Public investment and electric vehicle design: a model-based market analysis framework [1]

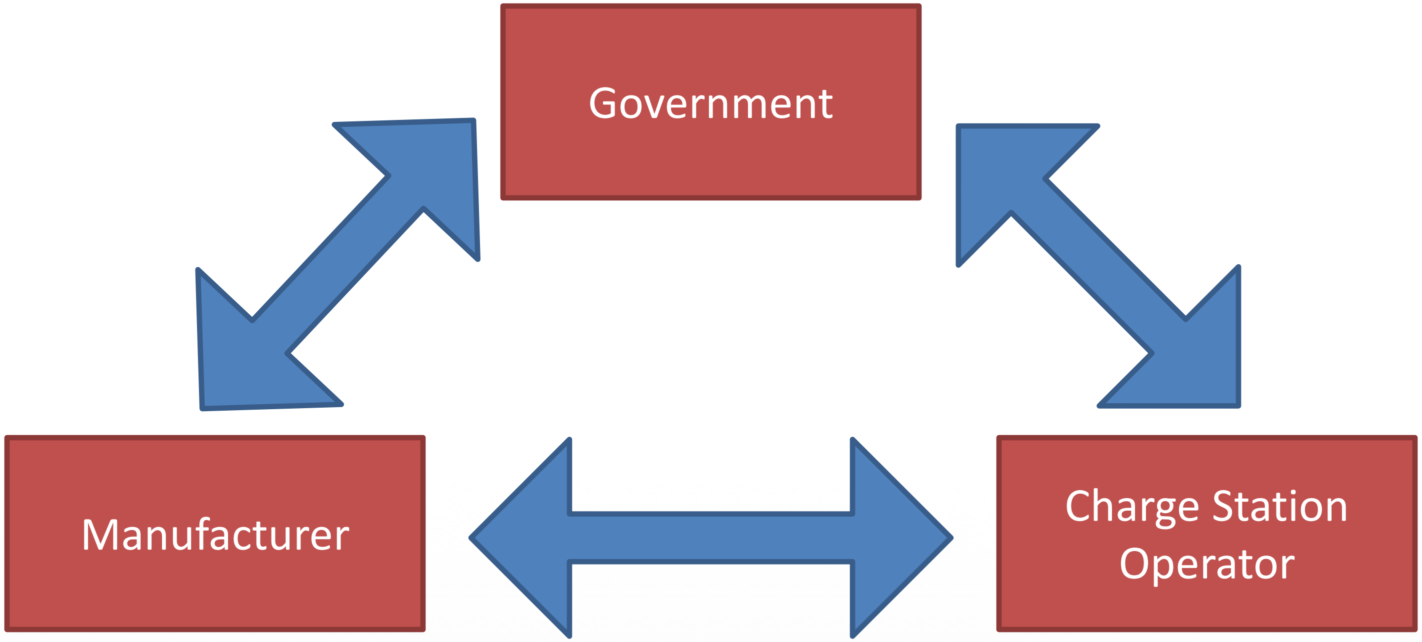
Benjamin M. Knisely
Department of Mechanical Engineering, University of Maryland

Overview

- Electric vehicles (EVs) could provide social and environmental benefits through reduction of GHG emissions, but struggles with widespread adoption
- Government regulation and investment influences adoption
- Ancillary services also influence adoption
    - E.g. Vehicle charging stations (CS)

Overview

- A game-theoretic optimization framework analyzing public policy's effect on the EV market is proposed



Background – Public Policy and EV Market

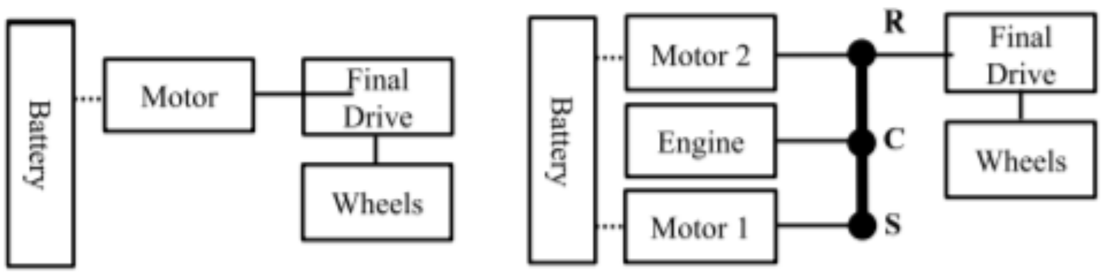
- Primary barriers to adoption:
  - Price
  - Social preference
  - “Range Anxiety”
- Policy can influence:
  - Consumer choices
  - Manufacturer decisions
  - Charge station design

Background – EV Engineering Design

- Powertrain governs fuel economy and emissions
    - Battery, motor, engine size
    - Final drive ratio

Battery EV Drivetrain

Plug-in Hybrid EV Drivetrain



(a) Nissan Leaf

(b) Toyota hybrid system (for Prius)

