Envisioning Profitable Autonomous Transit Networks

by Alain L. Kornhauser

Professor, Operations Research & Financial Engineering
Faculty Chair, Princeton Autonomous Vehicle Engineering
Princeton University

Presented @ MIT Mobility Forum (Spring 2023)
Friday, February 17, 2023
Agenda:

achieving safe, equitable, affordable, sustainable high-quality mobility for our towns and cities

• What’s been tried & why it failed

• Where we’ve been recently & why it is struggling

• Where might we be going & what are the challenges
My Current Collaborators:

Annika Kelly’24, Bryce Rasmussen’25, Jerry He*21, Gabe Laniewski’23, Chris Dragomir’21, *23

Nick Taylor’24 & Floyd Benedikter’23
5th U23 pairs ’22 World Rowing Championships
Agenda:

• What’s been tried & why it failed
Evolution of Automated Vehicles

AHS: Automated Highway Systems: 1939 -> 1950s

In the 1950s we thought....
In the 1950s we thought....
At one time we thought....
At one time we thought....

http://www.youtube.com/watch?v=Rx6keHpeYak
At one time we thought....
Evolution of Automated vehicles

In the 1970s the focus turned to the with Personal Rapid Transit (PRT)
~45+ years ago...

- Personal Rapid Transit (PRT)
  - Morgantown
    - (circa 1976)
    - 3.6 miles, 71 vehicles

“System Centric”: Vehicle + Infrastructure

Today
3.6 miles, 71 vehicles

Ultra Pod at [Heathrow Airport](#)

[Masdar City PRT](#)
Evolution of Automated vehicles

In the 1990s we went back to AHS:

AHS Platooning Demo 1997
In the 1970s the focus turned to the cities with Personal Rapid Transit (PRT) 1970 ->

Evolution of Automated vehicles

AHS: Automated Highway Systems: 1939 ->

Reliance on Infrastructure to ensure safety

Unscalable!

Platooning Demo 1997
Agenda:

• What’s been tried & why it failed

• Where we’ve been recently & why it’s struggling
2004 -> Vehicle Centric (& sharie existing Roadways)
Focus on the vehicle! Ask as little as possible from the infrastructure

2004

CMU’s Sandstorm (7.3 miles)

2005

Princeton’s Prospect 11 (9.8 miles)

2007

Princeton’s Prospect 12 (DNMF)
Prospect Eleven & 2005 Competition
2005 Grand Challenge

Andrew Saxe'08
Brendan Collins'08
Anand Atreya'07
Bryan Cattle '07
Scott Schiffres'06
Gordon Franken '08
Josh Herbach'08
Rachel Blair'06
Alain Kornhauser*69. *71
Scott Schiffres'06
Gordon Franken '08
Josh Herbach'08
Rachel Blair’06
Alain Kornhauser*69. *71
It Wasn’t So Easy
Went back out during Fall break 3 weeks later..
Fixed One Line of Code (memory management)
Link to GPS Tracks
Can Virtual Reality Games/Simulators

Teach Computers How To Drive Safely?

by

Alain L. Kornhauser, PhD

Professor, ORFE
(Operations Research & Financial Engineering)
Director, CARTS
(Center for Automated Road Transportation Safety)
Faculty Chair, PAVE
(Princeton Autonomous Vehicle Engineering)
Princeton University

Presented at
Amazon’s
Radical Urban Transportation Salon

April 21, 2017
Seattle, WA


Chenyi Chen’s PhD dissertation: “Extracting Cognition out of Images for the Purpose of Autonomous Driving”, May 2016

Collaborators

• Dr. Chenyi Chen*16  nVIDIA & Cruise (TORCS)
• Ari Sheff*18
• Mark Martiez*18
• Jeremiah Liu*19
• Artur Filipowicz’17  Waymo (GTA5)
• Nayan Bhat’17
• Prof. Jianxiong Xiao (CEO & Founder AutoX)
The Problem: Obtaining Millions of Relevant Images with ‘Perfect’ Affordances

