PRINCETON UNIVERSITY

PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

# *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, Febuary, 17, 2023

MIT Mobility Initiative

# 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**

PRINCETON UNIVERSITY

PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

# My Current Collaborators:

*Annika Kelly'24, Bryce Rasmussen'25, Jerry He*21, Gabe Laniewski'23, ChrisDragomir'21, *23*


*Nick Taylor'24 & Floyd Benedikter'23*

*5th U23 pairs '22 World Rowing Championships*

MIT Mobility Initiative

# Agenda:

- **What's been tried & why it failed**

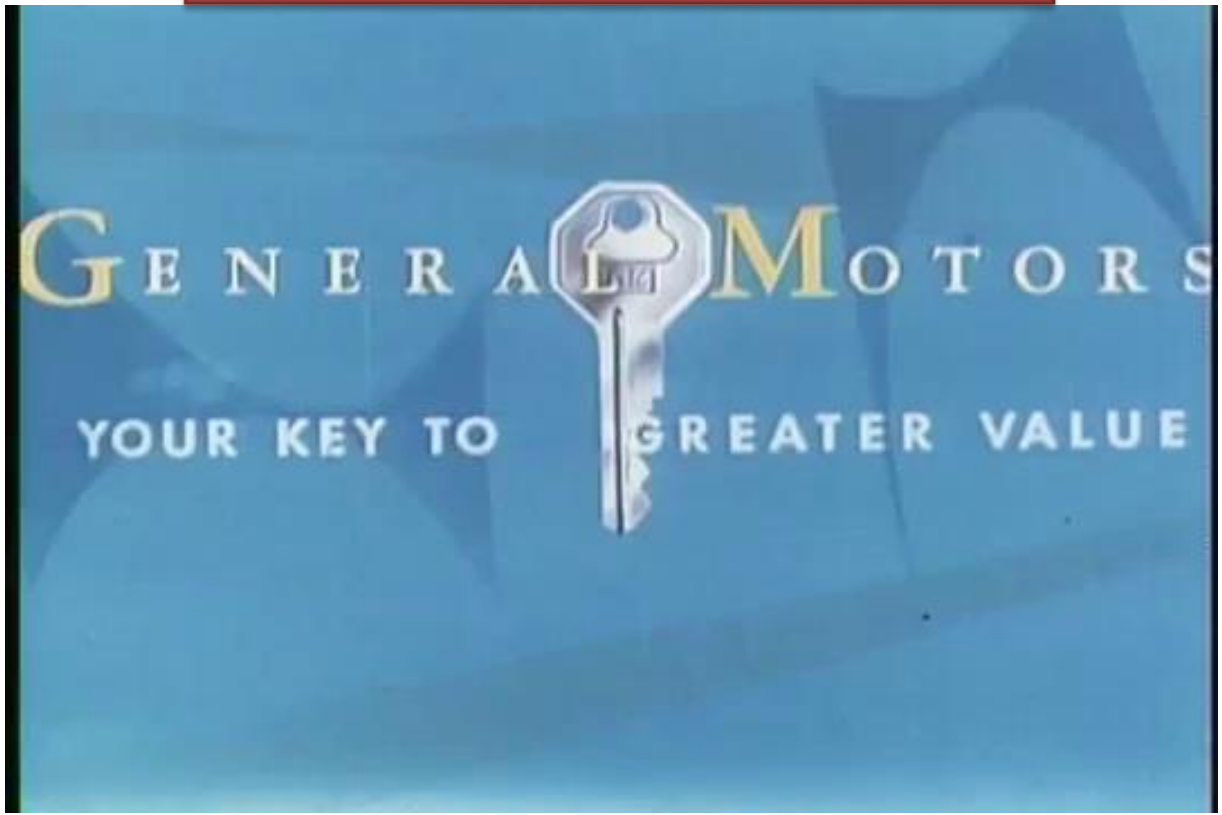
# Evolution of Automated Vehicles

AHS: Automated Highway Systems: 1939 -> 1950s

In the 1950s we thought….

http://www.youtube.com/watch?v=Rx6keHpeYak

# In the 1950s we thought….



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# At one time we thought….

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# At one time we thought….

# Evolution of Automated vehicles


In the 1970s the focus turned to the with **Personal Rapid Transit (PRT)**

**1975**

# ~45+ years ago…

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

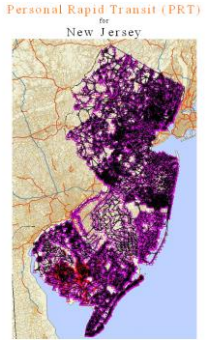
Today

3.6 miles, 71 vehicles

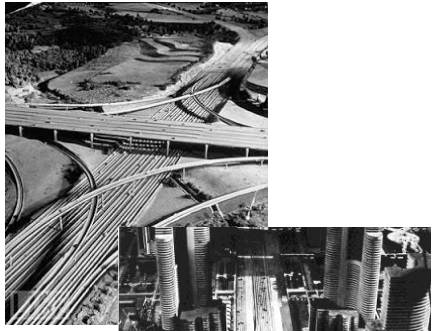
**"System Centric": Vehicle + Infrastructure**

Ultra Pod at Heathrow Airport

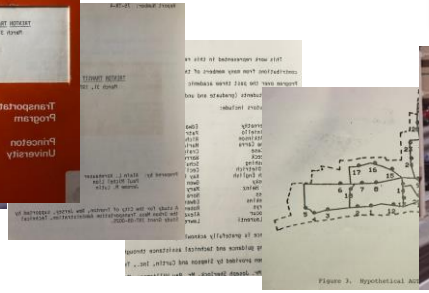
Masdar City PRT



# Evolution of Automated vehicles







In the 1990s we went back to **AHS:**

**AHS Platooning Demo 1997**

# Evolution of Automated vehicles

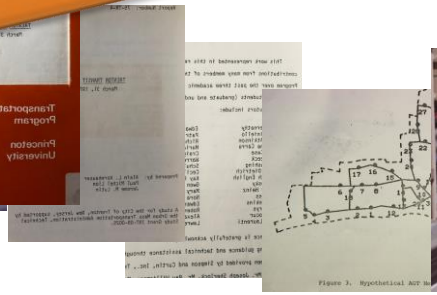
**AHS: Automated Highway Systems: 1939 ->**

In the 1970s the focus turned to the cities with
**Personal Rapid Transit (PRT) 1970 ->**

**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

Scott Schiffres'06 Gordon Franken '08
Anand Atreya'07 Josh Herbach'08 Rachel Blair'06
Andrew Saxe'08 Brendan Collins'08 Bryan Cattle '07 Alain Kornhauser*69. *71

Princeton University

# It Wasn't So Easy

ORFE

CARTS
The Center for Automated Road Transportation Safety


41
PROSPECT ELEVEN
COLEMAN
GMC

# 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



(TORQs & Grand Theft Auto 5)



## 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*

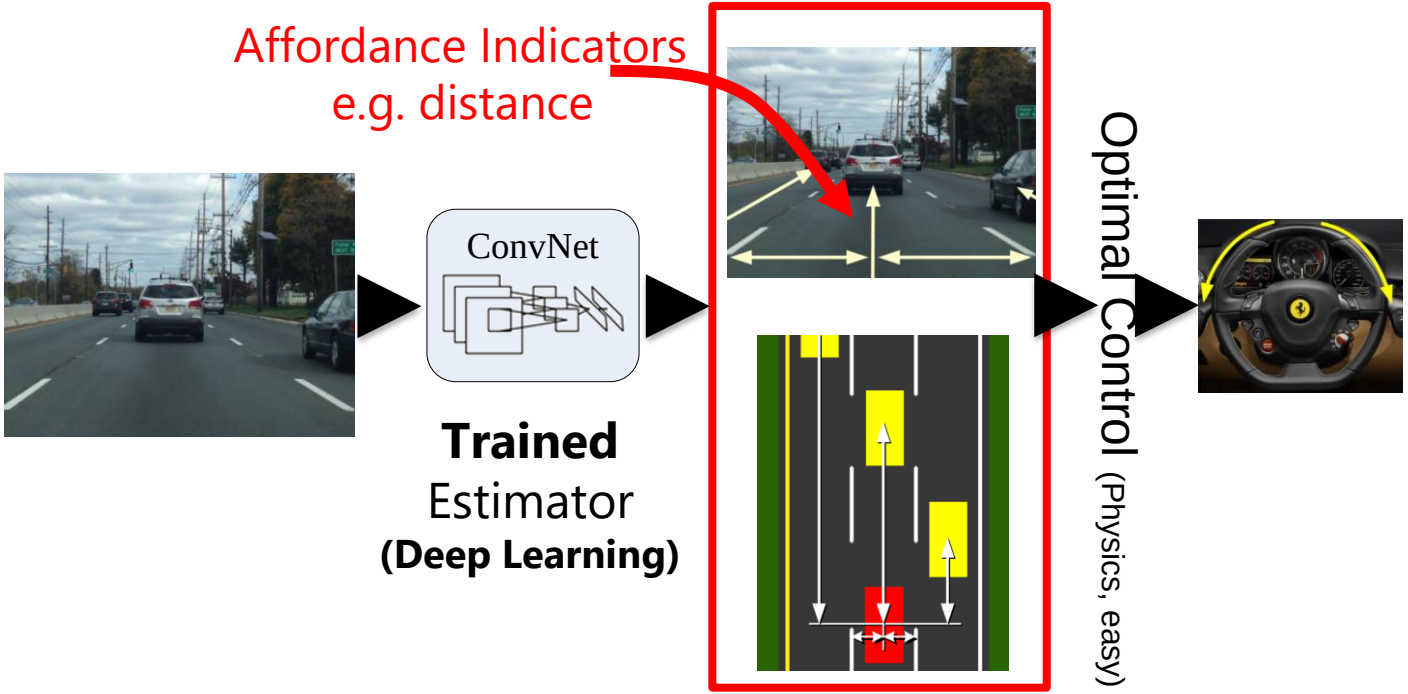



(with C. Chen, A. Seff, J. Xiao) "*DeepDriving: Learning Affordance for Direct Perception in Autonomous Driving* " Pro. of 15th IEEE Int. Conference on Computer Vision (ICCV2015)
Chenyi Chen's PhD dissertation: "*Extracting Cognition out of Images for the Purpose of Autonomous Driving*", May 2016
A. Filipowicz, et al (2016) "*Learning to Recognize Distance to Stop Signs Using the 1Virtual World of Grand Theft Auto 5*"

# 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)**

# Direct Perception




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

(with C. Chen, A. Seff, J. Xiao) "DeepDriving: Learning Affordance for Direct Perception in Autonomous Driving " Proceedings of 15th IEEE International Conference on Computer Vision (ICCV2015)

# Many Interesting Research Questions

- Perception / Cognition
  - Deep Learning
    - Deep Driving

Deep Convolutional Neural Network (CNN)

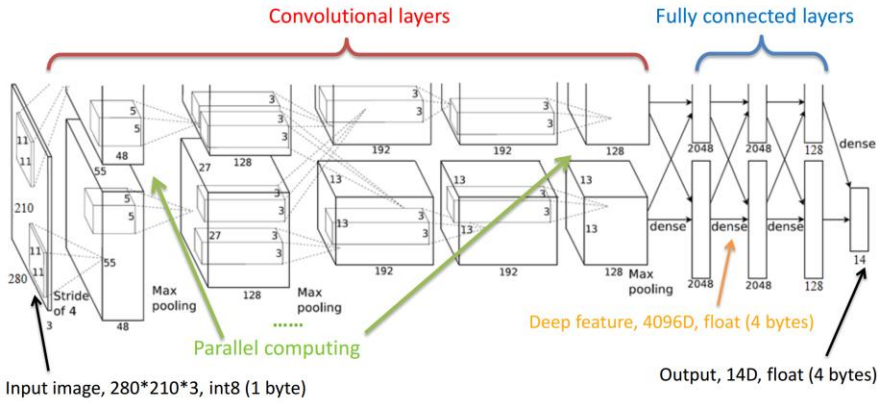



Figure courtesy and modified of Alex Krizhevsky, Ilya Sutskever, Geoffrey E. Hinton

Outstanding Issues:

