Predicting the Demand for Connected Autonomous Vehicles: A New Approach Based on the Theory of Diffusion of Innovations

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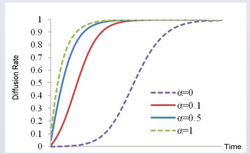
Motivation

- Connected autonomous vehicles (CAVs) are about to become a reality, and they are arriving much earlier than many would think.
- Most automobile manufacturers have already incorporated some degrees of automation into the existing cars by incorporating features such as parking assist, adaptive cruise control, and collision avoidance systems.
- Also, some manufacturers have already developed and tested prototypes of the first fully autonomous vehicles.
- Transportation network companies (TNCs) are also pushing the introduction of automation by aggressive testing of autonomous peer-to-peer ridesharing services.
- Key questions: how much will be the demand for ownership of CAVs and how will be the timing of adoption in long-term?
- The relevant literature is mainly focused on understanding individuals' willingness-to-pay (WTP) as well as their opinions, concerns, and determinants of adoptions.
- The majority of studies on adoption forecasting are based on expert knowledge, projection of adoption trends of other technologies, and sales estimates.
- Discrete choice modeling has been the prevailing approach in understanding various aspects of the demand for CAVs.
- Empirical evidence suggests that individuals heavily rely on the information they receive from their peers when assessing adoption of a radical innovation.
- Traditional discrete choice models, however, have limited capability to capture the effects that adoption of an individual may have on other individuals within his/her network.



Diffusion rate at various levels of social influence (Source: Namatame et al., 2009)

- An alternative approach is to use the theory of Diffusion of Innovation (DOI).
- Diffusion research has been of interest to the academic community for an extended period of time. However, application of DOI in forecasting CAV demand is limited.
- We couple DOI with agent-based simulation modeling (ABSM) to forecast adoption at a disaggregate level.
- Our modeling approach explicitly allows for communication among individuals, as a result of which perceptions about CAVs will be dynamic.
- Unlike previous studies assuming ad-hoc changes in willingness-to-pay, our approach let each individual's WTP positively or negatively alter due to communication with adopters who are satisfied or dissatisfied with their purchases.
- Using a survey of the University of Memphis (UofM) employees, we show the applicability of the proposed approach.

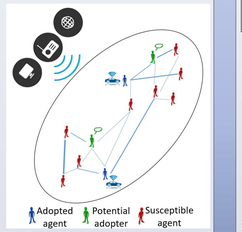
Resistance Concept

- The concept of resistance is a fundamental notion in explaining adoption using DOI theory.
- Industrialized nations are recognized by advanced technological innovations. Why then do individuals resist to some innovations?
- Automobile manufacturers certainly realize the benefits of automated features on vehicles but individuals do not see this new technology from that perspective.
- Consumers are typically resistant to innovations, especially revolutionary ones, as innovations can change their established routines and day-to-day existence.

Resistance Concept (Cont'd)

- We consider nine aspects for resistance, segmented into two categories:
  - Functional barriers: arise when the innovation challenges an individual's current workflows and habits.
  - Psychological barriers: arise when there are conflicts with the consumers' prior beliefs.
- We also recognize four dis-barriers (incentives) for CAV adoption:
  - CAVs can be synched with traffic signals and other vehicles and lower travel time.
  - Having a CAV can improve one's status among his/her peers.
  - CAVs can use real time traffic information in order to efficiently navigate to their destination and thus generate less pollutants.
  - CAVs can provide a greater degree of mobility to consumers with impairment.
- Two factors can impact the individual resistances and incentives and facilitate the adoption process:
  - Mass communication (marketing): media advertisement can target a broad spectrum of consumers to reduce both functional and psychological barriers.

    Marketing, for example, can weaken tradition barrier by convincing consumers that they can take the full power of their vehicles at any time.
  - Peer-to-peer communication (word-of-mouth): once individuals received initial information through media advertisement, the information that propagates among peers will be the main propeller of diffusion. Communication between satisfied and potential adopters strengthens incentives and weakens barriers. Communication occurs within a social network in which nodes represent individuals and communication channels are shown using directed arcs. The frequency and intensity of communication between a pair of individuals determine how effective a communication channels is. For example, some individuals talk to others more frequently and some are more communicative; thus there will be a greater influence on the potential adopters from more socialized adopters.