Many Interesting Research Questions

• Perception / Cognition
  – Deep Learning
    • Deep Driving

Deep Convolutional Neural Network (CNN)

Outstanding Issues:

1. Where do you get the training set?

Virtual reality

Direct Perception

**The Problem:** Obtaining Millions of Relevant Images with ‘Perfect’ Affordances

- **Real World**
  - Hard (Expensive) to get ‘Perfect’ Affordances
  - It’s Real

- **Virtual World**
  - Trivial to get ‘Perfect’ Affordances
  - Easy (Cheap) to re-create Corner Cases
  - Is it good enough?
Autonomous driving, 4x speed
Many Interesting Research Questions Remain

- Perception / Cognition
  - Deep Learning
    - Deep Driving

Deep Convolutional Neural Network (CNN)

Outstanding Issues:

1. Where do you get the training set?

   Virtual reality

2. What about the time dimension?

On a more Macro Level...
Where are we with SmartDrivingCars?

Preliminary Statement of Policy Concerning Automated Vehicles

**Level 0 (No automation)**
The human is in complete and sole control of safety-critical functions (brake, throttle, steering) at all times.

**Level 1 (Function-specific automation)**
The human has complete authority, but cedes limited control of certain functions to the vehicle in certain normal driving or crash imminent situations. Example: electronic stability control

**Level 2 (Combined function automation)**
Automation of at least two control functions designed to work in harmony (e.g., adaptive cruise control and lane centering) in certain driving situations.

Enables hands-off-wheel and foot-off-pedal operation.

*Driver still responsible for monitoring and safe operation and expected to be available at all times to resume control of the vehicle.* Example: adaptive cruise control in conjunction with lane centering

**Level 3 (Limited self-driving)**
Vehicle controls all safety functions under certain traffic and environmental conditions.

Human can cede monitoring authority to vehicle, which must alert driver if conditions require transition to driver control.

*Driver expected to be available for occasional control.* Example: Google car

**Level 4 (Full self-driving automation)**
Vehicle controls all safety functions and monitors conditions for the entire trip.

The human provides destination or navigation input but is not expected to be available for control during the trip. *Vehicle may operate while unoccupied.* Responsibility for safe operation rests solely on the automated system

SmartDrivingCars & Trucks

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*On a more Macro Level...*
• Only 3 “Levels”
  – “Safe-Driving”
    • On all the time!! + Driver driving all the time -> Safety
    • Extends Electronic Stability Control, Anti-lock brakes to Intelligent Cruise Control, Lane Keeping, Automated Emergency Braking,
  – “Self-Driving” (feet-off, brain-on)
    • On some of the time + Engaged Driver Oversight -> some Comfort & Convenience
    • Driver’s choice in “OEM certified” areas at “OEM certified” times!
      – Ultimate “Texting Machine” -> Increase VMT (Vehicle Miles Traveled)
  – “Driverless”
    • On all the time: In “certified” areas at “certified” times!! Called: Operational Design Domain (ODD) + Passengers, or Empty
      – Mobility for all, revolutionary impact on quality of life and urban form
Market for/ Implications of …Driverless Cars

• Ownership/ Market Model
  – 1. Privately owned.. (I’m not a fan!!)
Market for/Implications of ... Driverless Cars

Ownership/Market Model

- 2. Fleet Managed/Operated
  
  Focus is on provision of mobility of people
  
  - & goods
Where are we in this Driverless Technological Evolution?
Where are we in this Driverless Technological Evolution?

Did you Notice....

Google/Waymo’s Buying Spree

Cars "Purchased"
Where are we in this Driverless Technological Evolution?

Did you Notice....
Google/Waymo’s Buying Spree

Cars “Purchased”

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</tbody>
</table>
Where are we in this Driverless Technological Evolution?

Did you Notice….

