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Smart Driving Cars:

Transit Opportunity

of NHTSA Level 4 Driverless Vehicles

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Princeton University

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TRB Automated Vehicle Workshop
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Palo Alto, CA

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TRANSPORTATION RESEARCH BOARD WORKSHOP ON ROAD VEHICLE AUTOMATION

PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

Fundamental Value of Driverless Technology

- Eliminates the Labor variable cost of transit service.
  - Not that significant for vehicles serving many passengers simultaneously.
    - Unfortunately, very little travel demand is sufficiently correlated that it can be effectively served simultaneously
      - For example, the small percentage of bus users need to walk, wait and transfer in order to be sufficiently correlated to utilize the capacity of buses in the peak hours in the peak directions. The rest of the time, they are essentially empty.
  - Very significant for vehicles serving few if any passengers simultaneously
    - The norm simply because there exists insufficient correlation in travel demand
      - Very few people want to go from about the same place at about the same time heading to locations that are sufficiently correlated such that they could be encouraged to travel together.
      - The opportunity of driverless vehicles is consequently directly tied to the correlation of travel demand

How Correlated is Travel Demand?

- Aggregate Data on Travel Patterns suggest that it is very uncorrelated
  - Transit entrepreneurs and public agencies that could thrive in correlated situations struggle
  - The personal auto industry that could serve correlated trips thrives on serving individual trips irrespective of possible correlations.
    - Each car serves essentially only one fundamental travel demand. If the vehicle happens to be occupied by more than one person, then the others in the vehicle are essentially "along for the ride" and not satisfying their fundamental travel demand
      - One person is chauffeuring the other person
      - Family members traveling together to satisfy a common travel purposes
      - Rarely is it two independent individuals that just happened to have correlated origin, origin time, and destination.
        - » Thus, fundamental Av Vehicle Occupancy for the personal car is ~ 1.0
- Are there independent individuals that have correlated travel demand that could be served simultaneously?

Are there independent individuals that have correlated travel demand that could be served simultaneously?

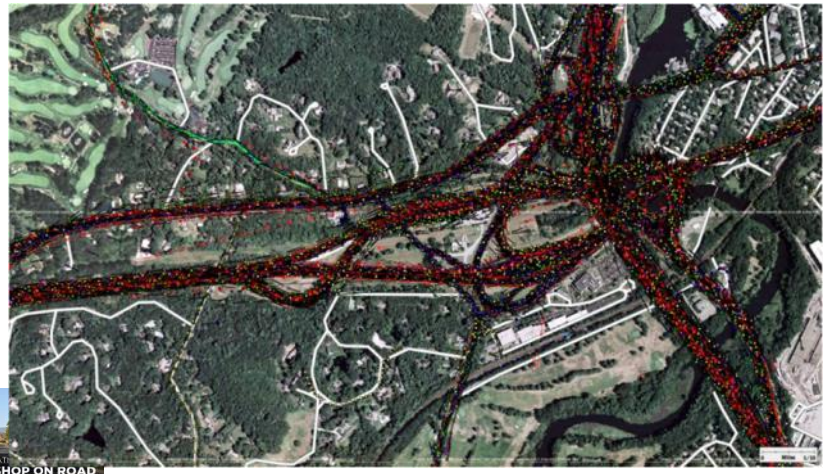
- Existing travel demand data is insufficiently precise to address this question

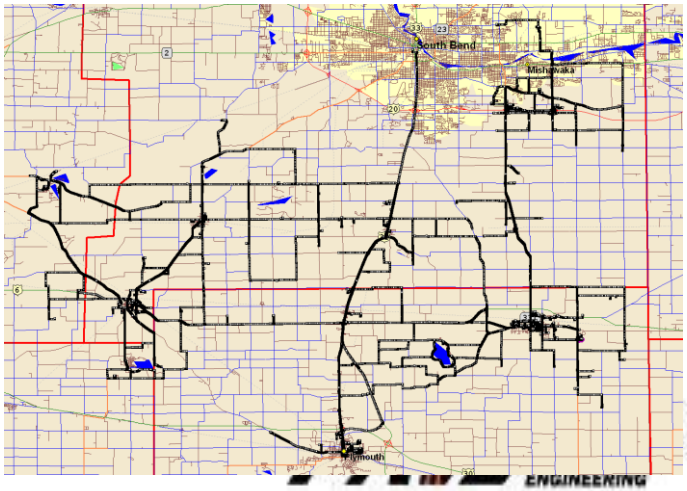
Most every day…

- Almost 9 Million NJ residents
- 0.25 Million of out of state commuters
- Make 30+ Million trips
- Throughout the 8,700 sq miles of NJ
- Where/when do they start?
- Where do they go?
- Does anyone know???
  - I certainly don't
    - Not to sufficient precision for credible analysis

I've Tried…

- I've harvested one of the largest troves of GPS tracks
  - Literally billions of individual trips,
  - Unfortunately, they are spread throughout the western world, throughout the last decade.
  - Consequently, I have only a very small ad hoc sample of what happens in NJ on a typical day.