1. Where do you get the training set?

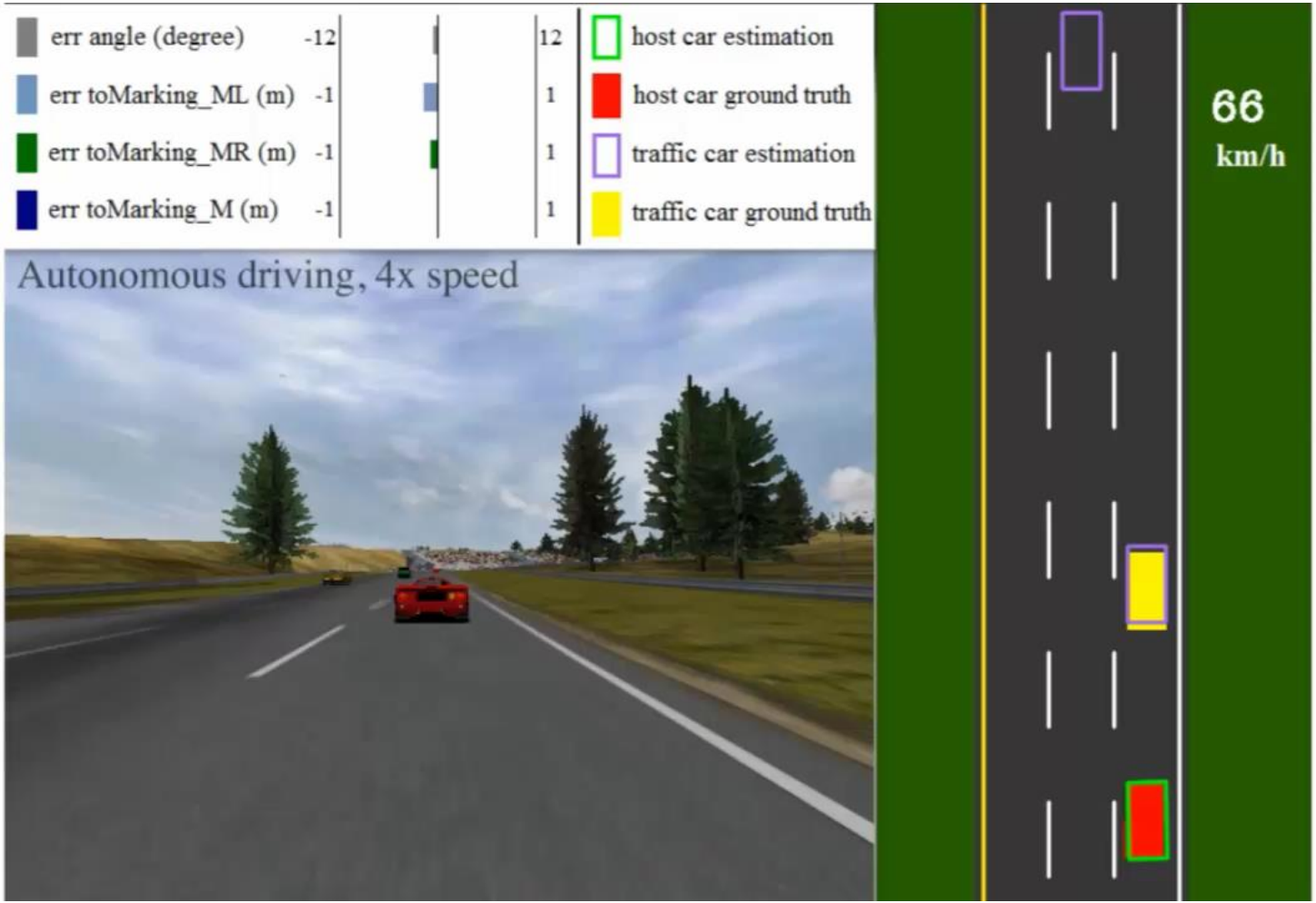
**Virtual reality**

A. Filipowicz, et al (2016) "*Learning to Recognize Distance to Stop Signs Using the Virtual World of Grand Theft Auto 5.*

# Direct Perception

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

| Real World | Virtual World |
| --- | --- |
| Hard (Expensive) to get 'Perfect' Affordances | Trivial to get 'Perfect' Affordances<br><br>Easy (Cheap) to re-create Corner Cases |
| It's Real | Is it good enough? |


err angle (degree) -12 12
err toMarking_ML (m) -1 1
err toMarking_MR (m) -1 1
err toMarking_M (m) -1 1
host car estimation
host car ground truth
traffic car estimation
traffic car ground truth
Autonomous driving, 4x speed
66
km/h


host car estimation
traffic car estimation

# Many Interesting Research Questions Remain

- Perception / Cognition
  - Deep Learning
    - Deep Driving

Deep Convolutional Neural Network (CNN)

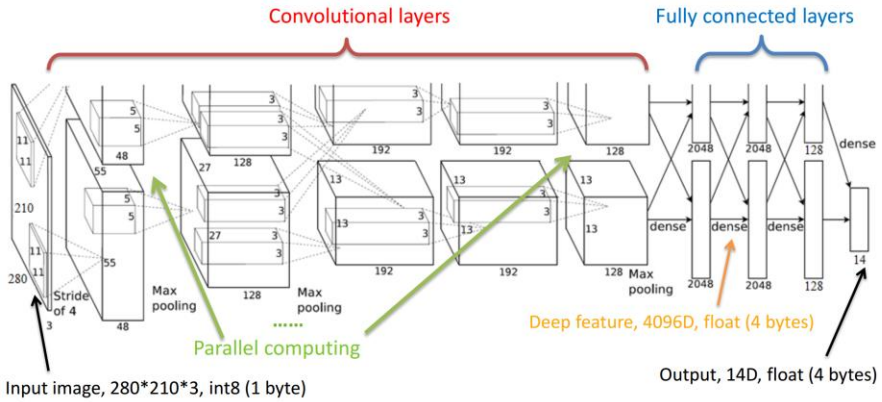



Figure courtesy and modified of Alex Krizhevsky, Ilya Sutskever, Geoffrey E. Hinton

Outstanding Issues:

1. Where do you get the training set?

**Virtual reality**

**2. What about the time dimension?**

A. Filipowicz, et al (2016) "*Learning to Recognize Distance to Stop Signs Using the Virtual World of Grand Theft Auto 5.*

# On a more Macro Level…

# Where are we with SmartDrivingCars?

NHTSA
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

## Preliminary Statement of Policy Concerning Automated Vehicles

SmartDrivingCars & Trucks

**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

# Where are we with SmartDrivingCars?

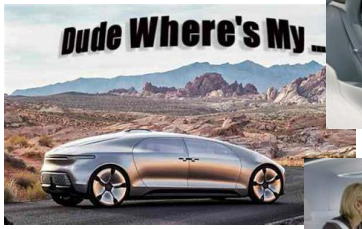
- Only 3 "Levels"
  - **"Safe-Driving"**
    - **On all the time!! + Driver driving all the time -> Safety**
    - **Extends Electronic Stability Control, Anti-lock brakes to Intelligent Cruise Control, Lane Keeping, Automated Emergency Braking,**

  - **"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!!)**




Personal Family Car

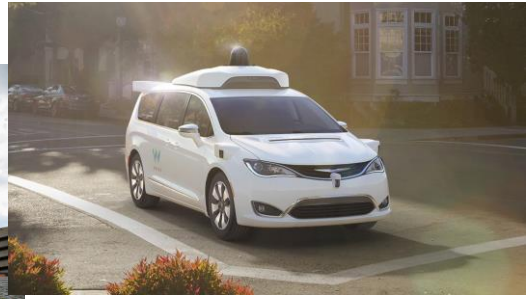
**Entitled Elitists Toy**

# Market for/ Implications of …Driverless Cars

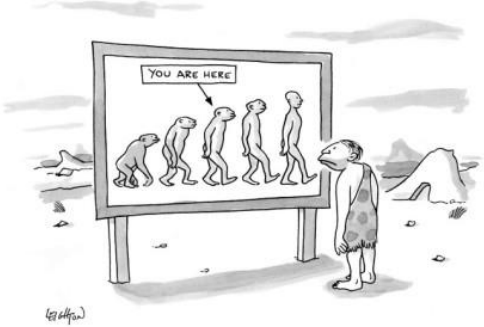
- **Ownership/ Market Model**
  - **2. Fleet Managed/Operated**

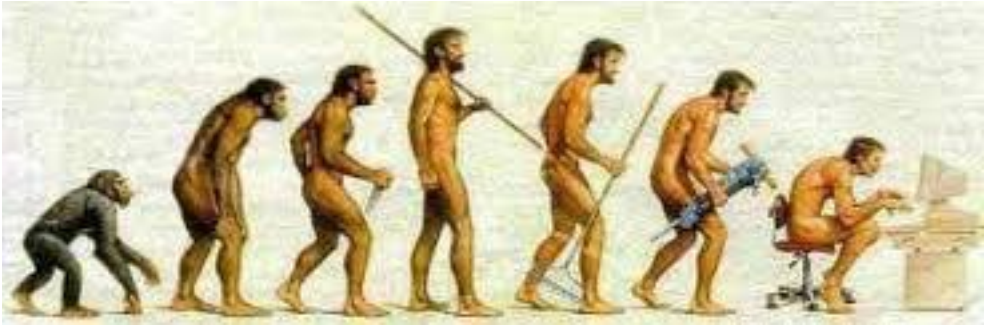
    **Focus is on provision of mobility of people**

    - **& goods**

# Where are we in this Driverless Technological Evolution?

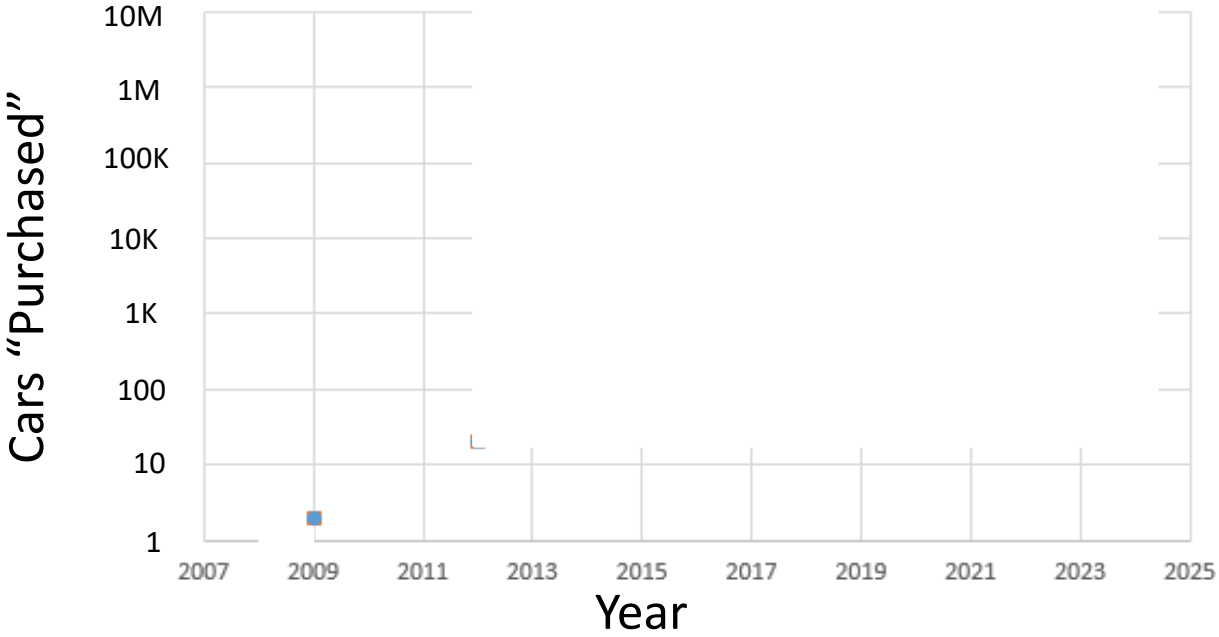


# Where are we in this Driverless Technological Evolution?

## Did you Notice….

### Google/Waymo's Buying Spree




2009

2

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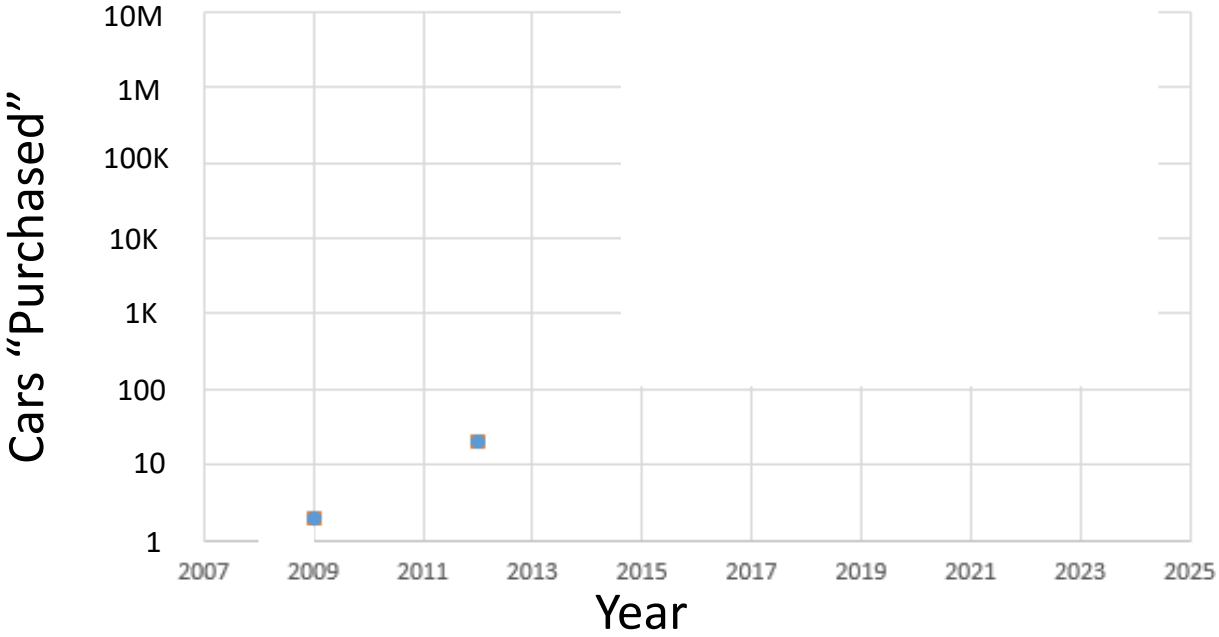