Google/Waymo’s Buying Spree

Year

Cars “Purchased”

10M
1M
100K
10K
1K
100
10
1


2009 2012 2015

2 20 200
Did you Notice....

Google/Waymo’s Buying Spree

Where are we in this Driverless Technological Evolution?
Where are we in this Driverless Technological Evolution?

Did you Notice....

Google/Waymo’s Buying Spree

Cars “Purchased”

Year

2009  2012  2015  2017  2018.2

2  20  200  2,000  20,000
Where are we in this Driverless Technological Evolution?

Did you Notice....

Google/Waymo’s Buying Spree

‘> 10X every 2 years’

Waymo’s ‘Kornhauser Law’
Back, before COVID, I was wondering?
What will Waymo do with 20,000 Jaguars?

Provide housing for the homeless in San Francisco?
Where will Waymo Deploy
20,000 + 60,000 autonomous Taxis

• Maybe they’ll “Geographically Market Test the aTaxi Mobility Experience”
  – Start by operating 1K in 20 different “cities”
    • Geo-fenced “communities of ~ 300,000” (serve 5% of personTrips)
  – Add 2K to 1st 20 (grow to 15% personTrip share) + 1K in 20 more “Communities of 300k

Will they notice that Central Jersey exists?
Where will Waymo Deploy
20,000 + 60,000 autonomous Taxis
Will they notice that Central Jersey exists?

• “Central New Jersey”
  • Pop: ~400K
  • Intra-area Trips/day: ~ 1.0M/day
  • aTaxi Productivity: ~100 personTrips/day
  • 500 aTaxis could serve ~ 5% personTrips
    – Focused initially on Mobility Disadvantaged
      • whose quality-of-life would be improved substantially by serving
        their latent demand!
  • Hmmmmm…. Is there an operational level-of-service whereby one might be able to
    realize a vehicle productivity that might approach a 100 personTrips/day?
What is the Total Addressable personTrip Market?

Synthesizing Individual Travel Demand in New Jersey
Trips everyone in NJ wants/needs to make on a typical day

Philip Acciarito ’12
Luis Quintero ’12
Spencer Strobel ’12
Natalie Webb ’12
Heber Delgado-Medrano ’12
Talal Mufti ’12
Bharath Alamanda ’13

Christopher Brownell ’13
Blake Clemens ’13
Charles Fox ’13
Sarah Germain ’13
Akshay Kumar ’13
Michael Markiewicz ’13
Tim Wendland ’13

Professor Alain L. Kornhauser ’71

Department of Operations Research & Financial Engineering
Princeton University
January, 2012
Creating the **USA_Resident** file

Start with Publicly available data:

- Journey to Work

Created a record for “every” USA Traveler on a typical day

**USA_Resident file**

308,745,538 records

(Home census block, household, age, sex, demographic data)
### Bergen County @ Block Level

<table>
<thead>
<tr>
<th>County</th>
<th>Population</th>
<th>Census Blocks</th>
<th>Median Pop/Block</th>
<th>Average Pop/Block</th>
</tr>
</thead>
<tbody>
<tr>
<td>BER</td>
<td>907,128</td>
<td>11,116</td>
<td>58</td>
<td>81.6</td>
</tr>
</tbody>
</table>

#### Bergen County Population per Census Block

![Graph showing population distribution per census block](image)

#### Cumulative Population Over Census Blocks, BER

![Graph showing cumulative population distribution over census blocks](image)
US_PersonTrip file has:

- **308,745,538** records
  - One for each person in US_Resident file
  - Includes where they live
## Nation-Wide Businesses