Are there independent individuals that have correlated travel demand that could be served simultaneously?

- Existing travel demand data is insufficiently precise to address this question
- Developed a trip synthesizer that generates sufficiently precise data to address this issue

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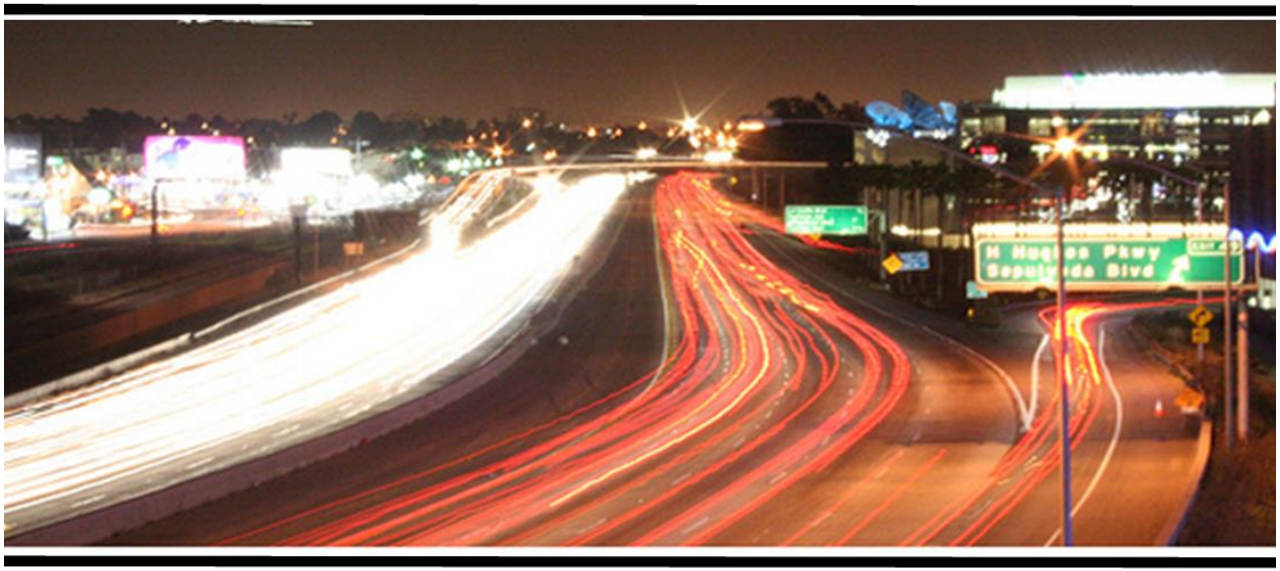
Synthesizing Individual Travel Demand in New Jersey

Trips everyone in NJ wants/needs to make on a typical day



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January, 2012

TRANSPORTATION RESEARCH BOARD WORKSHOP ON ROAD VEHICLE AUTOMATION

PRINCETON AUTONOMOUS VEHICLE ENGINEERING

Trip Synthesizer

- Motivation – Publicly available travel demand data do not contain:
  - Spatial precision
    - Where are people leaving from?
    - Where are people going?
  - Temporal precision
    - At what time are they travelling?

Why do I want to know **every** trip?

- Academic Curiosity
- If offered an alternative, which ones would likely "buy it" and what are the implications.
- More specifically:
  - If an alternative transport system were available, which trips would be diverted to it and what operational requirements would those trip impose on the new system?
- In the end…
  - a transport system serves **individual** decision makers. It's patronage is an **ensemble of individuals**,
  - I would prefer analyzing each individual trip patronage opportunity.

PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

Synthesize from publically available data:

- "every" NJ Traveler on a typical day **NJ_Resident file**
  - Containing appropriate demographic and spatial characteristics that reflect trip making

- "every" trip that each Traveler is likely to make on a typical day. **NJ_PersonTrip file**
  - Containing appropriate spatial and temporal characteristics for each trip

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Creating the **NJ_Resident** file

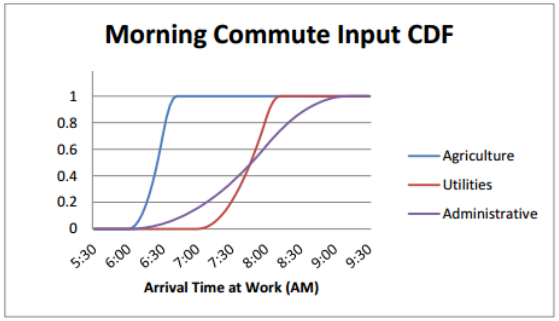
for “every” NJ Traveler on a typical day

NJ_Resident file

Start with Publically available data:

United States Census 2010

AMERICAN COMMUNITY SURVEY
U.S. CENSUS BUREAU

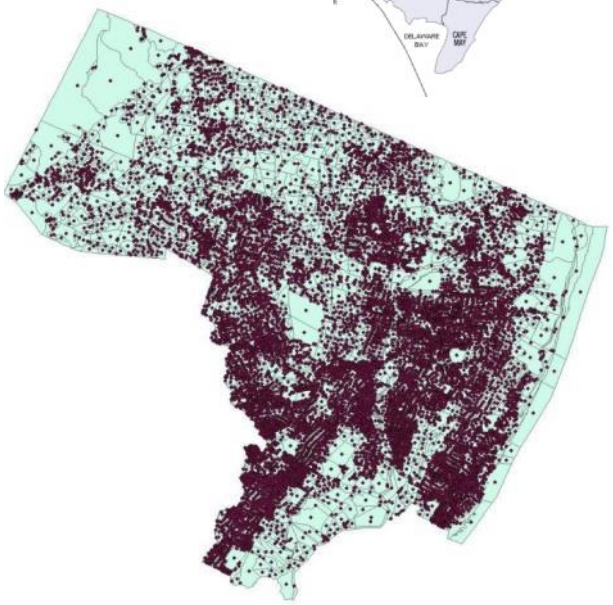


TRANSPORTATION RESEARCH BOARD WORKSHOP ON ROAD VEHICLE AUTOMATION

PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

2010 Population census @Block Level

– 8,791,894 individuals distributed 118,654 Blocks.



County	Population	Census Blocks	Median Pop/ Block	Average Pop/Block
ATL	274,549	5,941	26	46
BER	905,116	11,171	58	81
BUR	448,734	7,097	41	63
CAM	513,657	7,707	47	67
CAP	97,265	3,610	15	27
CUM	156,898	2,733	34	57
ESS	783,969	6,820	77	115
GLO	288,288	4,567	40	63
HUD	634,266	3,031	176	209
HUN	128,349	2,277	31	56
MER	366,513	4,611	51	79
MID	809,858	9,845	50	82
MON	630,380	10,067	39	63
MOR	492,276	6,543	45	75
OCE	576,567	10,457	31	55
PAS	501,226	4,966	65	101
SAL	66,083	1,665	26	40
SOM	323,444	3,836	51	84
SUS	149,265	2,998	28	50
UNI	536,499	6,139	61	87
WAR	108,692	2,573	23	42
Total	8,791,894	118,654		74.1

Publically available data:

- Distributions of Demographic Characteristics
  - Age
  - Gender
  - Household size
  - Name (Last, First)

Ages (varying linearly over interval):	input:	output:
[0,49]	67.5%	67.5%
[50,64]	18.0%	17.9%
[65,79]	12.0%	12.1%
[80,100]	2.5%	2.5%

Gender:	Input:	Output:
female	51.3%	51.3%

Household:	Size:	Probability:	cdf:	Expectation:
couple	2	0.30	0.300	0.6
couple + 1	3	0.08	0.380	0.24
couple + 2	4	0.06	0.440	0.24
couple + 3	5	0.04	0.480	0.2
couple + 4	6	0.04	0.520	0.24
couple + grandparent:	3	0.01	0.525	0.015
single woman	1	0.16	0.685	0.16
single mom + 1	2	0.07	0.755	0.14
single mom + 2	3	0.05	0.805	0.15
single mom + 3	4	0.03	0.835	0.12
single mom + 4	5	0.03	0.865	0.15
single man	1	0.12	0.985	0.12
single dad + 1	2	0.01	0.990	0.01
single dad + 2	3	0.005	0.995	0.015
single dad + 3	4	0.005	1.000	0.02
				2.42

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Final NJ_Resident file

- Home County
- Person Index
- Household Index
- Full Name
- Age
- Gender
- Worker Type Index
- Worker Type String
- Home lat, lon
- Work or School lat,lon
- Work County
- Work or School Index
- NAICS code
- Work or School start/end time

ATL	274,549
BER	905,116
BUR	448,734
CAM	513,657
CAP	97,265
CUM	156,898
ESS	783,969
GLO	288,288
HUD	634,266
HUN	128,349
MER	366,513
MID	809,858
MON	630,380
MOR	492,276
OCE	576,567
PAS	501,226
SAL	66,083
SOM	323,444
SUS	149,265
UNI	536,499
WAR	108,692
NYC	86,418
PHL	18,586
BUC	99,865
SOU	13,772
NOR	5,046
WES	6,531
ROC	32,737
Total:	9,054,849