2009

2

2012

20

# Where are we in this Driverless Technological Evolution?

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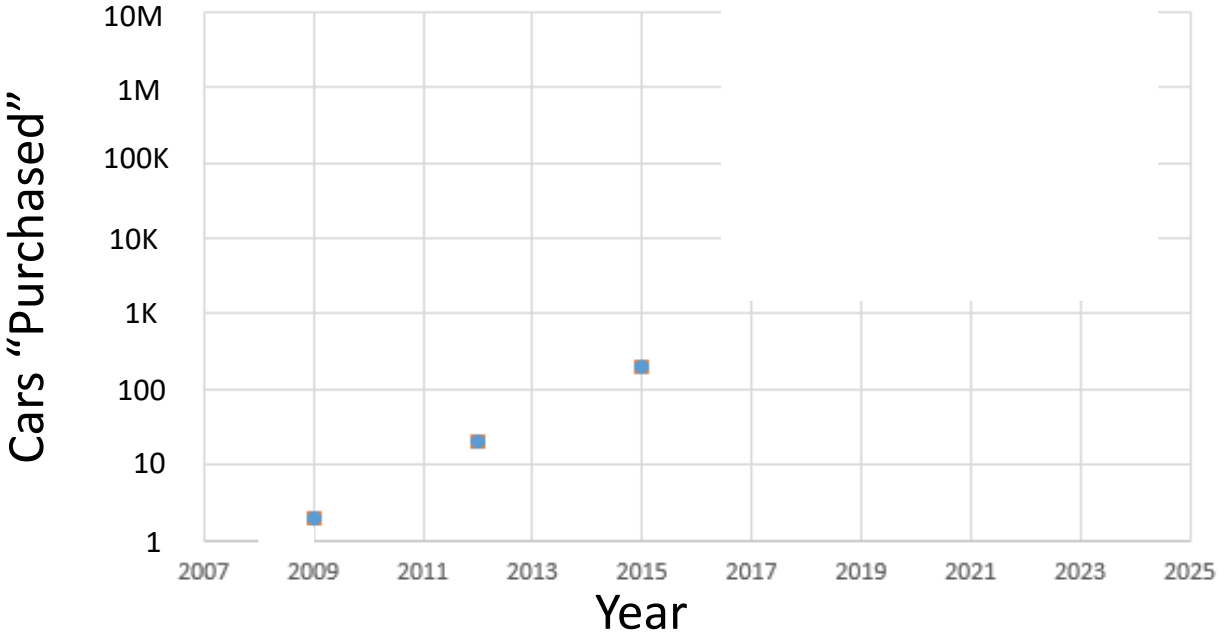


2009

2

2012

20

2015

200

# Where are we in this Driverless Technological Evolution?

## Did you Notice….

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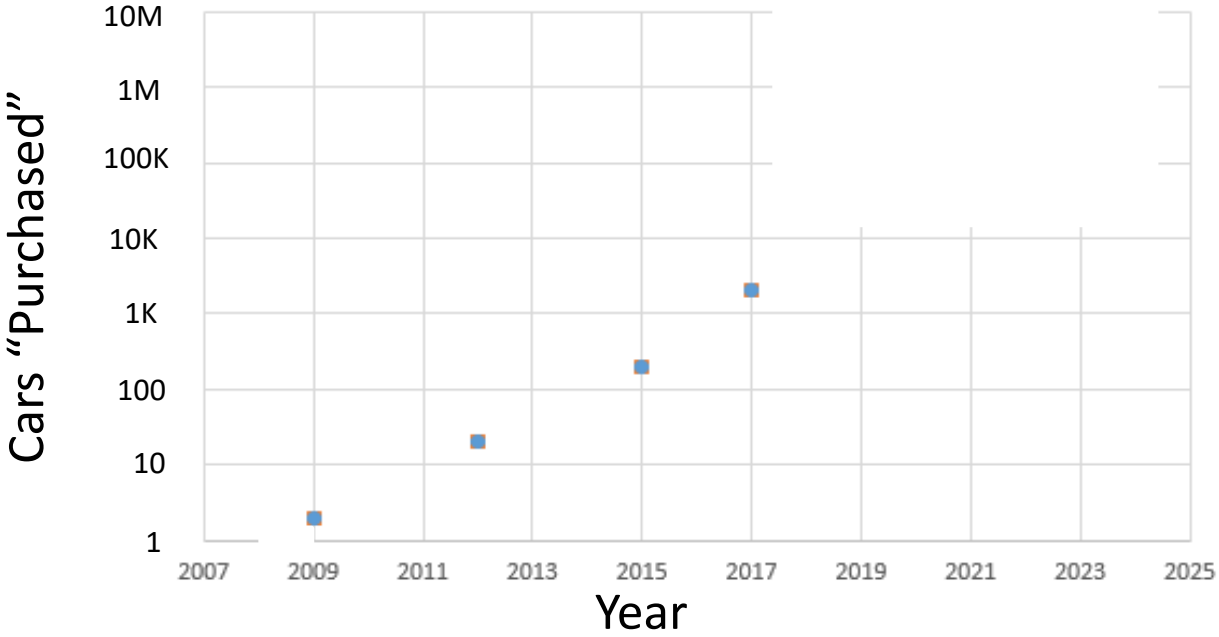


2009

2

2012

20

2015

200

2017

2,000

# Where are we in this Driverless Technological Evolution?

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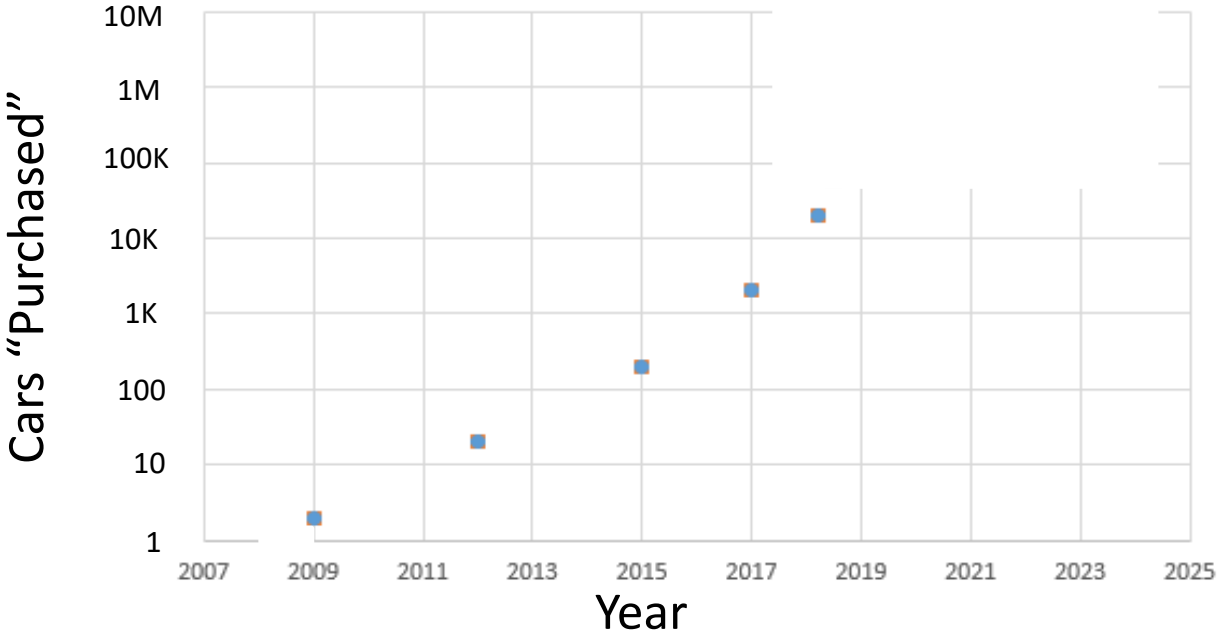



2009

2

2012

20

2015

200

2017

2,000

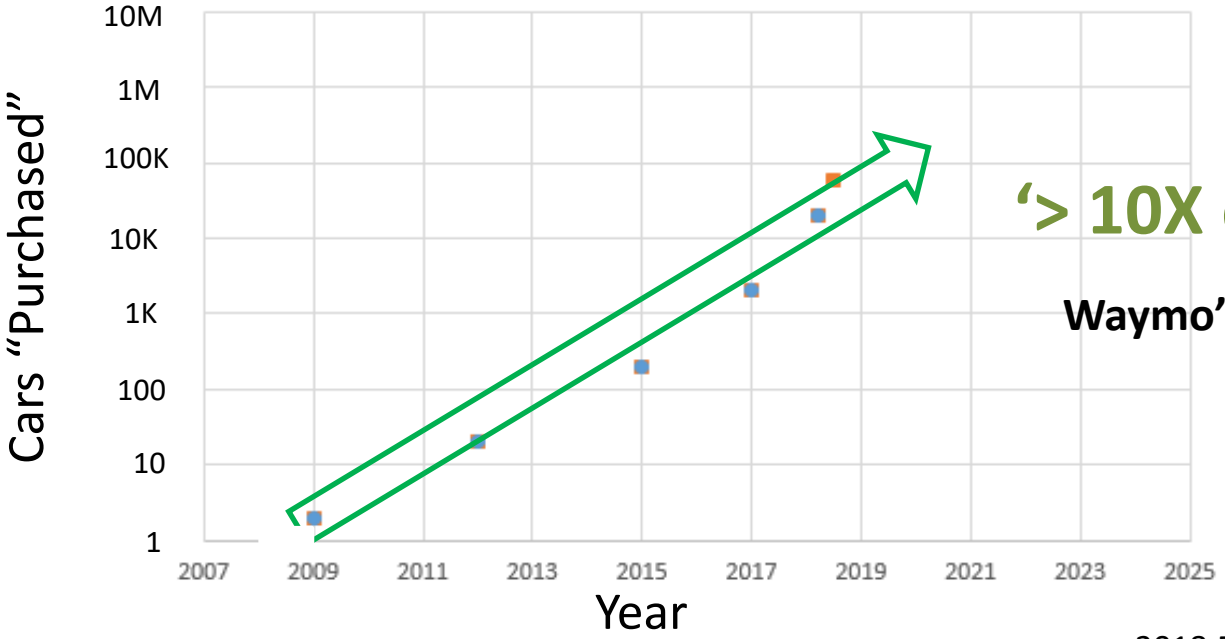
2018.2

20,000

# Where are we in this Driverless Technological Evolution?

## Did you Notice….

### Google/Waymo's Buying Spree

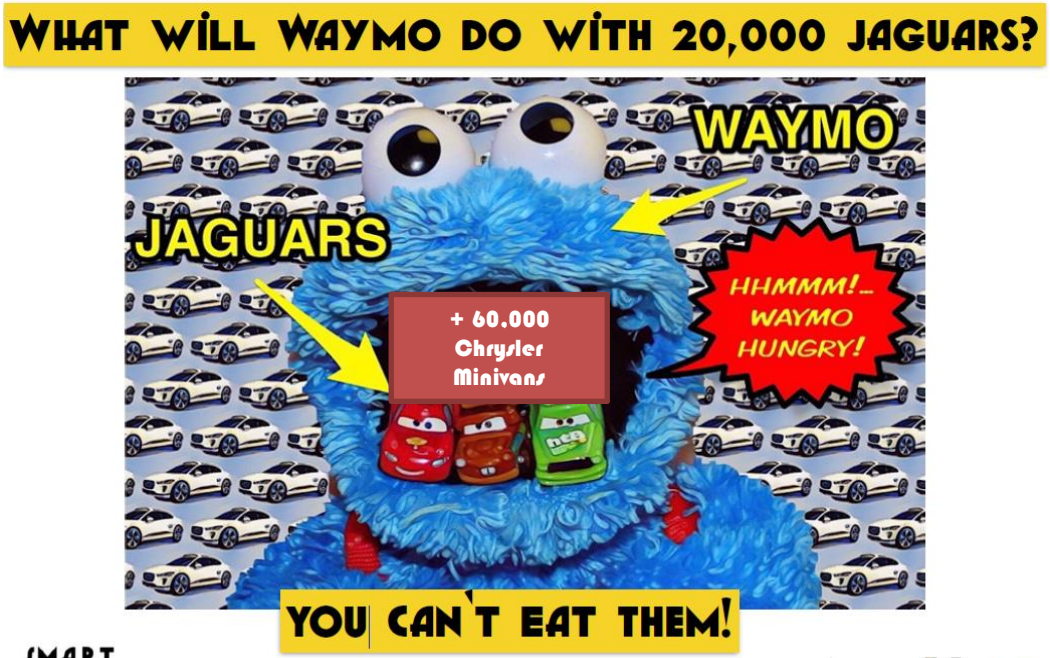



**'> 10X every 2 years'**

**Waymo's 'Kornhauser Law'**

| 2009 | 2012 | 2015 | 2017 | 2018.2 | 2018.5 |
|---|---|---|---|---|---|
|  |  |  |  |  |  |
| 2 | 20 | 200 | 2,000 | 20,000 | 62,000 |