13.6 Million Businesses
{Name, address, Sales, #employees}

<table>
<thead>
<tr>
<th>Rank</th>
<th>State</th>
<th>Sales Volume</th>
<th>No. Businesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>California</td>
<td>$1,889</td>
<td>1,579,342</td>
</tr>
<tr>
<td>2</td>
<td>Texas</td>
<td>$2,115</td>
<td>999,331</td>
</tr>
<tr>
<td>3</td>
<td>Florida</td>
<td>$1,702</td>
<td>895,586</td>
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<tr>
<td>4</td>
<td>New York</td>
<td>$1,822</td>
<td>837,773</td>
</tr>
<tr>
<td>5</td>
<td>Pennsylvania</td>
<td>$2,134</td>
<td>550,678</td>
</tr>
<tr>
<td>9</td>
<td>New Jersey</td>
<td>$1,919</td>
<td>428,596</td>
</tr>
<tr>
<td>45</td>
<td>Washington DC</td>
<td>$1,317</td>
<td>49,488</td>
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<tr>
<td>47</td>
<td>Rhode Island</td>
<td>$1,814</td>
<td>46,503</td>
</tr>
<tr>
<td>48</td>
<td>North Dakota</td>
<td>$1,978</td>
<td>44,518</td>
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<tr>
<td>49</td>
<td>Delaware</td>
<td>$2,108</td>
<td>41,296</td>
</tr>
<tr>
<td>50</td>
<td>Vermont</td>
<td>$1,554</td>
<td>39,230</td>
</tr>
<tr>
<td>51</td>
<td>Wyoming</td>
<td>$1,679</td>
<td>35,881</td>
</tr>
</tbody>
</table>
Assigning a Daily Activity (Trip) Tour to Each Person

<table>
<thead>
<tr>
<th>Trip Chain Type Number</th>
<th>What it looks like</th>
<th>Number of trip ends</th>
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<tbody>
<tr>
<td>0</td>
<td>( \square )</td>
<td>0</td>
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<tr>
<td>1</td>
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<td>6</td>
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<td>7</td>
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</table>

<table>
<thead>
<tr>
<th>Trip Chain Type</th>
<th>Grade School</th>
<th>Middle School</th>
<th>High School</th>
<th>College Commuter</th>
<th>College on Campus</th>
<th>Worker</th>
<th>Out of State Worker</th>
<th>At Home Worker</th>
<th>Nursing Home &amp; Under 5</th>
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<tbody>
<tr>
<td>0</td>
<td>0.050</td>
<td>0.025</td>
<td>0.025</td>
<td>0.050</td>
<td>0.300</td>
<td>0.010</td>
<td>0.000</td>
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<tr>
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<td>0.175</td>
<td>0.150</td>
<td>0.050</td>
<td>0.075</td>
<td>0.300</td>
<td>0.050</td>
<td>0.000</td>
<td>0.300</td>
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<td>0.000</td>
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<td>6</td>
<td>0.075</td>
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<td>7</td>
<td>0.050</td>
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<td>0.090</td>
<td>0.000</td>
<td>0.050</td>
<td>0.000</td>
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</table>

**Probabilities**

- AVG: 3.625, 3.850, 4.150, 4.000, 2.140, 4.480, 2.500, 3.150, 0.000
• **1,009,332,835** individual personTrips
  – Each characterized by a precise
    • \{oLat, oLon, oTime, dLat, dLon, est._dTime, personPointer, tripType (W,S,O)\}
Agenda:

• What’s been tried & why it failed
  Where we’ve been recently & why it is struggling

• Where might we be going & what are the challenges

  *Envisioning Profitable Autonomous Transit Networks*
Today we may have some Vehicles that may be able to operate safely on some streets to deliver viable mobility between some locations.