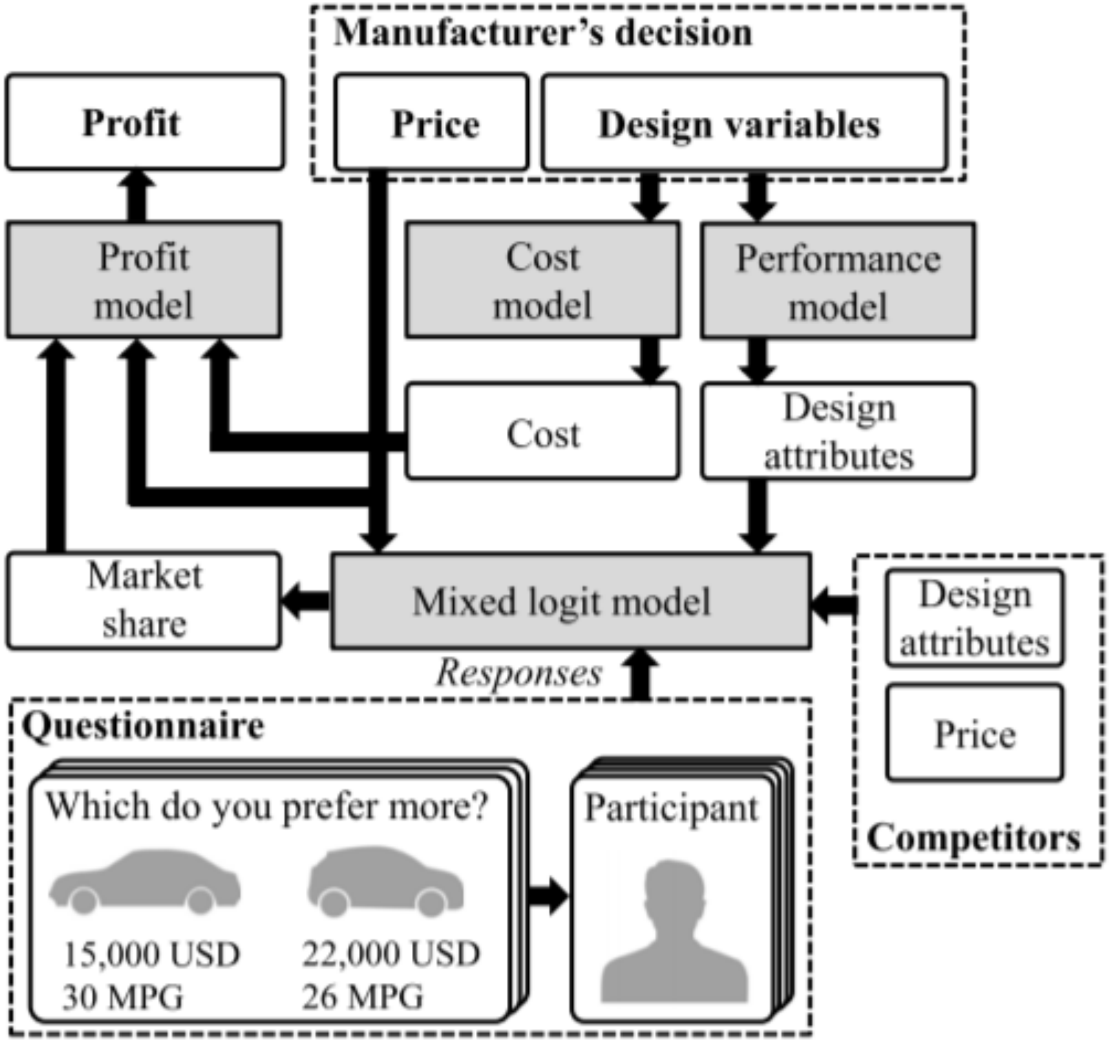
Background – Design for Market Systems

- Maximizes expected value of product, as opposed to engineering performance
- Demand model used to estimate profit

Consumer Demand = f(Design Attribute A)

Design Attribute A = f(Design Variables X)

Background – Design for Market Systems



Design for Market Systems Framework

Key Assumptions

- Subsidy-related policies only
- Time independent
- Market consists of 2 manufacturers:
  - BEV and PHEV producer
  - Conventional vehicle producer
- Study focuses on 2 markets (Central Beijing and Ann Arbor, MI) suited well for charger installation