# Back, before COVID, I was wondering?




SMART DRIVING CARS
BLOG AND PODCAST

PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

# WHAT WILL WAYMO DO WITH 20,000 JAGUARS?


# PROVIDE HOUSING FOR THE HOMELESS IN SAN FRANCISCO?

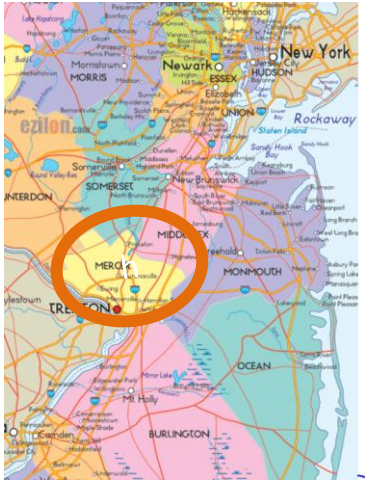
# Where will Waymo Deploy
# 20,000 + 60,000 autonomousTaxis

- 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 autonomousTaxis
# Will they notice that Central Jersey exists?

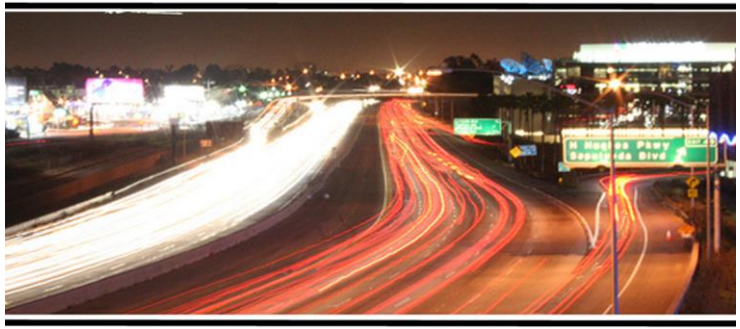
- "Central New Jersey"
  - Pop: ~400K
  - Intra-area Trips/day: ~ 1.0M/day
  - aTaxi Productivity: ~100 personTrips/day
  - 500 aTaxis could serve ~ 5% personTrips
    - Focused initially on ***Mobility Disadvantaged***
      - whose quality-of-life would be improved substantially by serving their latent 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 pesonTrip 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 Stroeble '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 Wenzlau '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:

United States Census 2010

AMERICAN COMMUNITY SURVEY
U.S. CENSUS BUREAU

Journey to Work

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

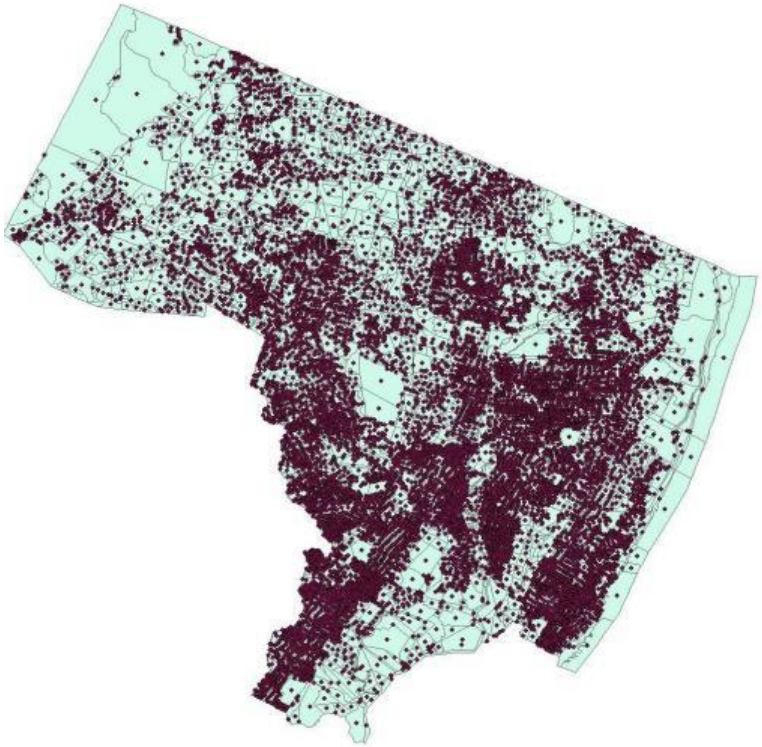
**USA_Resident file**

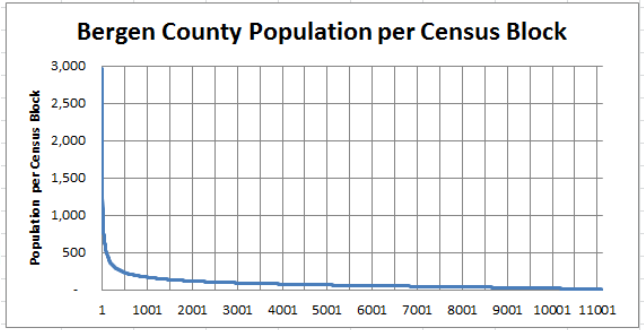
**308,745,538** records

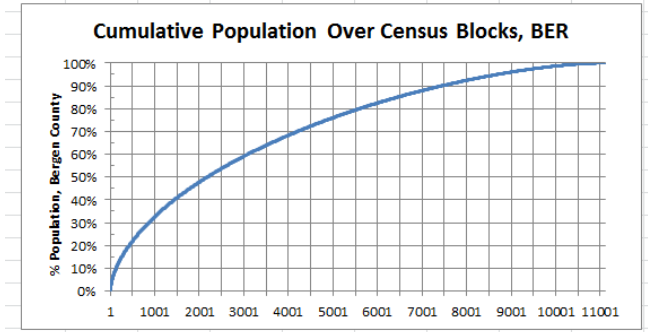
(Home census block, household, age, sex, demographic data)

# Bergen County @ Block Level

| County | Population | Census Blocks | Median Pop/ Block | Average Pop/Block |
|---|---|---|---|---|
| BER | 907,128 | 11,116 | 58 | 81.6 |





# **US_PersonTrip** file has..

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

# Public Schools in the US (~200k)

# Nation-Wide Businesses

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

| Rank | State | Sales Volume | No. Businesses |
|---|---|---|---|
| 1 | California | $1,889 | 1,579,342 |
| 2 | Texas | $2,115 | 999,331 |
| 3 | Florida | $1,702 | 895,586 |
| *4* | *New York* | *$1,822* | *837,773* |
| 5 | Pennsylvania | $2,134 | 550,678 |
| **9** | **New Jersey** | **$1,919** | **428,596** |
| *45* | *Washington DC* | *$1,317* | *49,488* |
| *47* | *Rhode Island* | *$1,814* | *46,503* |
| 48 | North Dakota | $1,978 | 44,518 |
| 49 | Delaware | $2,108 | 41,296 |
| 50 | Vermont | $1,554 | 39,230 |
| 51 | Wyoming | $1,679 | 35,881 |

# Mercer County Pixel {181,93} Chambersburg


| Item | Value |
|---|---|
| Activity Locations | 113 |
| Employment | 2,295 |
| Population | 5,622 |
| School Enrollment | 594 |

Work

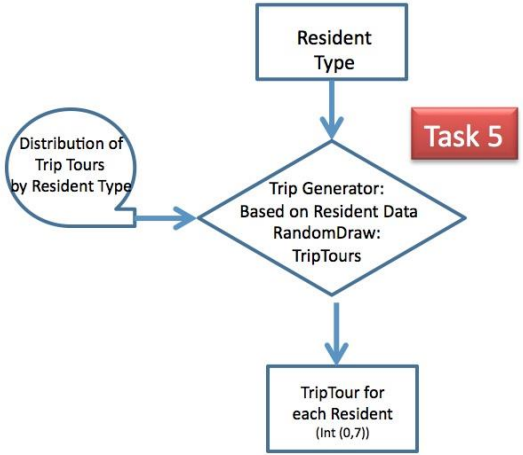
Home (Block Centroid)

School

Pixel Centroid

# Assigning a Daily Activity (Trip) Tour to Each Person

| TripChainType Number | What it looks like | Number of trip ends |
|---|---|---|
| 0 | H | 0 |
| 1 | W H | 2 |
| 2 | H W | 3 |
| 3 | W H | 4 |
| 4 | W H | 4 |
| 5 | H W | 5 |
| 6 | W H | |
| 7 | H W | |




| | Probabilities | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Trip Chain Type | Grade School | Middle School | High School | College Commuter | College on Campus | Worker | Out of State Worker | At Home Worker | Nursing Home & Under 5 |
| 0 | 0.050 | 0.025 | 0.025 | 0.050 | 0.300 | 0.010 | 0.000 | 0.100 | 1.000 |
| 1 | 0.175 | 0.150 | 0.050 | 0.075 | 0.300 | 0.050 | 0.600 | 0.300 | 0.000 |
| 2 | 0.250 | 0.200 | 0.200 | 0.250 | 0.200 | 0.100 | 0.300 | 0.200 | 0.000 |
| 3 | 0.200 | 0.275 | 0.225 | 0.225 | 0.100 | 0.150 | 0.000 | 0.150 | 0.000 |
| 4 | 0.000 | 0.000 | 0.050 | 0.000 | 0.000 | 0.150 | 0.100 | 0.000 | 0.000 |
| 5 | 0.200 | 0.200 | 0.250 | 0.150 | 0.040 | 0.250 | 0.000 | 0.100 | 0.000 |
| 6 | 0.075 | 0.100 | 0.150 | 0.150 | 0.040 | 0.200 | 0.000 | 0.100 | 0.000 |
| 7 | 0.050 | 0.050 | 0.050 | 0.100 | 0.020 | 0.090 | 0.000 | 0.050 | 0.000 |
| **AVG** | **3.625** | **3.850** | **4.150** | **4.000** | **2.140** | **4.480** | **2.500** | **3.150** | **0.000** |

# Created US_PersonTrip file containing..

- **1,009,332,835** individual personTrips
  - Each characterized by a precise
    - **{oLat, oLon, oTime, dLat, dLon, est._dTime, personPointer, tripType (W,S,O)}**

| State | Trip Count | State | Trip Count | State | Trip Count |
|---|---|---|---|---|---|
| Alabama | 15,825,280 | Kentucky | 14,349,637 | North Dakota | 2,196,072 |
| Alaska | 2,397,128 | Louisiana | 8,148,094 | Ohio | 38,087,870 |
| Arizona | 20,903,632 | Maine | 4,429,255 | Oklahoma | 12,262,687 |
| Arkansas | 9,554,065 | Maryland | 19,316,346 | Oregon | 12,730,747 |
| California | 123,852,078 | Massachusetts | 21,866,204 | Pennsylvania | 41,709,485 |
| Colorado | 16,839,860 | Michigan | 32,833,666 | Rhode Island | 3,489,284 |
| Connecticut | 11,850,814 | Minnesota | 11,167,667 | South Carolina | 15,262,810 |
| DC | 2,040,597 | Mississippi | 9,717,958 | South Dakota | 2,627,648 |
| Delaware | 2,970,506 | Missouri | 19,699,659 | Tennessee | 21,096,931 |
| Florida | 61,275,215 | Montana | 3,261,369 | Texas | 83,584,971 |
| Georgia | 32,302,424 | Nebraska | 5,979,671 | Utah | 9,047,267 |
| Hawaii | 4,437,926 | Nevada | 9,048,868 | Vermont | 2,104,664 |
| Idaho | 5,141,420 | New Hampshire | 4,444,770 | Virginia | 26,646,786 |
| Illinois | 42,657,513 | New Jersey | 29,237,285 | Washington | 22,475,312 |
| Indiana | 21,431,504 | New Mexico | 6,779,308 | West Virginia | 6,106,765 |
| Iowa | 9,943,451 | New York | 64,529,719 | Wisconsin | 18,824,313 |
| Kansas | 9,327,336 | North Carolina | 31,638,807 | Wyoming | 1,870,191 |
| **Total** | 1,009,322,835 | | | | |