0	1	1	PREVILLE	RICHARD	24	FALSE	5	worker	39.43937	-74.4951								22	0	39.95234	-75.1638	0	31162.18	28494.57
0	2	1	PREVILLE	JACK J.	7	FALSE	0	grade sch	39.43937	-74.4951	H. Ashton	PUBLIC E	39.43596	-74.4953	0.24 miles	32100	55800	7	0	0	0	0	0	0
0	3	1	PREVILLE	CHARLES	1	FALSE	7	under 5	39.43937	-74.4951								0	0	0	0	0	0	0
0	4	2	DEVEREU	SUE B.	24	TRUE	6	at-home w	39.43937	-74.4951								0	0	0	0	0	0	0
0	5	2	DEVEREU	ANTON F	2	FALSE	7	under 5	39.43937	-74.4951								0	0	0	0	0	0	0
0	6	2	DEVEREU	KATIE S.	6	TRUE	0	grade sch	39.43937	-74.4951	H. Ashton	PUBLIC E	39.43596	-74.4953	0.24 miles	32100	55800	0	0	0	0	0	0	0
0	7	3	WHEDBE	LINDA C.	26	TRUE	6	at-home w	39.43937	-74.4951								0	0	0	0	0	0	0
0	8	4	CARVER	ROBERT	24	FALSE	5	worker	39.43937	-74.4951								0	10101	39.44931	-74.4742	721	31392.93	31707.57
0	9	4	CARVER	JENNIFEF	25	TRUE	6	at-home w	39.43937	-74.4951								9	0	0	0	0	0	0
0	10	5	TINSLEY	ELLEN U	23	TRUE	4	college; o	40.85646	-74.1978	Montclair	NON_COL	40.8538	-74.2003	Within Ca	36000	59400	0	0	0	0	0	0	0

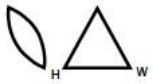
TRANSPORTATION RESEARCH BOARD
WORKSHOP ON ROAD VEHICLE AUTOMATION

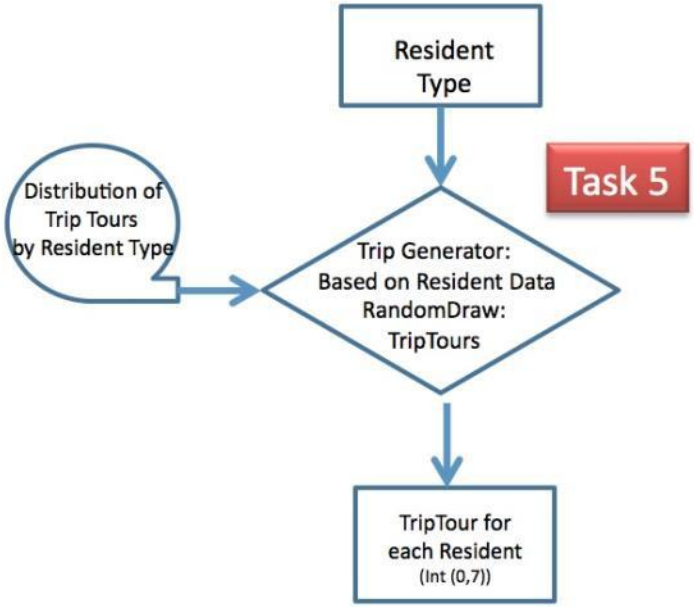
ENGINEERING

Overview of Trip Synthesis

1. Generate individuals comprising the population
2. Assign workers to work places
3. Assign kids to schools
4. Assign tours / activity patterns
5. Assign other trips
6. Assign arrival / departure times

