11-16-2018

Scenarios for Adoption of Autonomous Vehicle Technologies in Freight

Sabya Mishra

University of Memphis

Let us know how access to this document benefits you.

Follow this and additional works at: https://pdxscholar.library.pdx.edu/trec_seminar

Part of the Civil Engineering Commons, Transportation Commons, and the Transportation Engineering Commons

Recommended Citation


This Book is brought to you for free and open access. It has been accepted for inclusion in TREC Friday Seminar Series by an authorized administrator of PDXScholar. For more information, please contact pdxscholar@pdx.edu.
Scenarios for Adoption of Autonomous Vehicle Technologies in Freight

by

Sabya Mishra, University of Memphis

Friday Transportation Seminar
Portland State University, 11/16/2018
Adoption of innovations

• How a new technology diffuses
  – adopt
  – do not adopt
  – adopt later
• Rogers describes adoption in five categories
• Adoption typically follows a S-curve
• Rapid growth from 16%-80%
Learning from other innovations

Household Product Adoption Percentage by Year (1990-2010)

- VCR
- Television
- Automobile
- Electricity
- Radio
- Refrigerator
- Air Conditioning
- Clothes Dryer
- Color TV
- Microwave
- VCR
- Computer
- Cell Phone
- Internet
- Digital Camera

Source: Asymco
Motivation

• One key question: when do vehicle owners decide to shift to autonomous vehicle (AV) technology?
  – Partial automation
  – Fully automation

• Main approaches (for individual AVs)
  – Estimation based on sales forecasts
  – Employing adoption patterns of previous vehicle technologies
  – Discrete choice models
  – Building upon the theory of Diffusion of Innovations (DOI)- (Emerging)
    • Aggregate level (Bass model)
    • Disaggregate level (Agent-based)
Why autonomous trucks?

- 66.4 million single unit and combination trucks in the US in 2015 (~ 4.2% of the fleet)
- Trucks account for more than 9% of total VMT in 2015
- A Class 8 truck generates more than 68K miles each year while a passenger car travels about 11.2K miles
- We focus on autonomous trucks adoption in this presentation

Disruptive nature of AV technology

Crucial role of trucks in the transportation system

It is important to have a sound understanding about how and when trucking companies adopt connected autonomous trucks (CATs)
Individual versus organizational adoption

Individual versus organizational adoption

• The existing models of automobile adoption are inadequate as organizational adoption is more complex than individual adoption
  – Competition plays a role
  – Marketing may have moderate to less impact
  – Size and organizational structure count

• A pair of decision
  – When to adopt
  – How many units to adopt
Determinants of organizational adoption
Entrepreneurial character

- Organizational theory
  - Entrepreneurial character
  - Organizational attributes
  - Business environment

Small and Medium Firms
- Centralized decisions
- Gender: Male vs. Female
- Age: Younger (Risk seeker)
- Education / Experience Level
- Professional network

Large Firms
- Mostly decentralized
- Gender: Not much impact
- Does not apply
- Does not apply
- Does not apply
Determinants of organizational adoption -
Organizational attributes

Small and medium size firms

- **Age**: negatively correlates with spirit of small firms
- **Resource**: Wealthier firms more likely to adopt
- **Slack**: Scarcity of budget hinders adoption
- **Openness**: Depth and breadth of search strategies

Large firms

- All the above *plus*
- **Managerial ratio**: leadership, coordination, and support for innovation
- **Complexity**: index representing education, experience, and expertise
- **Interconnectedness**: Information flow
Determinants of organizational adoption - Business environment

Small and Medium Firms

- Firm performance (just one unit)
- Number of competitors (medium to large)
- Degree of competition (small)
- Profit level (low)

Large Firms

- Firm performance (function of units)
- Number of competitors (small)
- Degree of competition (large)
- Profit level (high)
Aggregate approach - Bass model

- One of the initial models in DOI – still used in many disciplines
- Bass sums the external and internal forces of diffusion of innovations with the Coefficient of Innovation (CoN) and Coefficient of Imitation (CoM)
  - CoN: Forces which are not influenced by the number of other adopters
  - CoM: Forces which grow more influential as the number of other adopters increases
- Extensions of the Bass model possible
  - To capture pricing and marketing strategies
Aggregate approach - Bass model

Generalized Bass Model:

\[ n(t) = \frac{dN(t)}{d(t)} = \left\{ p \cdot [m - N(t)] + \frac{q \cdot N(t)}{m} \right\} \cdot X(t) \]