# 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***

GM / Cruise

**Alphabet / Waymo**

***If so, where, when and at what price should they deploy, as a viable business, their mobility capability? One way, maybe…***

**Amazon / Zoox**

PRINCETON UNIVERSITY

PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

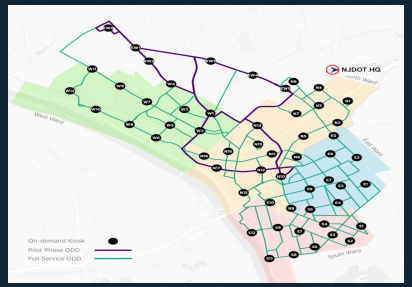
*Framework for **Deployment** of*
*Safe, Equitable, Affordable, Sustainable, High-quality Mobility*

# MOVES-style Deployment

(**M**obility **O**pportunity: **V**ehicle **E**quitable **S**ystem)

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

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


Interconnected to create an

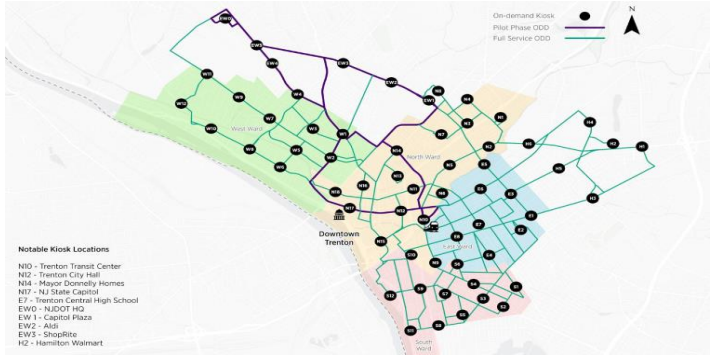
*Automated Transit Network*

MIT Mobility Initiative

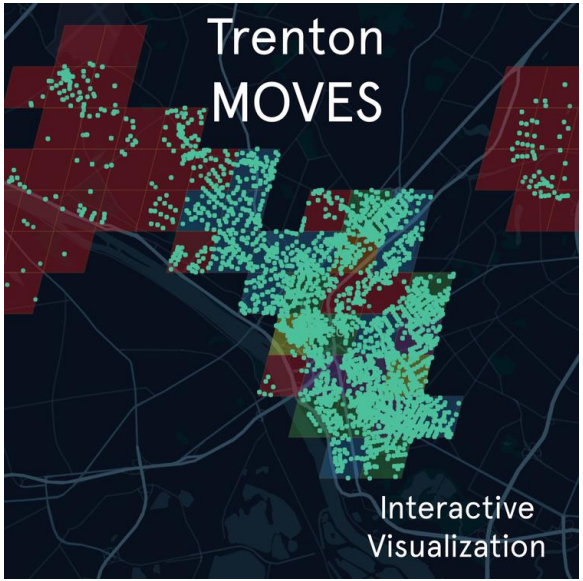
# Example… a Trenton MOVES Kiosk located at Trenton Public Housing's Donnelly Homes

## Trenton MOVES'
## Automated Transit Network
## Transforms
## Affordable Housing to Affordable Living

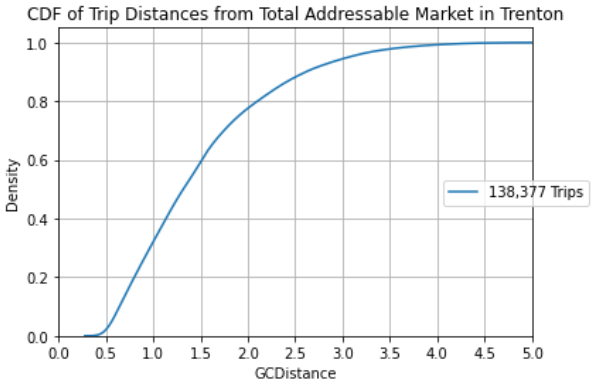
# Inspection of Total Addressable Market (TAM) of Daily personTrips for MOVES-style Automated Transit Network's Operational Design Domain (ODD)

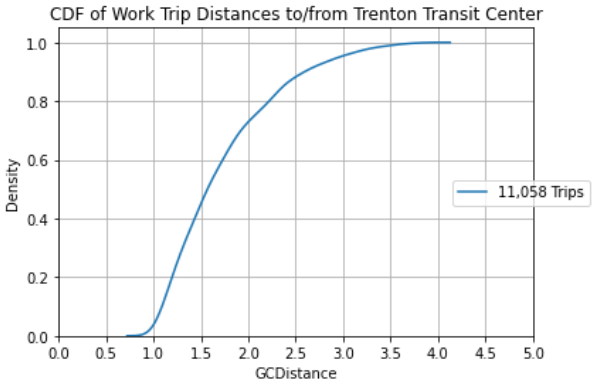


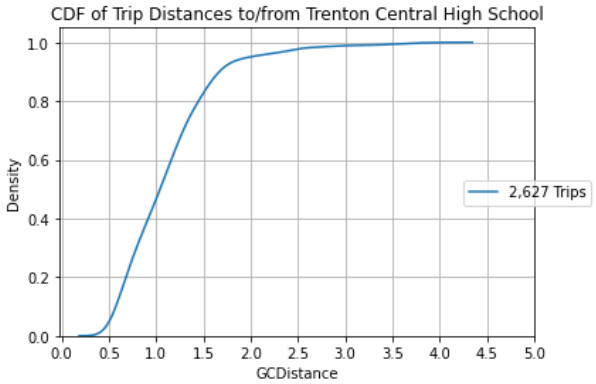

Phase 3 Pilot Operations
100 Vehicles (250 FTE Labor)