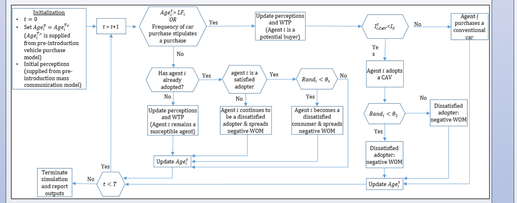


Visualization of the impact of communication and advertisement on adoption

Agent-Based Simulation Modeling of DOI

- Our framework consists of three components: (i) mass communication; (ii) pre-introduction vehicle purchase; and (iii) peer-to-peer communication models.
- Mass communication model:
  - Individuals watching TV or listening to radio are exposed to advertisement, and the impact of advertisement is a function of the frequency of exposure.
  - We consider two marketing stages: pre-introduction and post-introduction.
  - We reasonably assume that agents have memory and the effect of advertisement accumulates over time, but also dissipates as time goes by.
  - An individual's perceptions are dynamic and is updated with exposure to advertisement
- Pre-introduction vehicle purchase model: when no warm-up simulation is implemented, some agents who frequently purchase a car may get a car at the base year whose age is greater than the maximum age that corresponds to the agent's frequency of purchase. This model addresses this issue.
- Peer-to-peer communication model
  - We assume that there exists a learning process between a potential adopter and other adopted agents.
  - Each agent communicates with agents within its social network according to a certain frequency.
  - The time-dependant impact of social learning is then modeled mathematically.
  - Some adopted agents may not be satisfied with performance and features of CAVs, and thus start to propagate negative WOM. Behavioral research indicate that a dissatisfied consumer talks to more individuals, compared to a satisfied consumer. Moreover, the power of negative WOM is known to be at least two times greater than positive WOM. We allow that both types of WOM to be transmitted among agents.

Agent-Based Simulation Modeling of DOI (Cont'd)

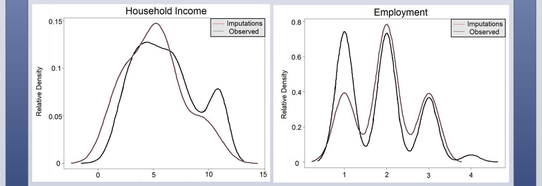


Agent-based simulation algorithm

- At each time period, each agent has a total perception index which is equal to a weighted sum of barriers and incentives about CAVs.
- If an agent is a potential buyer (i.e., someone who plans to purchase a car), it first evaluates if it can afford a CAV. If his WTP is greater than the cost of adding automation, the agent compares his/her total perception index against a cutoff value and decides whether he/she wants to purchase a CAV. One's cutoff value is assumed to remain constant over time.
- Once each agent's purchase decision is determined, we update perceptions and WTPs based on media exposures and peer-to-peer communications and proceed to the next time interval. This process continues until the last time period.

Data

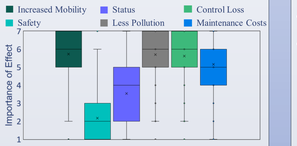
- Data was gathered from a survey distributed to the University of Memphis employees. The data was used to generate the synthetic population and network.
- 327 complete responses were gathered (13.3% response)
- The survey collected information on 8 distinct attributes, including socioeconomic characteristics, social behavior, personality, and perceived barriers to adoption.
- Missing entries in survey: multivariate normal imputation.
- Multivariate normal imputation (MNI) assumes that the distribution of the dataset, including missing and observed entries, is multivariate normal.
- Comparing density of imputed and observed data shows acceptable quality of imputation.