If so, where, when and at what price should they deploy, as a viable business, their mobility capability? One way, maybe…
Framework for Deployment of Safe, Equitable, Affordable, Sustainable, High-quality Mobility

MOVES-style Deployment
(Mobility Opportunity: Vehicle Equitable System)

Elevator-like on-demand, casually-shared (when appropriate)

Kiosk2Kiosk LoS:
wait < 5-minute, walk < 5-minute, 24/7/350

Interconnected to create an Automated Transit Network
Example... a Trenton MOVES Kiosk located at Trenton Public Housing’s Donnelly Homes

Trenton MOVES' Automated Transit Network Transforms Affordable Housing to Affordable Living
Inspection of Total Addressable Market (TAM) of Daily personTrips for MOVES-style Automated Transit Network’s Operational Design Domain (ODD)

Phase 3 Pilot Operations
100 Vehicles (250 FTE Labor)
Total Addressable Market’s personTrip Length (miles)
Total Addressable Market’s personTrip Temporal Distributions
(personTrip Originations/minute)
Total Addressable Market’s personTrip Spatial Distributions

Trenton MOVES - Interactive Graphic Visualization

[Link to Instructions] of Data Layers and Map Operations
All personTrips that originate from Trenton Central High School
All personTrips that originate from Ewing Shop Rite
All personTrips that originate from Capital Health Regional Center
All personTrips that originate from multiple McDonald’s in Trenton
All personTrips that originate from the Pixel of Mayor Donnelly Homes
All trip pickups within this pixel are aggregated at Donnelly Homes Kiosk (via a maximum of 5min walking).

Details: All personTrips that originate the Pixel of Mayor Donnelly Homes
Basic economic analysis of MOVES-style "safe, equitable, affordable, sustainable, high-quality" mobility systems
Proof of Concept & Phase 0 Operations

Proof of Concept Phase
2 Vehicles (5 FTE Labor)

Phase 0 Pilot Operations
5 Vehicles (12.5 FTE Labor)
Phase 1, 2 & 3 Pilot Operations

Phase 1 Pilot Operations
20 Vehicles (50 FTE Labor)

Phase 2 Pilot Operations
83 Vehicles (208 FTE Labor)

Phase 3 Pilot Operations
100 Vehicles (250 FTE Labor)
Mercer Coputy Expansion Phase
The Evolving ODDS

**PHASE IV**

Replication Throughout NJ: **Proof of Network-Scale Economics**
The Evolving ODDS

**Phase V** Repllication across US: Delivery of Societal Values at Scale

**BQX-MOVES**

~ 1M personTrips/Day  Total Addressable Market

~ 75 Kiosks

~500 Vehicles

~ 75,000 PersonTrips/Day
The Evolving ODDs

Source: B.Liang, J.He, A.Kornhauser, “Vehicle Immobility Map of USA”, 2021, CARTS
Thank you
Part I: Relevant Literature


Part II: Recent News


NJDOT Technology Transfer (2022, May 25). *Trenton MOVES and the SmartDrivingCARS Summit.* https://www.njdottechtransfer.net/2022/05/25/trenton-moves/

Part III: Summary

Alain Kornhauser began his talk with his vision for Autonomous Transit Networks (ATNs) as “safe, equitable, affordable, sustainable high-quality mobility for our towns and cities”. He discussed timeless excitement surrounding transportation innovation, which at times has been focused around technology that never really took off like Personal Rapid Transit (PRT). PRT was the focus of Kornhauser’s work in the 70s and was implemented in a few locations such as Morgantown, WV as driverless monorail-like systems. However, Kornhauser points out that despite the potential PRT offered to easily move just a few people at a time between a network of points of interest, the technology did not catch on widely due the “system centric” design demanding not only vehicles but also new, expensive, and highly-specific infrastructure.

This barrier prompted Kornhauser to return to the automobile as a familiar vehicle for which we already have extensive road infrastructure. He shared some stories and lessons learned from DARPA "SmartDrivingCar" Challenges and research behind autonomous vehicle image recognition and response training. He raised an interesting point in highlighting how the virtual world offers a cheap, accessible, and comprehensive solution to provide machine learning algorithms with a wide range of situations that autonomous vehicles may encounter and need to be prepared to respond to.