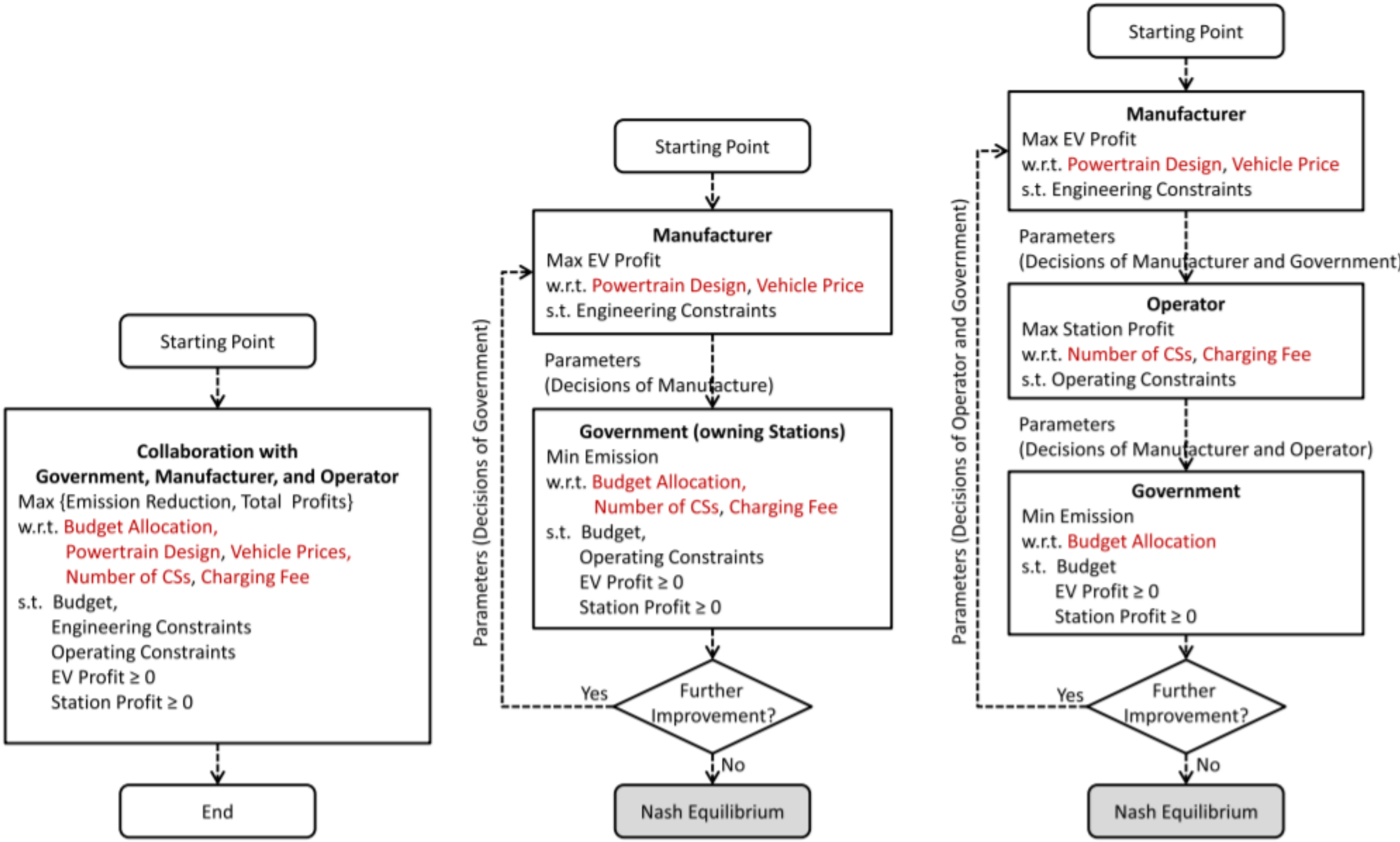
Key Assumptions

- Greenhouse gas emissions estimated based on CO_2 emission from gas consumption and electricity production
- Baseline tax and plate fees for all vehicles equal
- Gas prices
  - Ann Arbor: $2.51/gal
  - Beijing: $4.77/gal

Stakeholder Decisions

- Government
  - Public policies
- Manufacturer
  - Battery design
  - Powertrain design
  - Vehicle price
- CS Operator
  - # of stations
  - Charging price

Optimization Models



a) Collaboration scenario (S1a,S1b) b) Two-stakeholder scenario (S2) c) Three-stakeholder scenario (S3)

Variable Overview

- **EM**: Emissions
- **D**: Demand
- **P**: Price
- **A**: Vehicle Attributes
- **I**: Government Investment
- **C**: Cost
- **Π**: Profit