- \( n(t) \) is the number of adopters at time \( t \)
- \( m \) is the market potential, or maximum potential adopters of the innovation
- \( N(t) \) is the cumulative number of adopters at time \( t \)
- \( p \) is the coefficient of innovation (CoN)
- \( q \) is the coefficient of imitation (CoM)
- \( X(t) \) is the factor which accounts for all external influencer variables that are not covered explicitly by the CoN and CoM

\[ X(t) = 1 + \beta_i X_i \text{ where } \sum_{i=1}^{I} \beta_i X_i \geq -1 \text{ for } i \in I \]

- \( X_i \) represent the external influencer variables
- \( \beta_i \) represents the corresponding coefficients for each of the variables
Uniqueness of Firms

- Operation by
  - employee size
  - geographic coverage
  - structure of operation
  - management
  - fleet ownership

Spheres of influence and tendency toward innovativeness for organizations of differing sizes
Bass model application

- Organizational data in Memphis and Shelby County, TN
- 1,519 organizations in industries such as trucking, freight transportation, and consolidation, and moving agencies
- *K-Mean clustering* is used to categorize the organizations into small, medium-sized, and large groups
Bass model preliminary results

<table>
<thead>
<tr>
<th>Organization size</th>
<th>CoN</th>
<th>CoM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>0.005</td>
<td>0.08</td>
</tr>
<tr>
<td>Medium</td>
<td>0.008</td>
<td>0.09</td>
</tr>
<tr>
<td>Large</td>
<td>0.010</td>
<td>0.10</td>
</tr>
</tbody>
</table>
## Scenario analysis using Bass model (1)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Expected CoN</th>
<th>Expected CoM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>A number of accidents cause Organizations to have less faith in CAV technology</td>
<td>Lower</td>
<td>Unchanged</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>CAVs are not as economically viable as anticipated, and a number of problems with CAV technology are not sufficiently solved</td>
<td>Lower</td>
<td>Lower</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>The financial benefits of operating CAVs are not high enough to give an adopting organization a substantial competitive edge</td>
<td>Unchanged</td>
<td>Lower</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>CAV technology is responsible for preventing a number of crashes, which reduces the perceived risk of the technology</td>
<td>Higher</td>
<td>Unchanged</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>CAVs provide substantial economic benefits and perform better than standard trucks in most situations</td>
<td>Higher</td>
<td>Higher</td>
</tr>
<tr>
<td>Scenario 6</td>
<td>The advantages of using CAVs are such that non-adopters have a difficult time staying competitive with adopters.</td>
<td>Unchanged</td>
<td>Higher</td>
</tr>
</tbody>
</table>
CoN value has substantial impact on the adoption rate than the CoM
- CoM is a function of previous adopters
- Increasing initial adoption causes critical mass to be reached earlier, and this results in a faster overall market penetration rate
Disadvantages of Bass model

• Bass model disadvantages
  – Aggregate in nature
  – Provide little behavioral interpretation
  – CoM and CoN are the only parameters
  – Limited flexibility
  – Validation challenges

• What are some other avenues?
  – Disaggregate methods
    • Choice models (has limitations in current structure- no peer-to-peer communication)
    • Agent-based simulation
Why use agent-based-simulation

• We simulate connected and automated truck (CAT) adoption
  – to approximate real-world behaviors that cannot be captured in (analytical) models
  – account for stochasticity embedded in firm behavior and market environment

• Goal is not to replicate real-world adoption
  – approximate analytical representation
  – higher flexibility in defining structure
  – develop a tool to help understand the effects of various contingencies
Methodology

- Step-1: Organizational survey
- Step-2: Population synthesis
- Step-3: Network synthesis
- Step 4: Adoption diffusion modeling
  - Adoption criteria (sub-model)
  - Communication (sub-model)
  - Regulation (sub-model)
  - Process (sub-model)
  - Agent-based-simulation framework
Organizational survey

- Objectives
  - To investigate perceptions about CATs
  - Develop a seed for population synthesis
  - Explore determinants of adoption among firms in trucking industry

- Two different surveys are being designed: one for small firms and one for large firms

- Data to be collected: size, organizational attributes, business environment, entrepreneurial characteristics, etc.
Population synthesis (1)