Acknowledging that automation comes in various levels, Kornhauser proposed a framework simpler than NHTSA’s five levels of automation. Kornhauser sees three levels of smart driving cars: “safe-driving” to intercept in emergency situations, “self-driving” with additional but still limited automated driving, and finally truly “driverless” vehicles. Kornhauser believes truly driverless vehicles could provide mobility for all, especially through a fleet managed and operated service to focus on the mobility of people and goods. To understand what the demand for such a service would be, he used publicly available census data and origins and destinations such as homes, schools, and offices to build a representation of individual trip activity at a granular level. When trip demand is broken down temporally and spatially, it provides a tool to chart a network of trips that could be effectively served by an autonomous vehicle fleet. Kornhauser hopes this approach will provide a way to analyze and plan in such a way that allows ATN technology to be implemented at a large scale.

Q&A was moderated by Jinhua Zhao and John Moavenzadeh.

JZ: There are two types of scholars, those who look at technology itself and those who study the system that technology interacts with. Your work brings these two perspectives together. With that perspective and insight, under what conditions do you think your vision of ATNs will actually be realized?
AK: The technology is essentially there, with some limitations. The challenge we are facing now is primarily that we are aiming to implement autonomous vehicles everywhere – this isn’t the goal we should be striving for now. We should define where this technology works, implement it there, and constrain it to stay in those locations rather than force the technology to be perfectly suited to all environments before we can use it in urban environments.

JZ: I appreciate that you apply this technology particularly to the economic challenge of the household. At the same time, the technology penetration process for any technology typically starts by cherry picking the most profitable market and hoping for success. Will that ever naturally happen with autonomous vehicles?

AK: That will fail, there aren’t enough trips that would opt for driverless ride hailing to make up the huge capital investment that has funded development of this technology. The promise may lie in thinking about serving latent demand.

JM: Thinking about the social space of fleet-managed autonomous vehicles, what do you perceive as any people problems ATNs face?

AK: It’s a sociological problem that needs to be studied and addressed. ATNs should be designed to encourage people to choose shared rides in order to make the system actually sustainable.

JM: In what way would you imagine that density affects the ability for these fleets to operate profitably? Could the availability of these types of fleets actually nudge people towards density? Could the autonomous fleets feed into the public transportation system?

AK: Of course! In order for ATNs to be economically viable they will need to connect with public transportation to expand reach as a joint transportation network. Otherwise, ATNs alone will not take you very far.

Part IV: Summary of Memos

Having learned that “system centric” designs are hard to scale, it makes a great deal of sense in the age of automation to consider how on-demand autonomous vehicles can serve mobility needs without high infrastructure constraints. Still, Kornhauser’s argument for ATNs leaves questions unanswered as to how such a system would be successful in meeting the goals of affordability, safety, equity, and sustainability. Safety is one component that seems to be primarily technical, but almost as important as actual safety of autonomous vehicles is perceived safety. Perceived safety is essential to public uptake of technology – without trust in autonomous vehicles, Kornhauser’s vision of ATN as a transformative last-mile solution may end up unrealized, as was the original vision for PRT decades before. Sociological factors are incredibly important when
considering the potential for autonomous vehicles. Technological research alone does not provide the insight necessary to successfully implement a system that people will use, and especially not one that people will use in such a way that accomplishes the desired goals of decreasing environmental impact and equitably increasing mobility access.

Beyond this sociological factor, there are still more questions to be explored as to how ATNs would sustainably intersect with bus and rail networks and whether there is financial justification for how ATNs will simultaneously earn enough revenue to continue to operate and innovate while also offering an affordable service. It seems that a pillar of Kornhauser’s argument for affordability is that households would not individually purchase autonomous vehicles but rather would be served by fleet-based autonomous vehicles, though it is not obvious how this will create an affordable mode of transportation for households who are currently priced out of car ownership.

Though there are many questions left to be answered before this can be a reality, Kornhauser was convincing in exciting the audience about the idea of a safe, fleet-based ATN operated at affordable rates to all customers in conjunction with public transportation networks to increase mobility for populations who cannot drive due to age, disability, or cost and offer a valuable service to all.

**Part V: Literature Cited During Presentation**

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