Optimization Models

$$\min_{\bar{\mathbf{x}}} EM_{BEV} + EM_{PHEV} + EM_{gas}$$

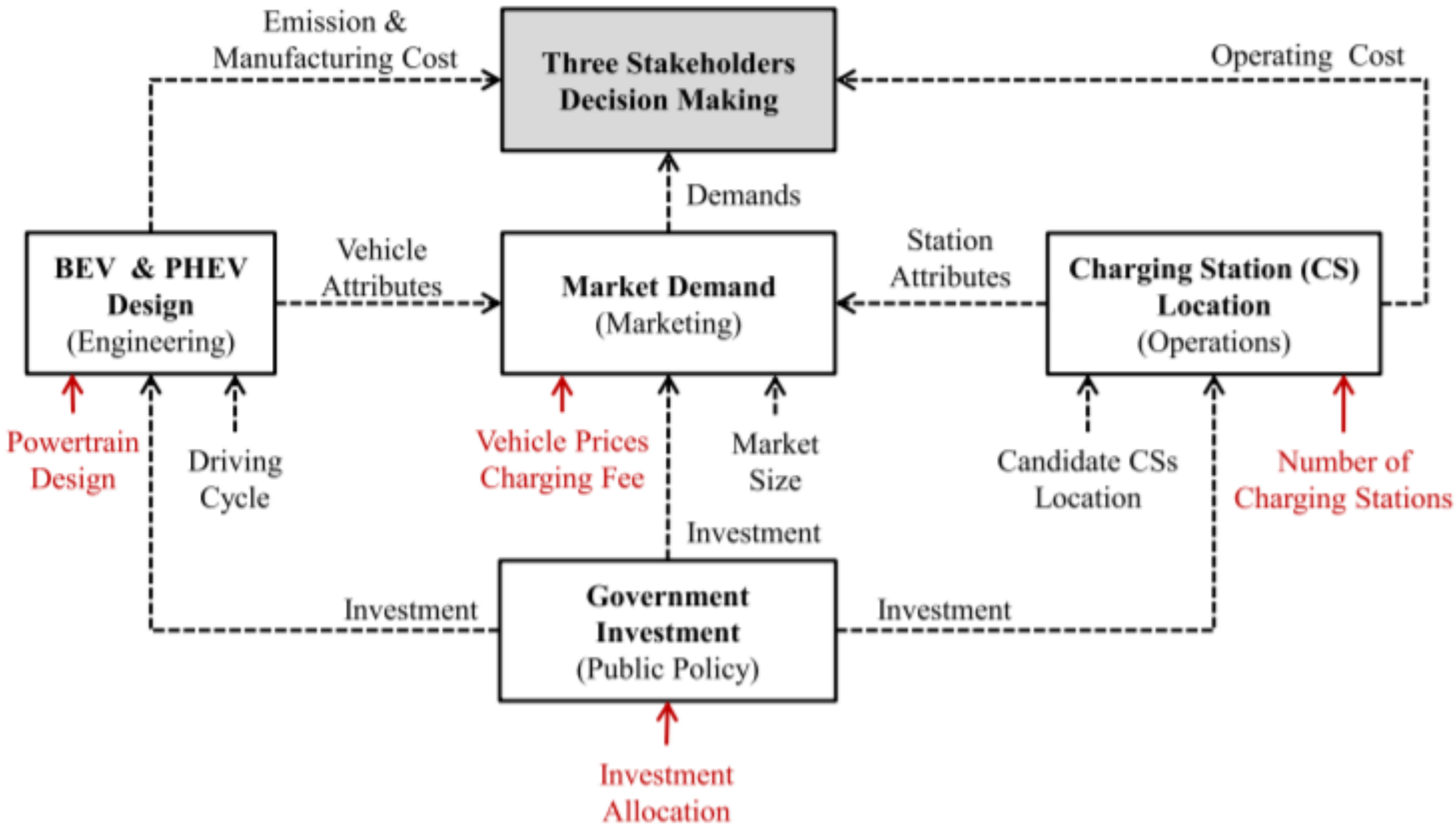
with respect to

$$\begin{aligned} \bar{\mathbf{x}} &= [\mathbf{x}_{gov}, \mathbf{x}_{man}, \mathbf{x}_{CS}] \\ \mathbf{x}_{gov} &= [I_{EV}, I_{CS}, I_{cu}] \\ \mathbf{x}_{manu} &= [P_{BEV}, \mathbf{B}_{BEV}, G_{BEV}, P_{PHEV}, \mathbf{B}_{PHEV}, G_{PHEV}] \\ \mathbf{x}_{oper} &= [P_{CS}, N_{CS}] \end{aligned}$$

subject to

$$\begin{gathered} lb \leqslant \bar{\mathbf{x}} \leqslant ub \\ g_{gov}(\bar{\mathbf{x}}) - budget \leqslant 0 \\ \mathbf{g}_{eng}(\mathbf{A}_{BEV}, \mathbf{A}_{PHEV}) \leqslant 0 \\ g_{oper}(N_{CS}, D_{CS}) \leqslant 0 \\ \Pi_{BEV} + \Pi_{PHEV} \geqslant 0 \\ \Pi_{CS} \geqslant 0 \end{gathered}$$

Decision-Making Framework



Policy Model

US Policy Model

Decision variable		Definition	Lower bound	Upper bound
EV investment (I_{EV})	1. EV subsidy (S_{EV})	Subsidy per kWh of battery capacity for the manufacturer	\$0/kWh	\$600/kWh
CS investment (I_{CS})	2. CS subsidy (S_{CS})	Percentage of subsidized installation and maintenance costs for the charging station operator	0 %	100 %
	3. Electricity cost cut (Cut_{EC})	Percentage of cut of electricity cost for station operator	0 %	100 %
Customer investment (I_{cu})	4. One-time tax cut ($Cut_{tax_{EV}}$)	Percentage cut of registration fee for EV user	0 %	100 %

$$I_{EV} = S_{EV} \times (BC_{BEV} \times D_{BEV} + BC_{PHEV} \times D_{PHEV})$$

$$I_{CS} = S_{CS} \times N_{CS} \times (C_{inst} + C_{main}) + Cut_{EC} \times C_{EC} \times (BC_{BEV} \times D_{CS_{BEV}} + BC_{PHEV} \times D_{CS_{PHEV}}),$$