- Any agent-based model requires a population of individuals
- Surveying of trucking firms across a region (or state or country)
- Sample survey data (representation sample of population)
- Inputs
  - Seed: survey data (imputation may be required to fill-in missing cells)
  - Marginal data
- Output: a set of synthetic firms, each has all attributes of firms in the sample data
Population synthesis (2)

• Approach: Iterative Proportional Updating (IPU) algorithm

• Value of innovativeness measure for each agent

• Using survey data and econometric methods,
  – Develop relationship between innovativeness and determinants of adoption

• Calculate the innovativeness measure for each synthetic agent
• We develop a *synthetic network*

• Synthetic network is a representation of the real world communication

• The Key concept is *homophily principle*:
  – the possibility that a pair of agents establish a connection is a function of geographical proximity and similarity of other characteristics

• Three networks and their *communication*:
  – one among small firms, one among large forms, one among medium-sized firms
• Medium sized firms have *ties* to both small- and large-sized firms

• Each agent is placed in a *multi dimensional space*
  – developed based on firm size, geographical location, firm age, resources, etc.

• *Euclidean distance* between each two firms is then calculated

• Using a heuristic approach, ties are established among agents
  – according to Euclidean distances
• Clustered firms are strongly tied
• Information sharing more common
• More distant nodes do not have peer-to-peer communication
• Each firm communicates with firms within its network according to a given frequency

• The frequency of interaction indicates
  – the relational dimension of social capital embedded in a social network

• The number of ties represents the structural dimension

• At personal level, the information received from peers is 2 to 7 times more effective than that received from advertisement in newspaper, radio, etc.

• Learning process
  – The impact dissipates over time (the impact of communication in the first round is greater than the impact in the second round)
  – The impact accumulate over time
Communication impacts expected utility and innovativeness

\[ X_i^t = X_i^{t-1} + \sum_{j \in E_i} z_{ij}^{t} \frac{w_{ij} \beta_{ij}^{t} (X_i^{t-1} - X_j^{t-1})}{(1+\alpha)^{f w_{ij}^{t-1}}}, \]

- \( X_i^t \) is expected utility of agent \( i \) at time \( t \)
- where \( E_i \) is agent \( i \)'s set of adopted peers
- \( z_{ij}^{t} \) dummy variable indicating if agents \( i \) and \( j \) communicated between time \( t-1 \) and \( t \)
- \( \beta_{ij} \) a stochastic scalar representing the effect of communication with agent \( j \) on expected utility of agent \( i \) (learning factor)
- \( f w_{ij}^{t} \) the total number of times that agent \( i \) has had communication with agent \( j \) until time \( t \)
- \( \alpha \) the dissipation rate of word of mouth (WOM)
- \( w_{ij} \) the weight of the social tie between agents \( i \) and \( j \) (calculated in network synthesis)
Advertisement / Regulation

- Advertisement can impact firm’s decision but to a lesser degree, compared to individuals

- $X_i^t = X_i^{t-1} + y_i^{t,t-1} \frac{X_{i,l}^t\tau_i,l}{(1+\rho)^{f_i^{t-1}}}$
  
  - $y_i^{t,t-1}$ a binary variable equating 1 if agent $i$ has been exposed to advertisement between $t - 1$ and $t$
  
  - $\tau_i$ a stochastic scalar between 0 and 1 indicating the impact of one round of advertisement on expected utility of agent $i$
  
  - $\rho$ dissipation rate of advertisement impact
  
  - $X_{i,l}^t$ is utility by agent $i$, at time $t$, for advertisement/regulation $l$
  
  - $f_i^t$ the total number of times that agent $i$ has been exposed to advertisement until time $t$
Adoption criteria (1)

- Explicit representation of the *decision to adopt*
- DOI literature offers a wide range of options: *deterministic and stochastic*
- Simplest rule: an adopt as soon as one agent in its network adopts (like *virus infection*)
- The prevailing approach: cutoff method
- Three criteria
  - Utility
  - Network
  - Innovativeness
Adoption criteria (2)

• Criteria-1: Utility
  – Typically, firms do not make any changes to their current practice unless they expect some benefits (or *utility*)
  – This means that firms are *utilitarian agents*
  – An agent *may* adopt when it perceives
    • Expected utility of adoption > cutoff utility
  – A probabilistic criterion
  – Expected utility of adoption is a dynamic measure that changes over time when
    • An agent is exposed to marketing
    • An agent communicates with other satisfied and dissatisfied adopters
  – This criterion is in place to account for the impact on adoption of firms’ rational behavior
Adoption criteria (3)