# Total Addressable Market's personTrip Length (miles)

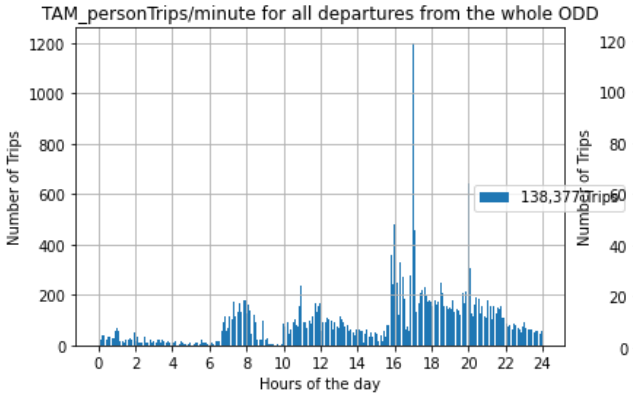


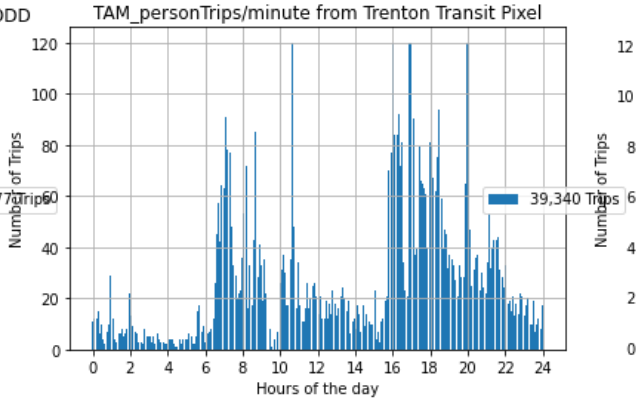



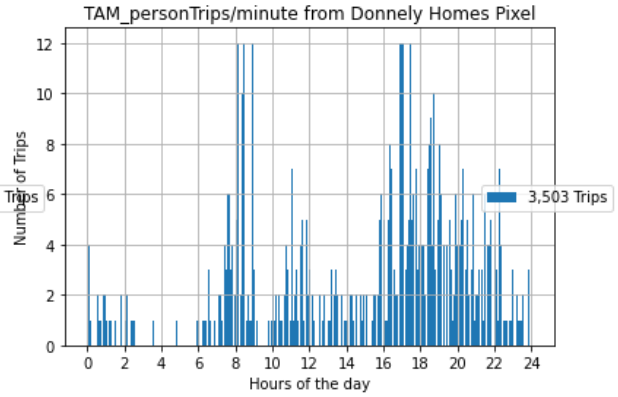



# Total Addressable Market's personTrip Temporal Distributions

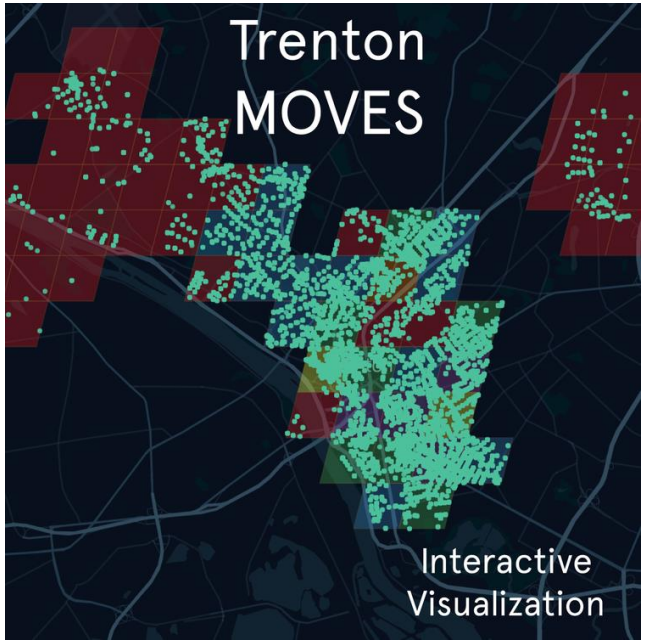
**(personTrip Originations/minute)**



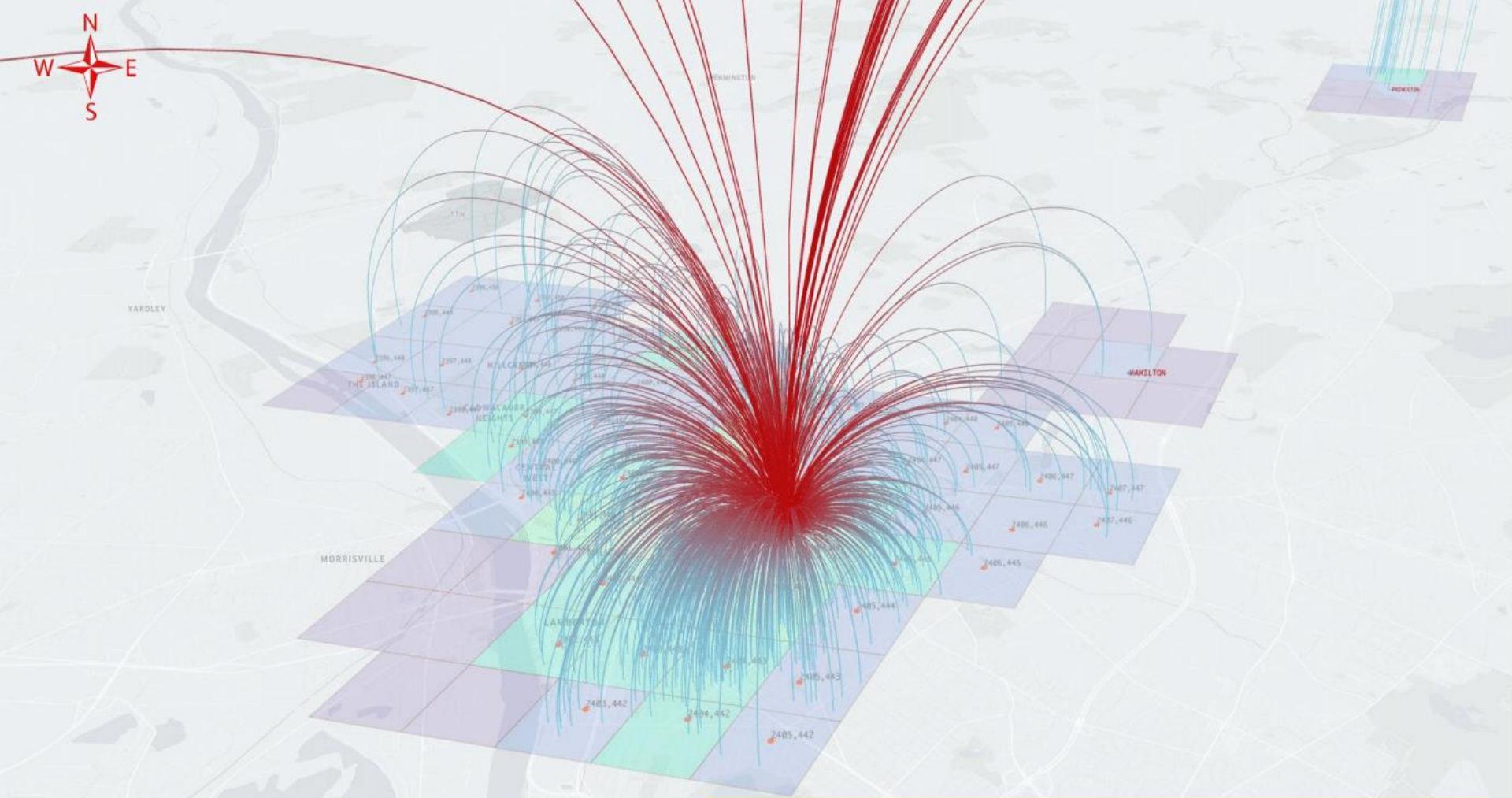



# Total Addressable Market's
# personTrip Spatial Distributions

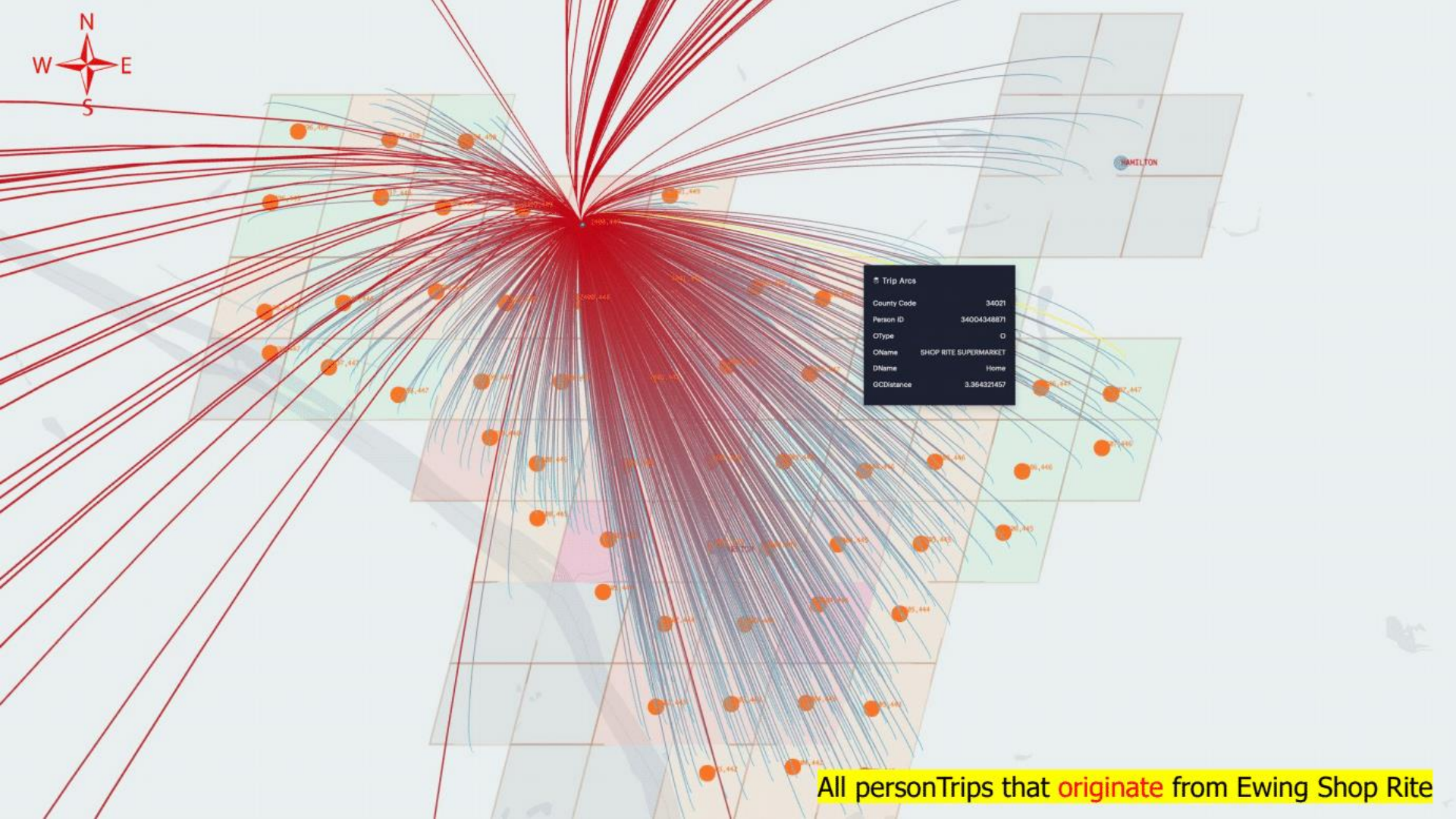



**Trenton MOVES - Interactive Graphic Visualization**

Link to Instructions of Data Layers and Map Operations

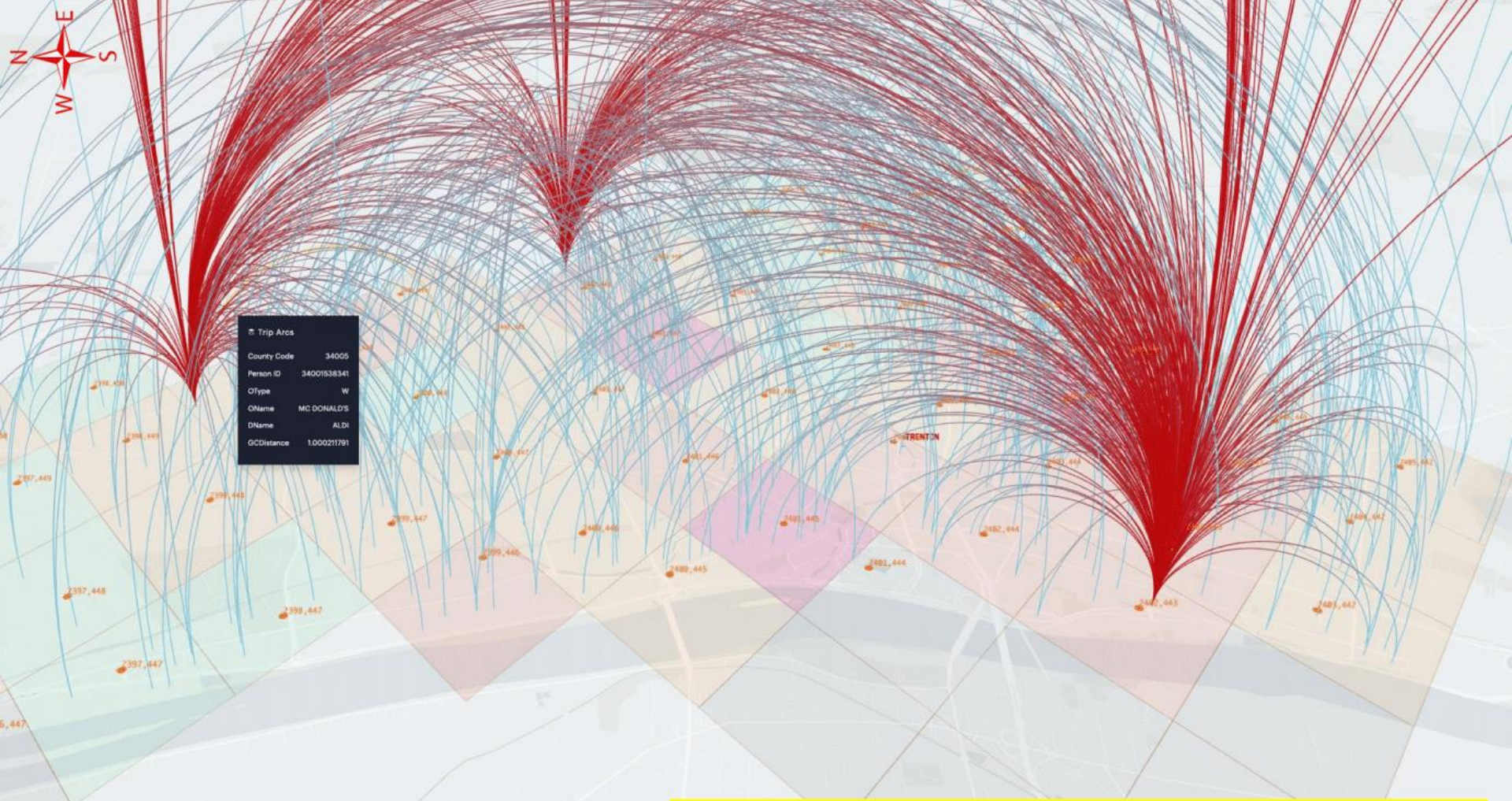


All personTrips that originate from Trenton Central High School



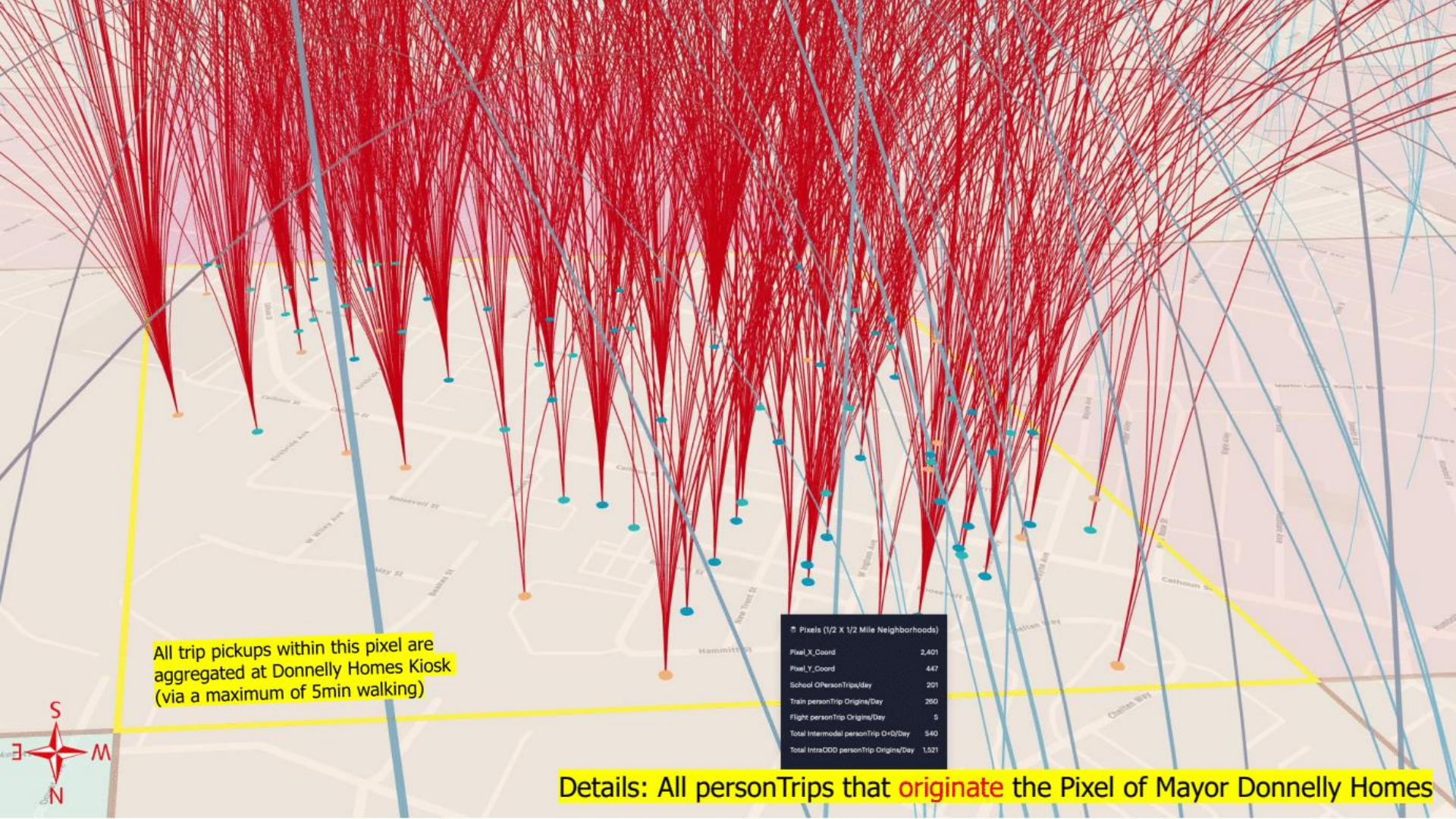

All personTrips that originate from Ewing Shop Rite


All personTrips that originate from Capital Health Regional Center



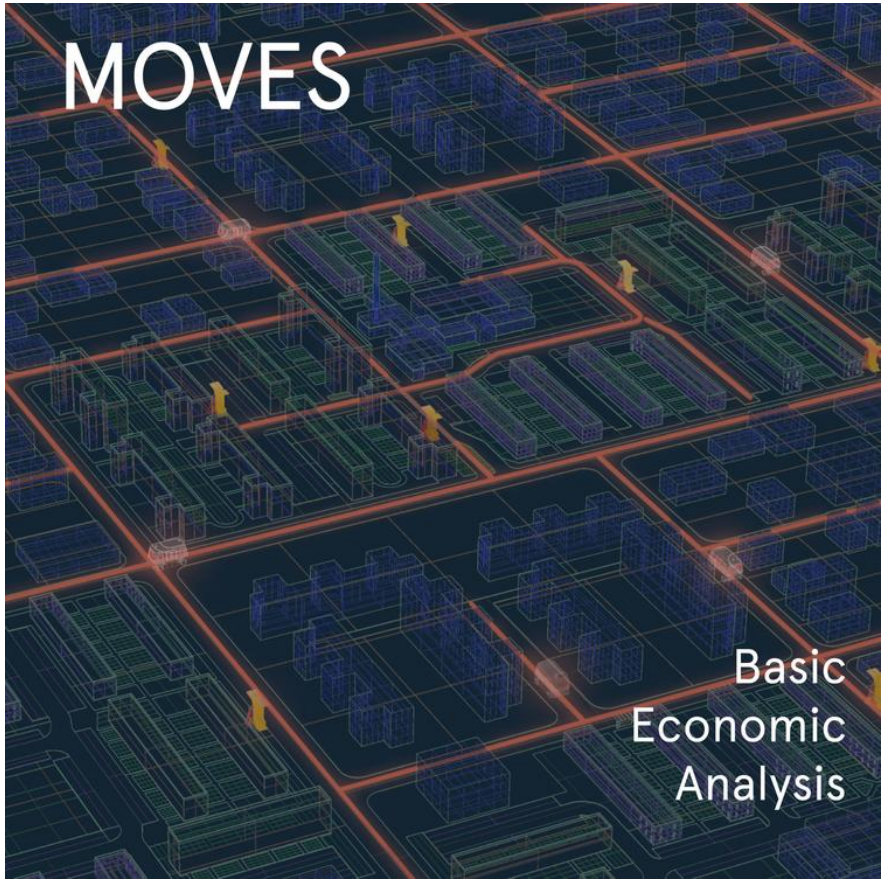

All personTrips that originate from multiple McDonald's in Trenton


All personTrips that originate from the Pixel of Mayor Donnelly Homes



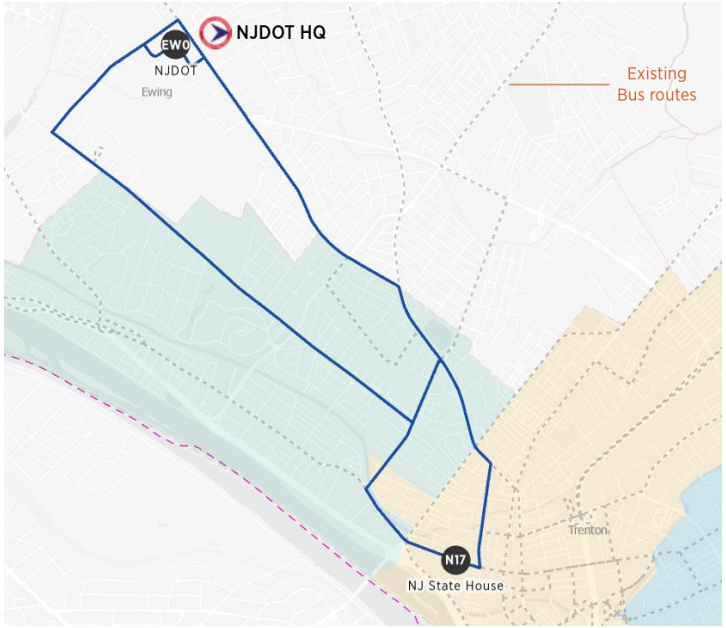