$$I_{cu} = Cut_{tax_{EV}} \times Tax_{gas} \times (D_{BEV} + D_{PHEV}),$$

Engineering Model

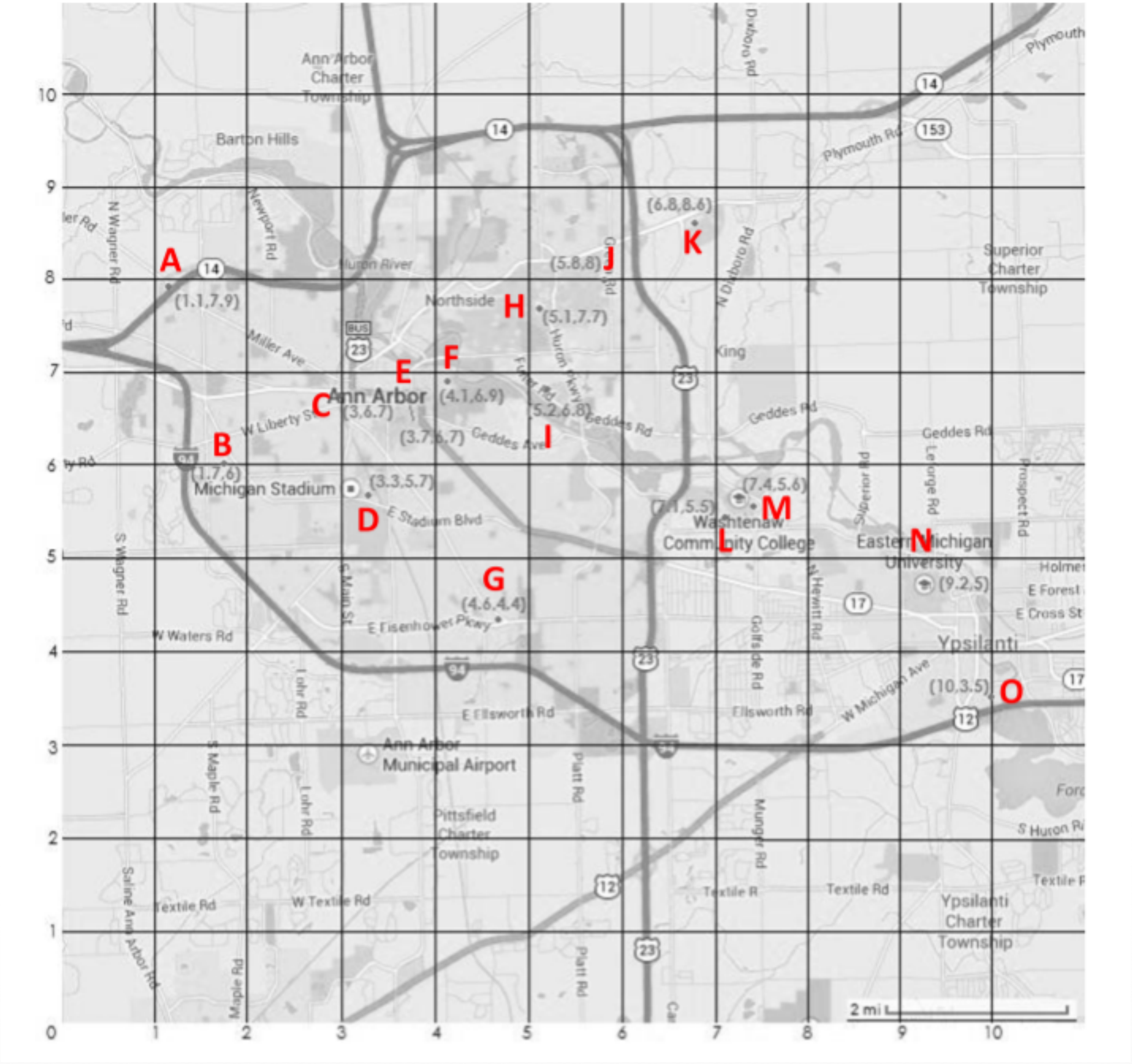
- 1 BEV and 1 PHEV
- Vehicles simulated with AMESim

	BEV	PHEV	Gasoline
Vehicle weight	1696 kg	1380 kg	1307 kg
Tire radius	315.95 mm	315.95 mm	300.3 mm
Coefficient of drag	0.29	0.29	0.3
Frontal area	2.27 m^2	2.27 m^2	2.10 m^2
Engine size	—	1.8 L	2.0 L
Engine max. torque	—	142.5 N m @ 4000 rpm	169.5 N m @ 4000 rpm
Engine max. speed	—	4500 rpm	6500–6900 rpm
Engine max. power	—	73 kW @ 5200 rpm	85.8 kW @ 5200 rpm
Fuel tank capacity	—	40.1 L	54.9 L
Motor(s) type	PMSM	PMSM	—
Motor(s) max. torque	280 N m	200 N m for both	—
Motor(s) max. speed	10390 rpm	12000 rpm for both	—
Motor(s) max. power	80 kW	60 kW and 42 kW	—
Battery cell capacity	33.1 Ah	33.1 Ah	—
Battery package capacity (before optimization)	24 kWh	12 kWh	—

Engineering Model

Design variable	Lower bound	Upper bound
1. Number of cells in series in one branch of BEV (B_{BEV_s})	80	200
2. Number of branches in parallel of BEV (B_{BEV_p})	1	4
3. Gear ratio of BEV (G_{BEV})	2	12
4. Number of cells in series in one branch of PHEV (B_{PHEV_s})	50	200
5. Number of branches in parallel of PHEV (B_{PHEV_p})	1	4
6. Gear ratio of PHEV (G_{PHEV})	5	7