Assigning a Daily Activity (Trip) Tour to Each Person

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



	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**

NJ_PersonTrip file

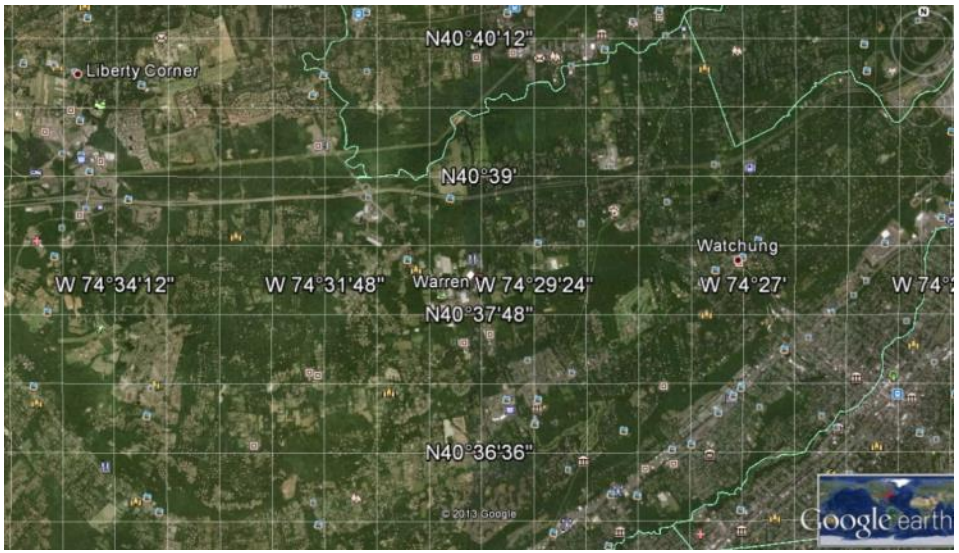
Home County	All Trips Trips #	TripMiles Miles	AverageTM Miles
ATL	936,585	27,723,931	29.6
BER	3,075,434	40,006,145	13.0
BUC	250,006	9,725,080	38.9
BUR	1,525,713	37,274,682	24.4
CAM	1,746,906	27,523,679	15.8
CAP	333,690	11,026,874	33.0
CUM	532,897	18,766,986	35.2
ESS	2,663,517	29,307,439	11.0
GLO	980,302	23,790,798	24.3
HUD	2,153,677	18,580,585	8.6
HUN	437,598	13,044,440	29.8
MER	1,248,183	22,410,297	18.0
MID	2,753,142	47,579,551	17.3
MON	2,144,477	50,862,651	23.7
MOR	1,677,161	33,746,360	20.1
NOR	12,534	900,434	71.8
NYC	215,915	4,131,764	19.1
OCE	1,964,014	63,174,466	32.2
PAS	1,704,184	22,641,201	13.3
PHL	46,468	1,367,405	29.4
ROC	81,740	2,163,311	26.5
SAL	225,725	8,239,593	36.5
SOM	1,099,927	21,799,647	19.8
SOU	34,493	2,468,016	71.6
SUS	508,674	16,572,792	32.6
UNI	1,824,093	21,860,031	12.0
WAR	371,169	13,012,489	35.1
WES	16,304	477,950	29.3
Total	**32,862,668**	**590,178,597**	**19.3**

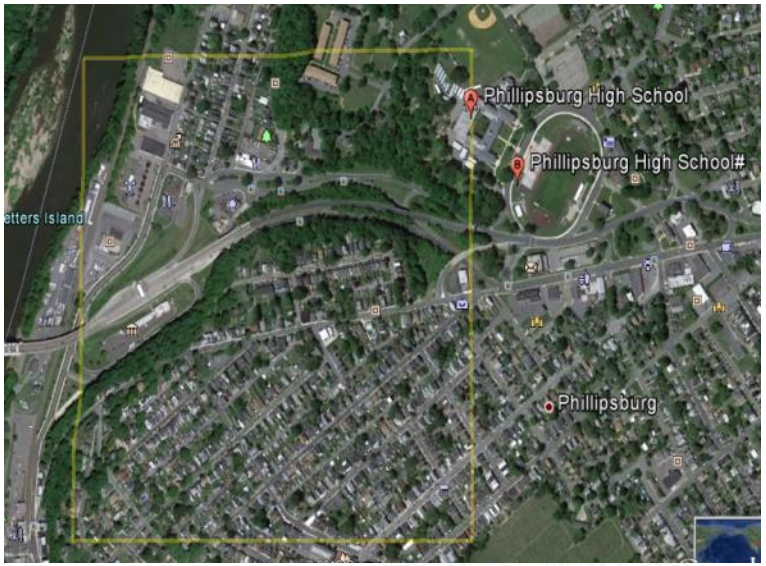
- **9,054,849** records
  - One for each person in **NJ_Resident** file
- Specifying **32,862,668** Daily Person Trips
  - Each characterized by a precise
    - Origination, Destination and Departure Time

Warren County

Population: 108,692

Warren County Summary Data	
Item	Value
Area (mi²)	363
# of Pixels Generating at Least One O_Trip	1,027
Area of Pixels (mi²)	257
% of Open Space	29.2%
# of Pixels Generating 95% of O_Trips	484
# of Pixels Generating 50% of O_Trips	45
# of Intra-Pixel Trips	4,116
# of O_Walk Trips	19,606
# of All O_Trips	317,325
Avg. All O_TripLength (miles)	22.8
# of O_aTaxi Trips	293,603
Avg. O_aTaxiTripLength (miles)	24.6
Median O_aTaxiTripLength (miles)	22.0
95% O_aTaxiTripLength (miles)	41.5





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Uncongested Mobility for All

New Jersey's Area-wide aTaxi System

ORF 467

Professor Alain L.Kornhauser

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Philip Oasis '13
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Alice Lin '14
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Hannah Rajeshwar '14
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Charquia Wright '14
Kristin Bergeson '15
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Roger Sperry '15
Andrew Swoboda '15

Operations Research and Financial Engineering
Princeton University

Fall 2012 - 2013

Focus of Analysis:

- **what is the ride-share potential?**
- **Ridesharing delivers:**
  - Congestion relief
  - Energy savings
  - Reduced costs/passenger
  - Environmental sustainability

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PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