**Criteria-2: Network**
- Each agent *may* adopt when a certain portion of agents in its network adopt
- A probabilistic criterion
- This criteria accounts for the impact on adoption business environment (*competition*)

**Criteria-3: Innovativeness**
- In population synthesis, each agent is assigned with a level of innovativeness
- Innovativeness is dynamic that changes as a result of *peer-to-peer communication* and exposure to advertisement
- An agent *may* adopt when its level of innovativeness is greater than a cutoff value
- A probabilistic criterion
- The impacts of various determinants of adoption are embedded in this criterion
**Initialization**

\[ t = 0 \]

Is \( t = T \)?

**No**

Terminate and Report adoption results

**Yes**

Update vehicle ages and mileages

Update expected utilities and innovativeness levels

Adoption decision

Communication sub-model determines if there will be communication between any agents \( i \) and \( j \) and if & if each agent \( i \) will be exposed to advertisement

Process sub-model updates vehicle ages and mileages

Decision sub-model determines if a potential adopter will switch to CATS

---

**ABM Simulation framework (1)**

- **Organizational Survey**
- **Population Synthesis**
- **Network Synthesis**
- **Communication**
- **Regulation**
- **Adoption Criteria**
- **ABM Simulation**
ABM Simulation framework (2)

- **Initialization sub-model (t=0)**
  - For each truck in each firm, assign an age and a life (marginal data from survey)
  - Estimate VMT for each vehicle
  - Load initial utilities and innovativeness levels

- **Communication sub-model**
  - At each time step $t$, for each agent $i$, find each agent $j$ with which agent $i$ is supposed to communicate (determined based on frequency of communication and previous round of communication)
  - If agent $j$ is already adopted, update agent $i$’s innovativeness and *expected utility* according to *strength of the tie*
  - Determine the time of the next round of communication
• Process sub-model
  – At each time $t$, for each agent $i$, for each vehicle $v$, determine whether vehicle $v$ should be replaced with a new vehicle based on
    • the age of vehicle $v$
    • total mileage that vehicle $v$ has covered
  – If vehicle $v$ needs to be replaced with a new vehicle, label $v$ as a candidate vehicle, otherwise update vehicle’s current age and mileage

• Adoption sub-model
  – At each time $t$, for each agent $i$, for each candidate vehicle $v$, determine whether the agent will adopt a CAT
  – Determine whether agent $i$ will be a satisfied adopter of this vehicle type
Initial Results: Impact of price reduction and advertisement

Impact of technology price reduction rate (annual rate) on adoption

Impact of intensity of marketing campaigns

![Graph showing CAT market share over years with different price reduction rates.](image1)

![Graph showing CAT market share over years with different marketing intensities.](image2)
Initial Results: Impact of networking and negative WOM

Impact of networking on adoption

Impact of negative WOM and how the number of dissatisfied agents would change
Potential applications

- Automated transit buses (source: olli.com)
- Platooning technology (source: oemofhighway.com)
- Drones for last mile deliveries (source: dhl.com)
- 3-D printing technology (source: cnn.com)
- RSU (source: dot.gov)
Discussion

• Advantage
  – Behavioral interpretation of organizational adoption using DOI+ABM
  – Change simulation over time if certain behavior change over time
  – Stepping stone before applying random utility based models
  – Flexibility in simulation setting

• Limitation
  – Acquiring organizational survey data
  – Representation of behavior in simulation
  – Validation (hold out sample / back-casting after the innovation is introduced)

• Current efforts
  – Full survey planning in process
Acknowledgement

• Freight Mobility Research Institute, USDOT Tier I Center at Florida Atlantic University
• Personnel
  – Dr. Mihalis Golias (Phase 1 and 2)
  – Dr. Evangelos Kaisar (Phase 1 and 2)
  – Dr. Miguel Figliozzi (Phase 2)
  – Dr. Ahmadreza Talebian (post-doctoral associate)
  – Jesse Simpson (doctoral student)
Publications and proceedings (so far..)

- Simpson, J., and Mishra, S. (2019). The adoption of connected autonomous vehicles and other innovations by freight transportation organizations. Presentation at the 98th *TRB Annual Meeting*, Washington DC. (also under review for journal publication)
- Other two papers in progress
Thank you and questions

Sabya Mishra
Associate Professor
Department of Civil Engineering
University of Memphis
Email: smishra3@memphis.edu