Charging Service Model



Charging Service Model

#of CSs	Optimal CS locations
1	I
2	D,N
3	D,K,N
4	A,G,K,N
5	A,B,G,K,N
6	A,B,G,H,K,N
7	A,B,G,H,K,L,N
8	A,B,G,H,K,L,N,O
9	A,B,E,G,H,K,L,N,O
10	A,B,D,F,G,H,K,L,N,O
11	A,B,C,D,G,H,I,K,L,N,O
12	A,B,C,D,G,F,H,I,K,L,N,O
13	A,B,C,D,G,F,H,I,J,K,L,N,O
14	A,B,C,D,G,F,H,I,J,K,L,M,N,O
15	A,B,C,D,E,G,F,H,I,J,K,L,M,N,O

- Optimal Locations = min distance to each EV user on map
    - Assumes uniform distribution of users

Charging Service Model

$$(D_{BEV} + D_{PHEV}) \times D_{CS_{daily}} \leqslant 12 \times N_{CS} \times N_{charger}.$$

- Every charger should serve 12 users/day

Market Model

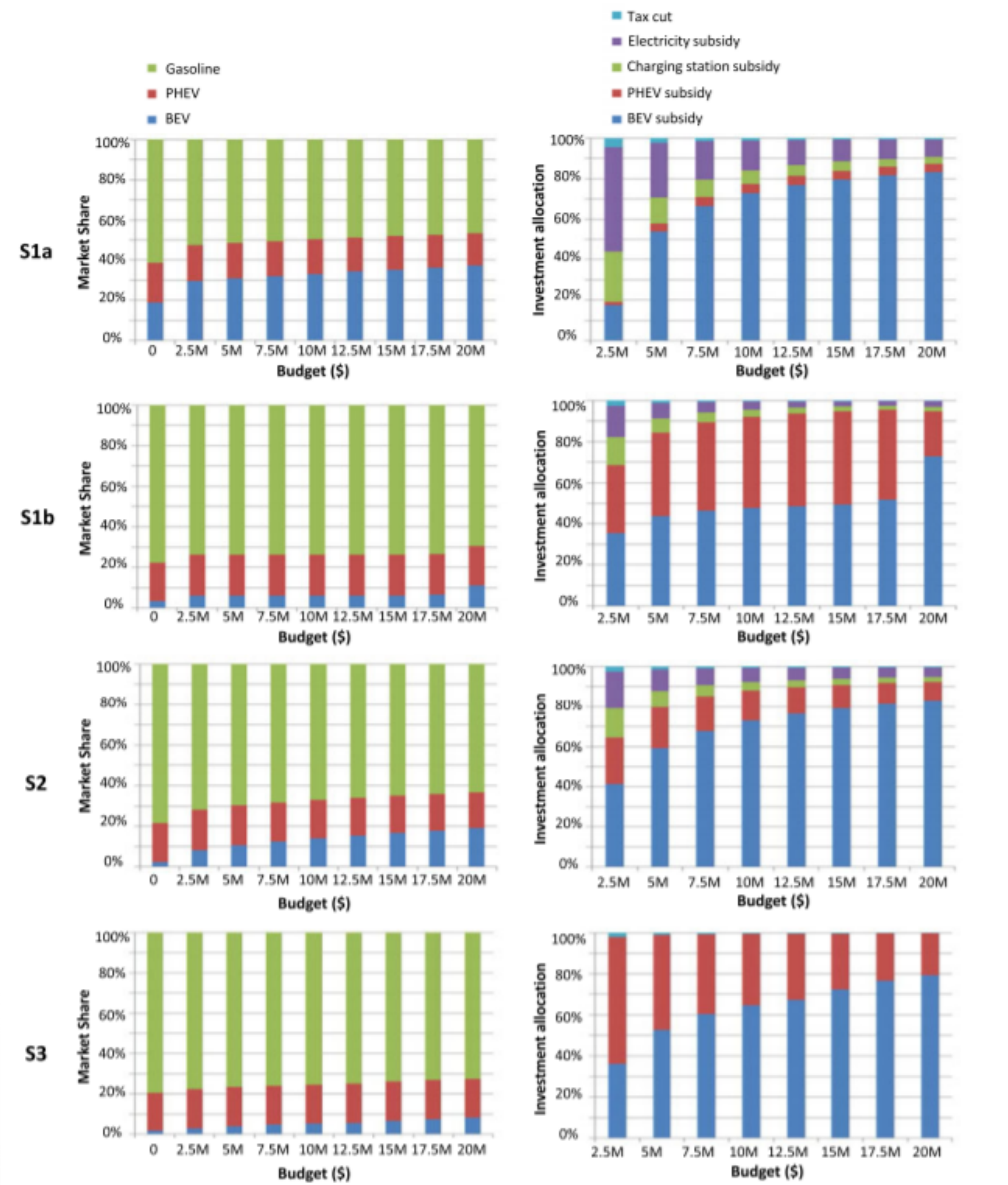
Table 8. Attributes levels and their part worths for US case