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"Pixelated" New Jersey

("1/2 mile square; 0.25mi^2)

aTaxi Concept – (PRT) Model
Personal Rapid Transit Model

- aTaxis operate between aTaxiStands
  - Autonomous vehicles wait for walk-up customers
  - Located in "center" of each pixel (max ¼ mile walk)
  - Departure is Delayed to facilitate ride-sharing
  - Vehicles are shared to Common Pixel destinations

aTaxi Concept – SPT Model
Smart Para Transit Model

- aTaxis circulate to pick up riders in 9-Pixel area (1.5 miles on side)
  - Vehicles are shared to Common 9-Pixel Destinations

PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

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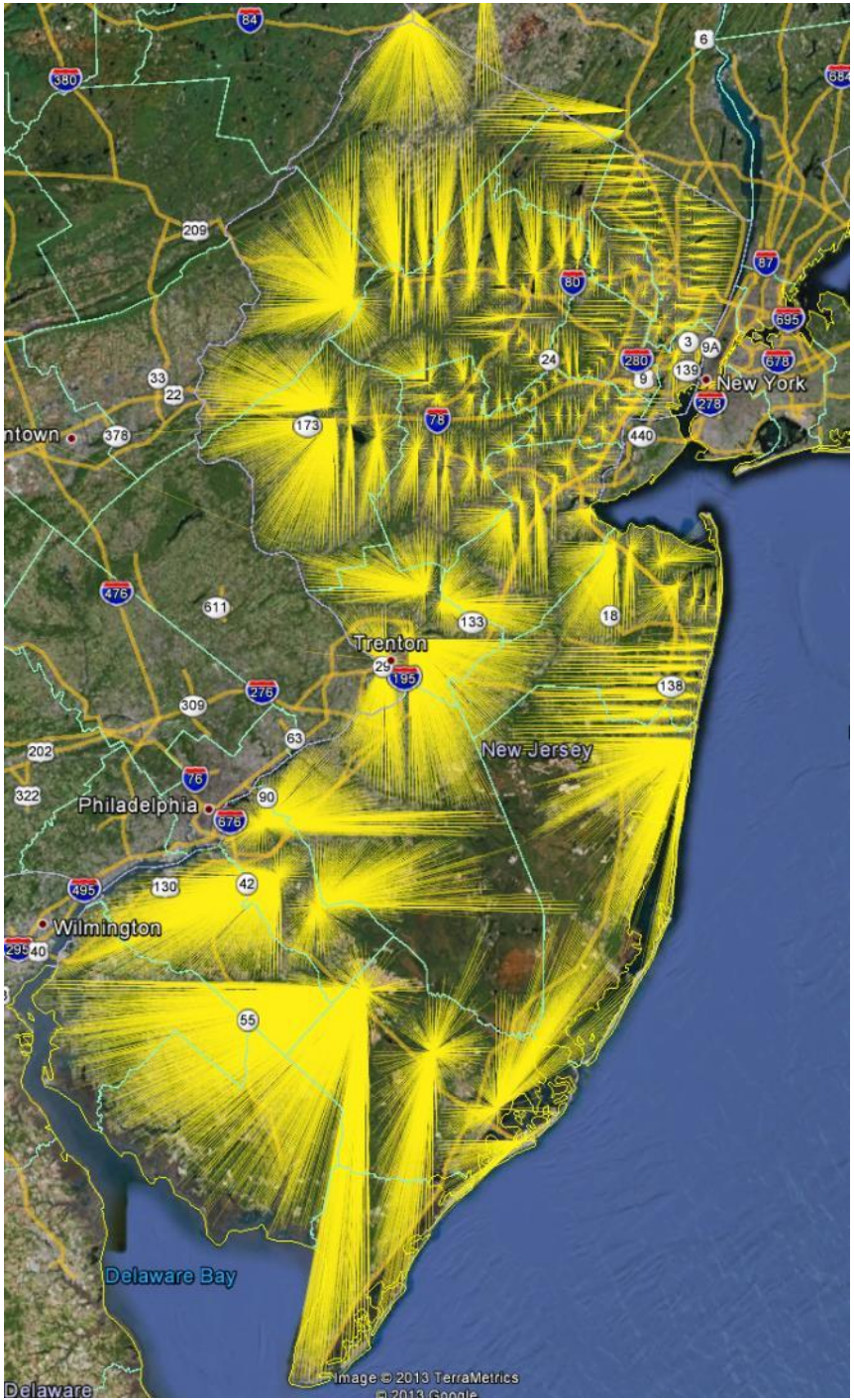

NJ Transit Train Station "Consumer-shed"