Observed and imputed values of employment and household income

Data (Cont'd)

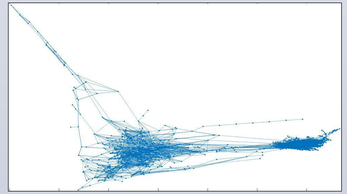
- Only a couple of respondents state that their household purchase a car every year. 29.4% of them purchase a car every five years and 45.6% do so every 10 years.
- Less than 5% of respondents state that their households are willing to pay an additional $20,000 to add automation and connectivity. 69.1% of respondents' households are willing to pay only an additional $5,000 or less to have the driverless option added to their car.
- On a seven-point scale (1 = *Very Unreliable* to 7 = *Very Reliable*), individuals consider an average reliability score of 5.58 ($\sigma = 1.08$) for the information they receive from their peers, while the scores for media and car dealership are 3.79 ($\sigma = 1.36$) and 3.63 ($\sigma = 1.44$), respectively. This highlights the necessity of incorporating WOM into adoption modeling.
- Work and non-work connections have comparable importance when purchasing a car.
- Mobility and reduction in pollution considered important.
- Improving social status among peers is the least important incentive.
- Risk of virus attack is considered as the most important barrier, with the highest average and lowest standard deviation
- Lost feeling of control more critical than safety concerns.



Some elements of resistance to CAV adoption

Synthetic Social Network

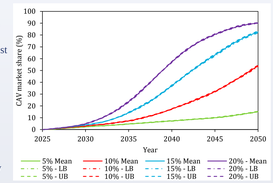
- Collecting a fully disaggregate dataset through survey is usually costly, especially when a large population is of interest.
- An alternative is to use aggregate data about the true population to generate an artificial population, thereby generating a synthetic population.
- We use Iterative Proportional Updating (IPU) algorithm to generate the synthetic population.
- We then use the synthetic population to generate a synthetic network among individuals.
- The central concept in doing so is the *homophily* principle which indicates that the possibility that a pair of agents establish a connection is a function of geographical proximity and socio-demographic similarity.
- We define an 8-dimentional coordinate system by age, gender, race, employment type, income level, disability status, teleworking habit, and college/division.
- Each agent is then placed in the 8-dimentional space, and then the distance between each two agents is calculated.
- We introduce a two-stage selection algorithm to choose the ties with the highest probability subject to the number of ties that each agent has.



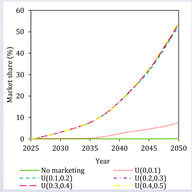
The synthetic network among UofM employees

Results

- Four experiments: CAV price reduces at 5%, 10%, 15%, and 20% rates, annually.
- The width of the confidence interval is at most 1.86% indicating that the simulation results are robust.
- CAV price reduction rate has significant impact not only on the ultimate amount of CAV market share in 2050 but also on the shape of adoption curve.
- With 5% rate, only some 15% of UofM employees will adopt by 2050.
- The latter share will reach about 90% if CAV price is reduced at 20%, annually.
- The impact of CAV price reduction is more evident in long-term –specifically after 2030.

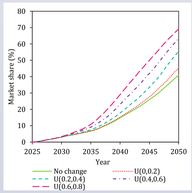


Mean CAV market share and 95% confidence interval (CI) bounds as a function of annual rate of CAV price reduction (LB: CI lower bound; UB: CI upper bound)



CAV market share as a function of marketing effect

- Five scenarios: the effect of marketing, which can be plausibly assumed to be correlated with marketing intensity, increases gradually.
- CAV market share will not be more than 4% if no advertisement is undertaken.
- Innovators, i.e., those that are more risk seeking and willing to obtain new technologies before others, form a tiny portion of population – typically less than 2.5%. WOM that is spread by such little portion can increase CAV market share by a limited extent.
- With more intense advertisement, the perceptions of more people will change. Starting from 2035, WOM propels the diffusion.
- The impact on innovation diffusion of marketing is capped.



CAV market share as a function change to WTP due to peer-to-peer communication

- Five experiments: WOM does not change in the first experiment. The stochastic impact of WOM on WTP (denoted by γ_{ij}) is $\mathcal{U}(0,0.2)$, $\mathcal{U}(0.2,0.4)$, $\mathcal{U}(0.4,0.6)$, and $\mathcal{U}(0.6,0.8)$ in the second to fifth experiments.
- CAV market share significantly grows with the increase of the effect of peer-to-peer communication on WTP.
- Changing γ_{ij} has no significant effect on CAV market share in the early stages of adoption. The reason is that even with high changes to WTP, a large number of individuals still envision CAVs as something incompatible with their existing practices and continue to defer adoption.

Acknowledgement

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