Vehicle type	Level	BEV	PHEV	Gasoline	
	Mean	−0.49	−0.37	0.86	
	(Std)	(1.14)	(1.17)	(2.01)	
Vehicle price (US$)	Level	20k	30k	40k	50k
	Mean	1.58	0.91	−0.55	−1.94
	(Std)	(1.65)	(0.98)	(0.94)	(1.88)
Registration fee (US$)	Level	0	40		
	Mean	0.01	−0.01		
	(Std)	(0.02)	(0.02)		
Vehicle range (miles)	Level	100	250	400	550
	Mean	−1.74	−0.09	0.82	1.01
	(Std)	(1.69)	(0.48)	(0.79)	(1.11)
Fuel cost (Full) (US$)	Level	0	20	40	60
	Mean	1.36	0.26	−0.34	−1.28
	(Std)	(1.44)	(0.55)	(0.69)	(1.19)
Number of stations	Level	5	15	25	35
	Mean	−0.14	−0.08	0.11	0.12
	(Std)	(0.21)	(0.15)	(0.17)	(0.19)
Distance to station (miles)	Level	0.5	2	4	6
	Mean	0.19	0.10	−0.10	−0.19
	(Std)	(0.32)	(0.20)	(0.18)	(0.26)

Optimization Model

Abbreviation	Scenario	Objectives
S1a	Collaboration scenario	Minimize emissions
S1b	Collaboration scenario	Maximize total profits
S2	Two-stakeholder scenario	Maximize profit (for the manufacturer) and minimize emissions (for the government)
S3	Three-stakeholder scenario	Maximize each profit (for the manufacturer and the operator) and minimize emissions (for the government)

Results



S1a	Collaboration scenario
S1b	Collaboration scenario
S2	Two-stakeholder scenario
S3	Three-stakeholder scenario

S1a	Collaboration scenario
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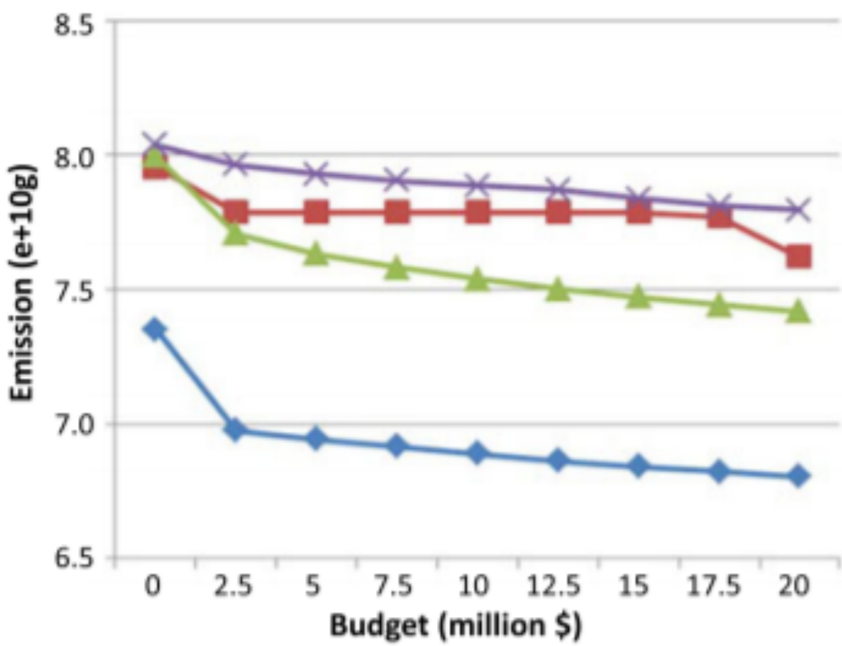
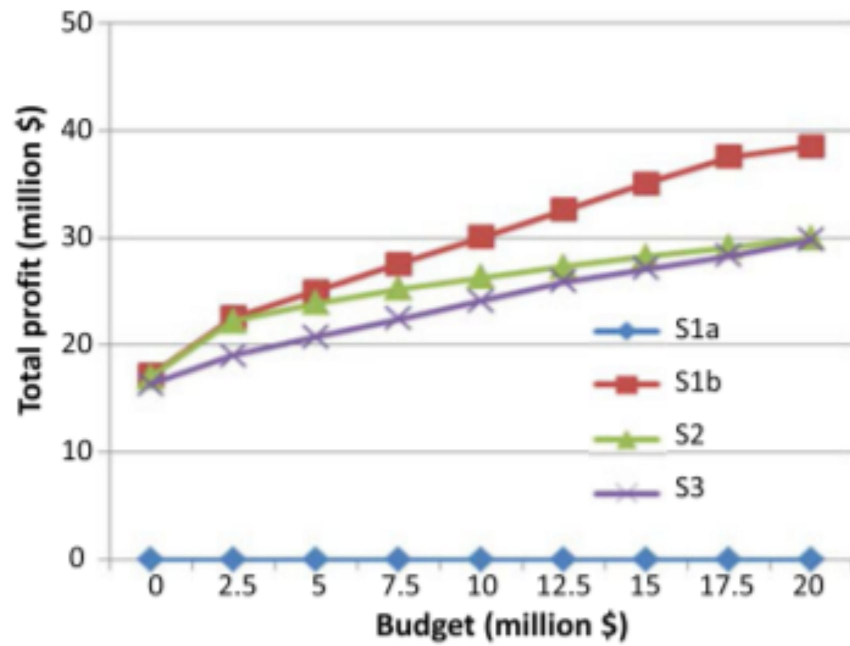
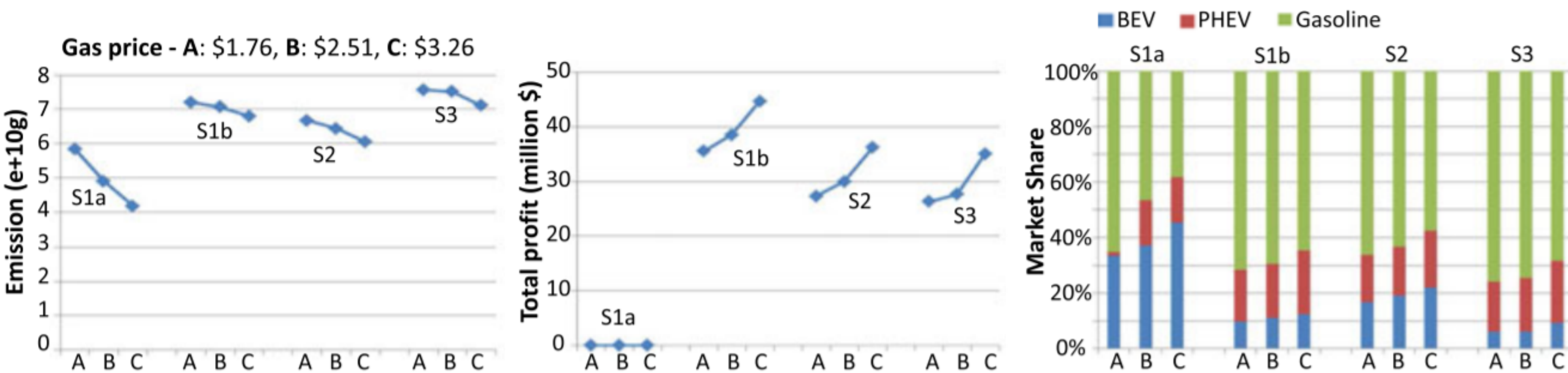