TRANSPORTATION RESEARCH BOARD WORKSHOP ON ROAD VEHICLE AUTOMATION

PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

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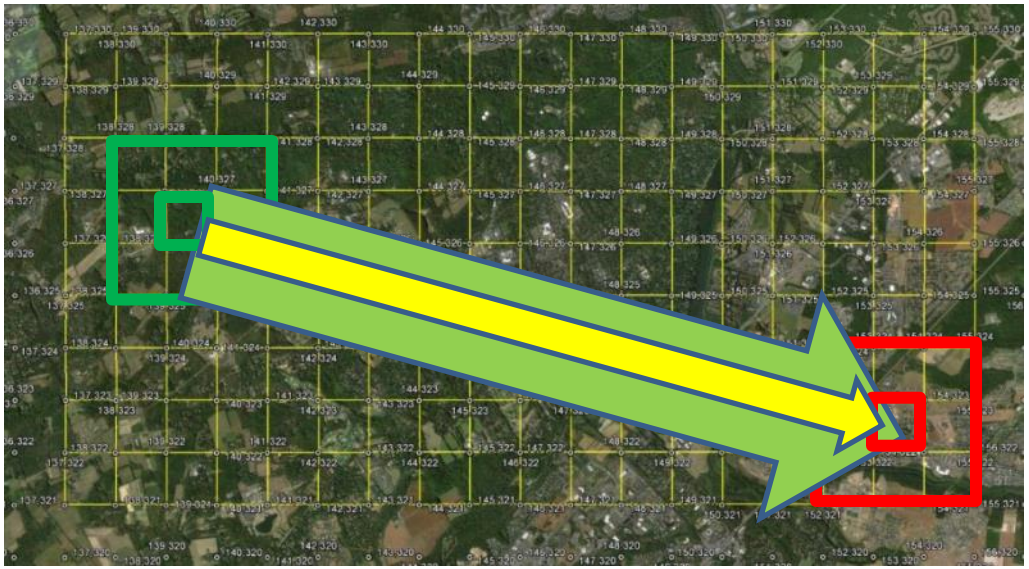
"Pixelated" New Jersey
("1/2 mile square; 0.25mi^2)

aTaxi Concept – (PRT) Model
Personal Rapid Transit Model



aTaxi Concept – SPT Model
Smart Para Transit Transit Model

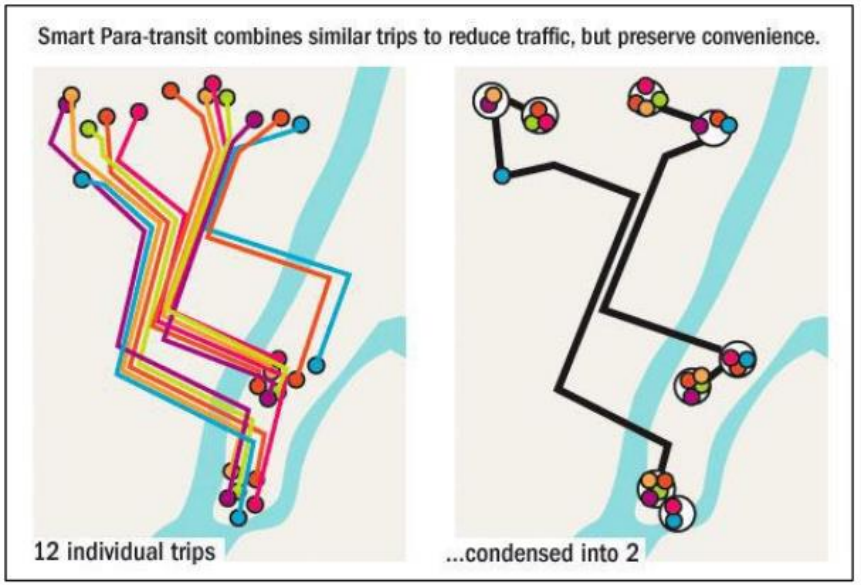


Figure 27: Representation of Mark Gorton's Smart Para-Transit System[93]

Ref: http://orfe.princeton.edu/~alaink/Theses/2013/Brownell,%20Chris%20Final%20Thesis.pdf

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New Jersey Summary Data

Item	Value
Area (mi²)	8,061
# of Pixels Generating at Least One O_Trip	21,643
Area of Pixels (mi²)	5,411
% of Open Space	32.9%
# of Pixels Generating 95% of O_Trips	9,519
# of Pixels Generating 50% of O_Trips	1,310
# of Intra-Pixel Trips	447,102
# of O_Walk Trips	1,943,803
# of All O_Trips	32,862,668
Avg. All O_TripLength (miles)	19.6
# of O_aTaxi Trips	30,471,763
Avg. O_aTaxiTripLength (miles)	20.7
Median O_aTaxiTripLength (miles)	12.5
95% O_aTaxiTripLength (miles)	38.0

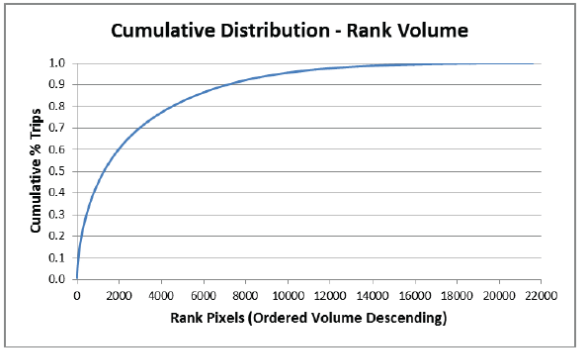


Figure 4.14: NJ State - Cumulative Distribution by Rank of Volume of Pixel.