Details: All personTrips that originate the Pixel of Mayor Donnelly Homes

# Basic economic analysis of MOVES-style "safe, equitable, affordable, sustainable, high-quality" mobility systems



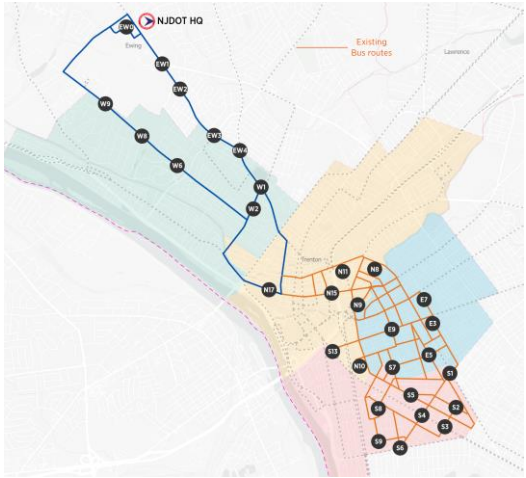
# Proof of Concept & Phase 0 Operations


**Proof of Concept Phase**
2 Vehicles (5 FTE Labor)

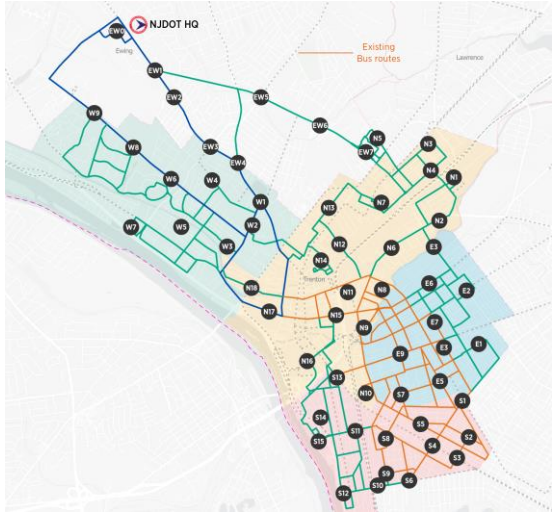



**Phase 0 Pilot Operations**
5 Vehicles (12.5 FTE Labor)

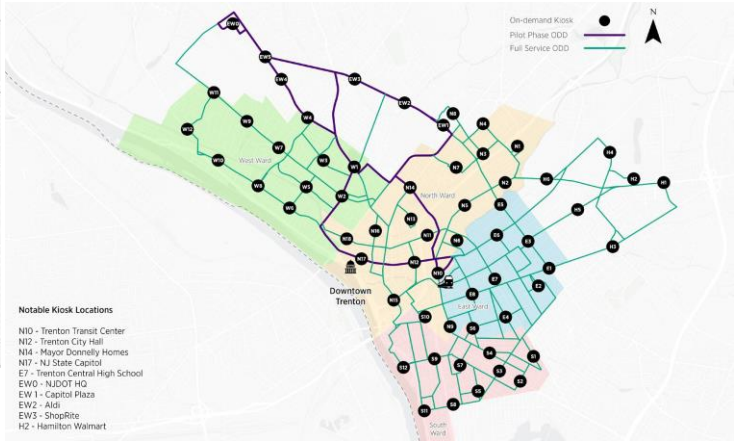
# Phase 1 ,2 & 3 Pilot Operations




**Phase 1 Pilot Operations**
20 Vehicles (50 FTE Labor)

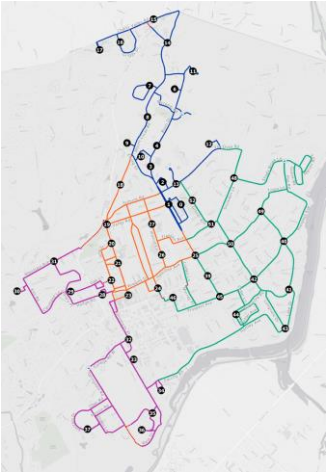



**Phase 2 Pilot Operations**
83 Vehicles (208 FTE Labor)

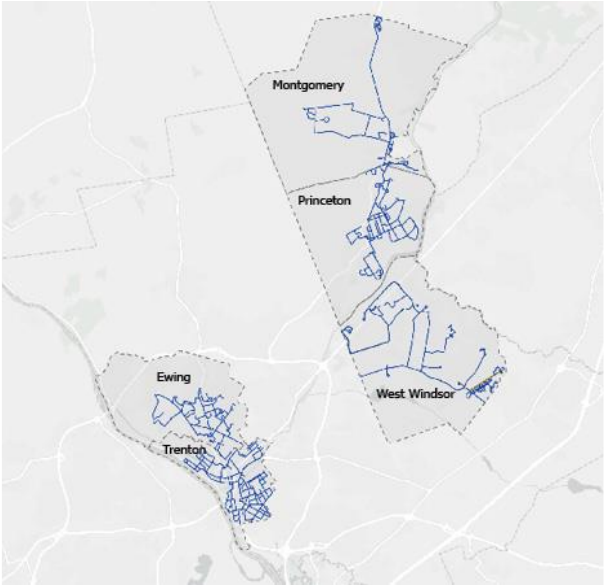


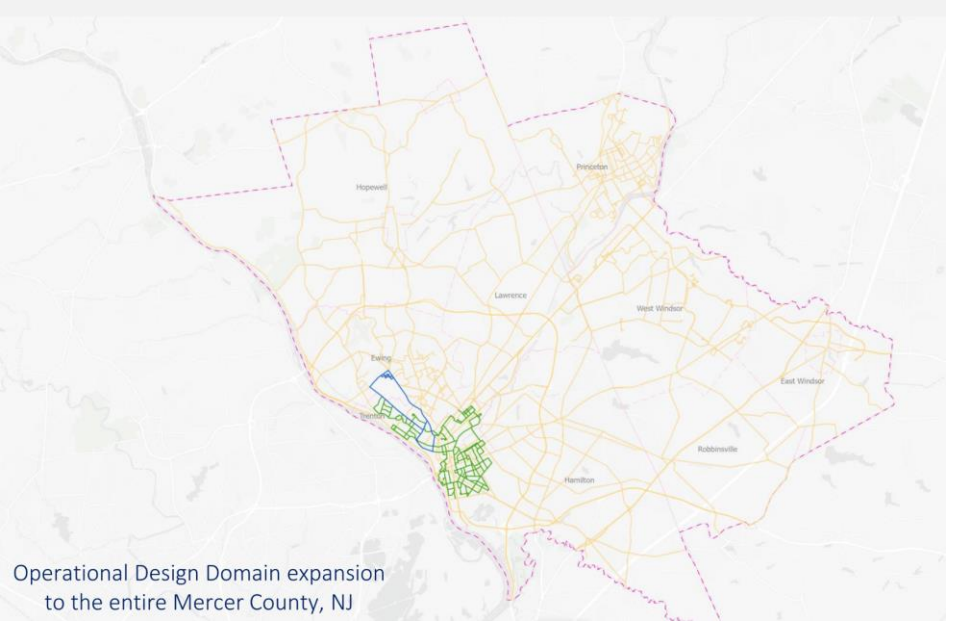

**Phase 3 Pilot Operations**
100 Vehicles (250 FTE Labor)

# Mercer Coputy Expansion Phase



Princeton




Operational Design Domain expansion
to the entire Mercer County, NJ

# The Evolving ODDs

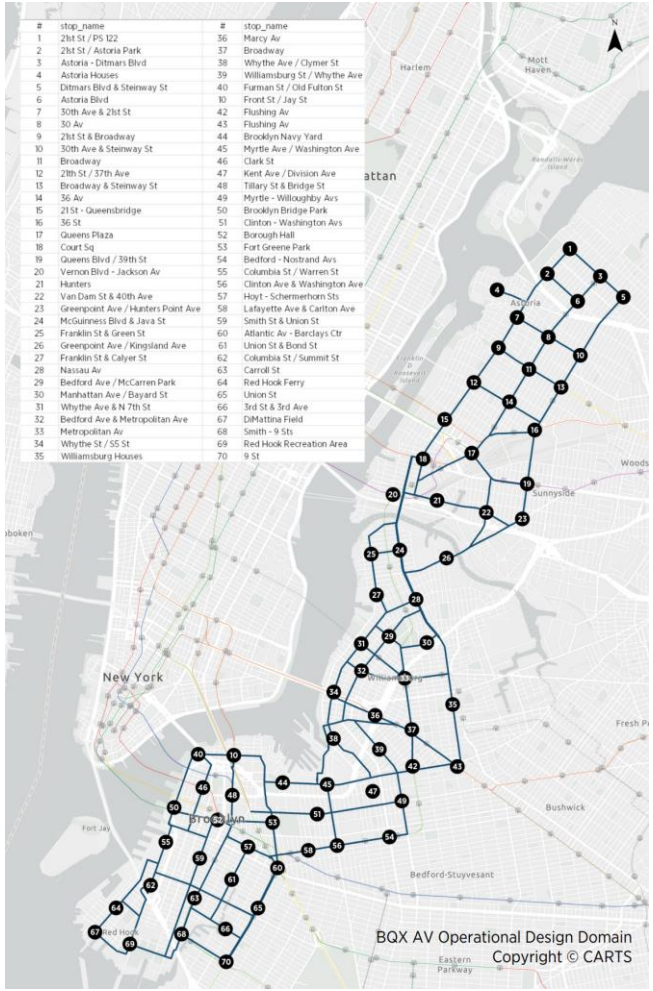
**PHASE IV** *Replication Throughut NJ:* ***Proof*** *of* ***Network-Scale Economics***