S1a	Collaboration scenario
S1b	Collaboration scenario
S2	Two-stakeholder scenario
S3	Three-stakeholder scenario



Conclusions

- Collaboration is the clear winning strategy
- Increasing budget has diminishing returns for EV adoption
- High vehicle price combined with low EV acceptance and high sensitivity to price is a adoption bottleneck + inefficient
- BEV-investments are most cost-effective
- Gas price changes have a significant impact on vehicle demand

References

[1] Kang, N., Ren, Y., Feinberg, F. M., and Papalambros, P. Y., 2016, “Public Investment and Electric Vehicle Design: A Model-Based Market Analysis Framework with Application to a USA–China Comparison Study,” Design Science, **2**.

[2] Michalek, J. J., Papalambros, P. Y., and Skerlos, S. J., 2005, “A Study of Fuel Efficiency and Emission Policy Impact on Optimal Vehicle Design Decisions,” J. Mech. Des, **126**(6), pp. 1062–1070.

Thank You

S1a	Collaboration scenario
S1b	Collaboration scenario
S2	Two-stakeholder scenario
S3	Three-stakeholder scenario

Table 11. Optimal policy with $20M budget for Ann Arbor

	Variable	S1a	S1b	S2	S3
Public policy	EV subsidy (per battery capacity)	$133	$600	$277	$563
	Charging station subsidy	100 %	100 %	100 %	0 %
	Electricity cost cut	100 %	100 %	100 %	0 %
	One-time tax cut	100 %	100 %	100 %	100 %
Engineering	BEV #cells/branch (#branch)	154 (3)	148 (2)	144 (3)	158 (3)
	PHEV #cells/branch (#branch)	52 (1)	52 (1)	52 (1)	52 (1)
	BEV gear ratio	5.59	5.17	5.52	5.63
	PHEV gear ratio	5.00	5.00	5.00	5.00
Operations	Number of charging stations	6	4	4	3
Marketing	EV price	$23,660	$32,192	$32,245	$24,485
	(before subsidy)	($31,375)	($54,531)	($47,281)	($58,031)
	PHEV price	$24,597	$27,193	$27,121	$26,188
	(before subsidy)	($25,465)	($31,117)	($28,931)	($29,868)
	Charging fee (per kWh)	$0	$0	$0	$0.78

S1a	Collaboration scenario
S1b	Collaboration scenario
S2	Two-stakeholder scenario
S3	Three-stakeholder scenario

Table 12. Optimal outcomes with $20M budget for Ann Arbor

	Response	S1a	S1b	S2	S3
Policy budget allocation	BEV subsidy	$16.67M	$14.46M	$16.65M	$15.82M
	PHEV subsidy	$0.82M	$4.43M	$1.88M	$4.12M
	Charging station subsidy	$0.67M	$0.45M	$0.45M	$0M
	Electricity price cut	$1.71M	$0.59M	$0.93M	$0M
	One-time tax cut	$0.13M	$0.07M	$0.09K	$0.06M
Market response	Emission	6.83e+10g	7.64e+10g	7.44e+10g	7.80e+10g
	BEV profit	− $11.47M	$17.85M	$13.51M	$9.54M
	PHEV profit	+ $11.47M	$20.17M	$16.23M	$18.53M
	Station profit	$0	$0	$0	$1.58M
	Market share - BEV	36.9 %	10.9 %	18.7 %	8.0 %
	Market share - PHEV	16.2 %	19.5 %	17.9 %	19.2 %
	Market share - Gasoline	46.9 %	69.6 %	63.4 %	72.8 %