	48,259	37,940
2025_cav-low (Т from 2025 base)	0.3%	4.1%	2.0%	0.1%	4%	8%
2025_cav-high (0 from 2025 base)	0.7%	7.4%	4.1%	3.1%	10%	13%
2040_base	569,590	2,003,973	80,515	24.9	31,493	11,243
2040_cav-low (– from 2040 base)	1.0%	8.5%	3.3%	5.0%	12.9%	16.6%
2040_cav-high (7 from 2040 base)	1.3%	12.1%	7.4%	4.4%	20.3%	26.0%

	Impacts of level 5 CAV				Fuel use (gallon)	
	trips	VMT	VHT	Avg. Speed (mph)	Tech-low	Tech-high
2040_base	569,590	2,003,973	80,515	24.9	31,493	11,243
2040_cav-low	693,229	2,708,164	116,035	23.3	45,028	17,339
% change from L4	*20.5%*	*24.6%*	*39.5%*	*-10.7%*	*26.7%*	*32.3%*
2040_cav-high	748,624	3,043,093	140,625	21.6	52,331	21,053
% change from L4	*29.7%*	*35.4%*	*62.6%*	*-16.7%*	*38.1%*	*48.6%*
2040_cav-low-ZOV charge	683,055	2,632,974	112,650	23.4	44,300	16,649
% change from L5-low no charge	*-1.5%*	*-2.8%*	*-2.9%*	*0.1%*	*-1.6%*	*-4.0%*
2040_cav-high-ZOV charge	731,801	2,951,574	134,485	21.9	50,729	20,051
% change from L5-high no charge	*-2.2%*	*-3.0%*	*-4.4%*	*1.4%*	*-3.1%*	*-4.8%*

CONCLUSIONS AND POTENTIAL NEXT STEPS

- Full AV have potential to disrupt traffic by induced demand and **Zero Occupancy Vehicles** (ZOV) travel
- In the absence of data, **simulation** with reasonable assumptions is best way to analyze possible outcomes
- **Optimization** model of household vehicle and ride-sharing developed and implemented in POLARIS
  - Simulate people's travel behavior changes in the presence of level 5 CAVs
- ZOV trips could:
  - **Increase SOV** trips more than **33%** (for low penetration rate) and **49%** (for high penetration rate)
  - **Increase VMT** by **36%** and **52%** respectively
  - Negate much of the gains in reducing fuel consumption due to baseline vehicle technology improvement
- Introducing **ZOV pricing** of $0.1 per mile could reduce impact somewhat (to 30.5% and 45.4% correspondingly)
- Results could **vary by city and context**, depending on their characteristics, as well as the assumptions used
- Future research will focus on analyzing additional scenarios for different regions, testing various regulations, Improving performance and developing models for analyzing changes in energy consumption based on physical/network characteristics of cities
- Next steps in current analysis
  - Comparison across different vehicle technology levels
  - Impact of CAV operating assumptions
  - Parametric exploration of ZOV assumptions:
    - ZOV charge, activity flexibility capital discount for unused veh

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