# The Evolving ODDs

**PHASE V** *Repliction across US:*
***Delivery** of **Societal Values at Scale***

## *BQX-MOVES*

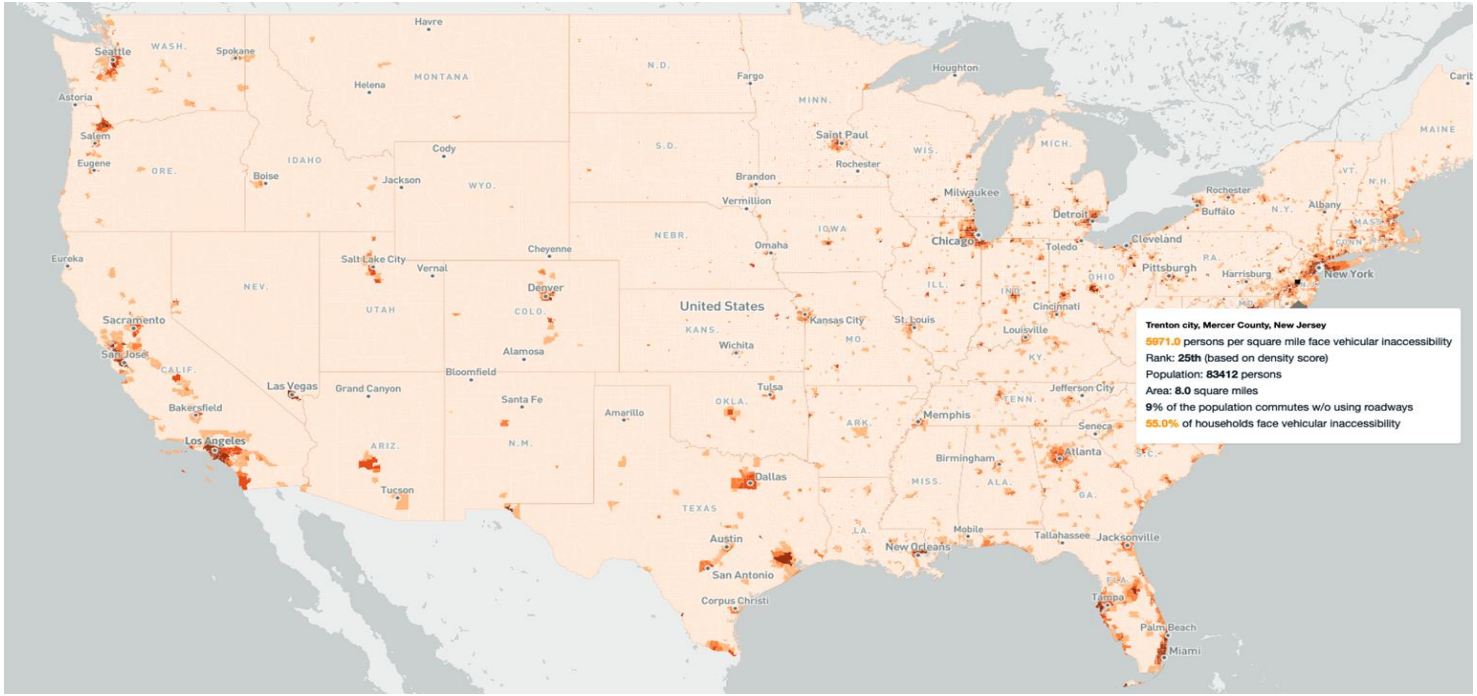
*~ 1M personTrips/Day* ***Total Addresable Market***
***~ 75 Kiosks***
*~500 Vehicles*
*~ 75,000 PersonTrips/Day*




| # | stop_name | # | stop_name |
|---|---|---|---|
| 1 | 21st St / PS 122 | 36 | Marcy Av |
| 2 | 21st St / Astoria Park | 37 | Broadway |
| 3 | Astoria - Ditmars Blvd | 38 | Whythe Ave / Clymer St |
| 4 | Astoria Houses | 39 | Williamsburg St / Whythe Ave |
| 5 | Ditmars Blvd & Steinway St | 40 | Furman St / Old Fulton St |
| 6 | Astoria Blvd | 10 | Front St / Jay St |
| 7 | 30th Ave & 21st St | 42 | Flushing Av |
| 8 | 30 Av | 43 | Flushing Av |
| 9 | 21st St & Broadway | 44 | Brooklyn Navy Yard |
| 10 | 30th Ave & Steinway St | 45 | Myrtle Ave / Washington Ave |
| 11 | Broadway | 46 | Clark St |
| 12 | 21th St / 37th Ave | 47 | Kent Ave / Division Ave |
| 13 | Broadway & Steinway St | 48 | Tillary St & Bridge St |
| 14 | 36 Av | 49 | Myrtle - Willoughby Avs |
| 15 | 21 St - Queensbridge | 50 | Brooklyn Bridge Park |
| 16 | 36 St | 51 | Clinton - Washington Avs |
| 17 | Queens Plaza | 52 | Borough Hall |
| 18 | Court Sq | 53 | Fort Greene Park |
| 19 | Queens Blvd / 39th St | 54 | Bedford - Nostrand Avs |
| 20 | Vernon Blvd - Jackson Av | 55 | Columbia St / Warren St |
| 21 | Hunters | 56 | Clinton Ave & Washington Ave |
| 22 | Van Dam St & 40th Ave | 57 | Hoyt - Schermerhorn Sts |
| 23 | Greenpoint Ave / Hunters Point Ave | 58 | Lafayette Ave & Carlton Ave |
| 24 | McGuinness Blvd & Java St | 59 | Smith St & Union St |
| 25 | Franklin St & Green St | 60 | Atlantic Av - Barclays Ctr |
| 26 | Greenpoint Ave / Kingsland Ave | 61 | Union St & Bond St |
| 27 | Franklin St & Calyer St | 62 | Columbia St / Summit St |
| 28 | Nassau Av | 63 | Carroll St |
| 29 | Bedford Ave / McCarren Park | 64 | Red Hook Ferry |
| 30 | Manhattan Ave / Bayard St | 65 | Union St |
| 31 | Whythe Ave & N 7th St | 66 | 3rd St & 3rd Ave |
| 32 | Bedford Ave & Metropolitan Ave | 67 | DiMattina Field |
| 33 | Metropolitan Av | 68 | Smith - 9 Sts |
| 34 | Whythe St / S5 St | 69 | Red Hook Recreation Area |
| 35 | Williamsburg Houses | 70 | 9 St |

# The Evolving ODDs

**PHASE V** *Repliction across US:* ***Delivery*** *of* ***Societal Values at Scale***




*Source: B.Liang, J.He, A.Kornhauser, "Vehicle Immobility Map of USA", 2021, CARTS*

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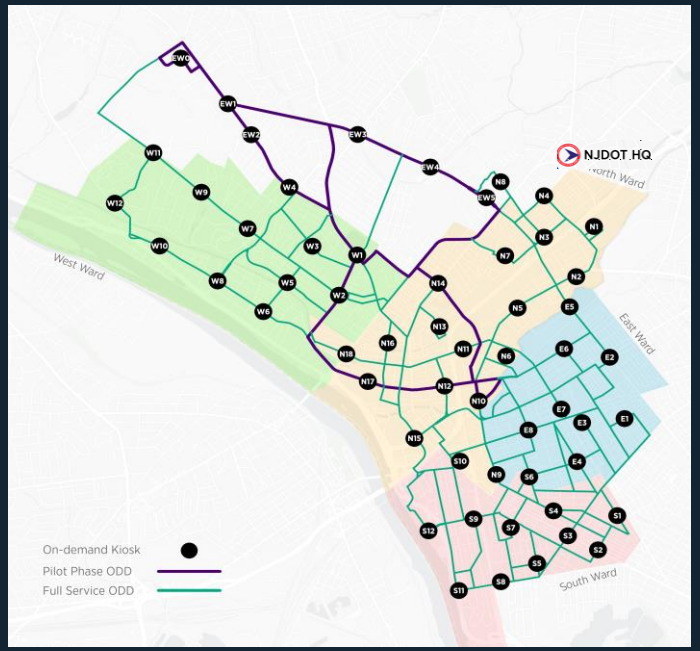
# *Thank you*




MIT Mobility Initiative

MIT Mobility Forum: Envisioning Profitable Autonomous Transit Networks
Alain Kornhauser, 02/17/2023
Annotation by: Nineveh O'Connell

**Part I: Relevant Literature**

Berrada, J., Mouhoubi, I., & Christoforou, Z. (2020). Factors of successful implementation and diffusion of services based on autonomous vehicles: Users' acceptance and operators' profitability. *Research in Transportation Economics*, *83*, 100902.

Dos Santos, F. L. M., Duboz, A., Grosso, M., Raposo, M. A., Krause, J., Mourtzouchou, A., ... & Ciuffo, B. (2022). An acceptance divergence? Media, citizens and policy perspectives on autonomous cars in the European Union. *Transportation Research Part A: Policy and Practice*, *158*, 224-238.

Zhong, S., Liu, A., Jiang, Y. *et al.* Energy and environmental impacts of shared autonomous vehicles under different pricing strategies. *npj Urban Sustain* 3, 8 (2023). https://doi.org/10.1038/s42949-023-00092-2

Fagnant, D. J., & Kockelman, K. M. (2015). *Dynamic ride-sharing and optimal fleet sizing for a system of shared autonomous vehicles* (No. 15-1962).

**Part II: Recent News**

Moye, B. (2023, March 2). *AAA: Fear of Self-Driving Cars on the Rise.* AAA Newsroom. https://newsroom.aaa.com/2023/03/aaa-fear-of-self-driving-cars-on-the-rise/

Kutterer, K. (2023, February 28). *May Mobility and Via formalize plans to transform public transit with AVs*. May Mobility. https://maymobility.com/may-via-extended-partnership/

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

Photopoulos, J. (2020, February 25). *Driverless shuttles: what are we waiting for?* Horizon: The EU Research & Innovation Magazine. https://ec.europa.eu/research-and-innovation/en/horizon-magazine/driverless-shuttles-what-are-we-waiting

**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 you do 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**

B. Liang, J. He, A. Kornhauser. "Vehicle Immobility Map of USA", 2021, CARTS. https://www.cartsmobility.com/vehicularimmobilitymap.

Dais, J. L., & Kornhauser, A. L. (1975). Economic and environmental aspects of personal rapid transit-A further study. *Transportation Research, 9(2-3)*, 149-157. https://doi.org/10.1016/0041-1647(75)90052-0

Chen, C., Seff, A., Kornhauser, A., & Xiao, J. (2015). Deepdriving: Learning affordance for direct perception in autonomous driving. In *Proceedings of the IEEE international conference on computer vision* (pp. 2722-2730).

Chen, C. (2016). *Extracting cognition out of images for the purpose of autonomous driving* (Doctoral dissertation, Princeton University).

Filipowicz, A., Liu, J., & Kornhauser, A. (2017). *Learning to recognize distance to stop signs using the virtual world of Grand Theft Auto 5* (No. 17-05456).

Kornhauser, A. (2012). Synthesizing Individual Travel Demand in New Jersey.