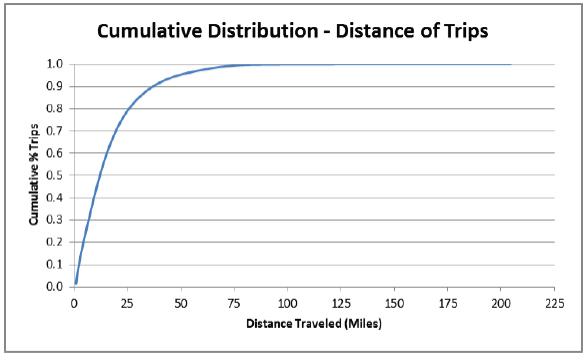


Figure 4.15: NJ State - Cumulative Distribution of Distance Traveled.

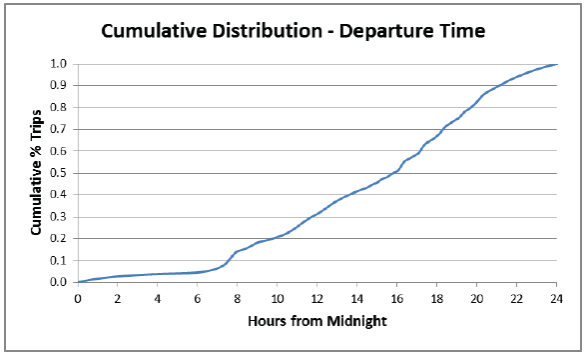
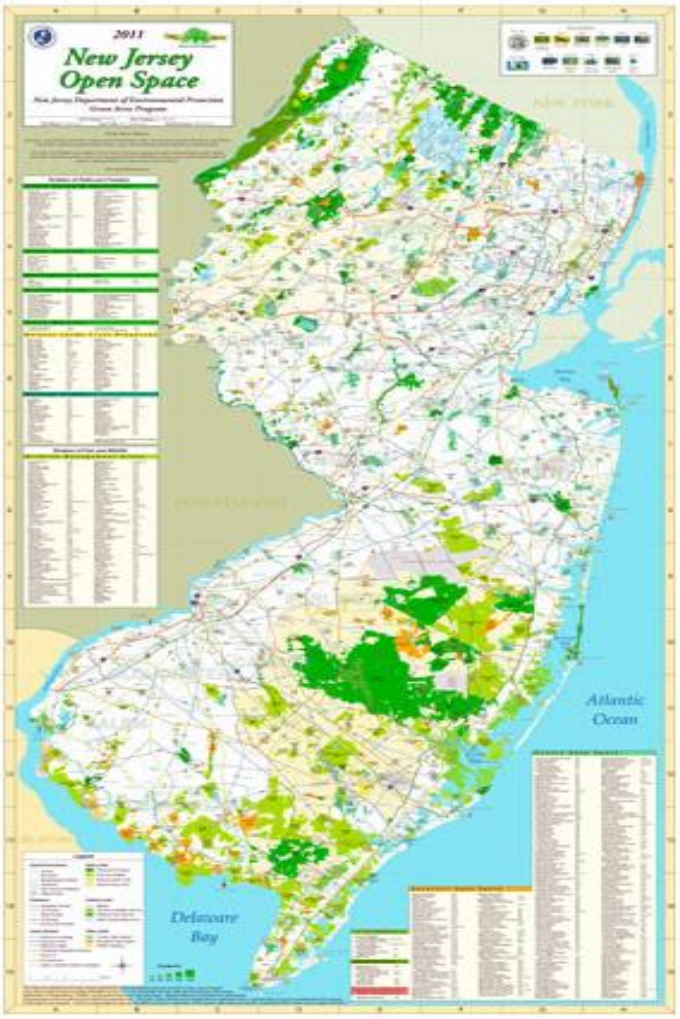


Figure 4.13: NJ State - Cumulative Distribution by Departure Time.

PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING


2011
New Jersey
Open Space
Atlantic
Ocean
Delaware
Bay


New Yo
Philadelphia
New Jersey
Delaware Bay
Delaware
© 2013 Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO

State-wide automatedTaxi (aTaxi)

- Serves essentially all NJ travel demand (32M trips/day)
- Shared ridership potential:

Statewide Occupancy for $(q_{max} = \infty); (t_{max} = 5\ min)$			
Model	**Total Person-Trips**	**Total Taxi Trips**	**Average Occupancy**
PRT	32,770,528	25,824,326	1.269
SPT	32,770,528	15,174,736	2.160

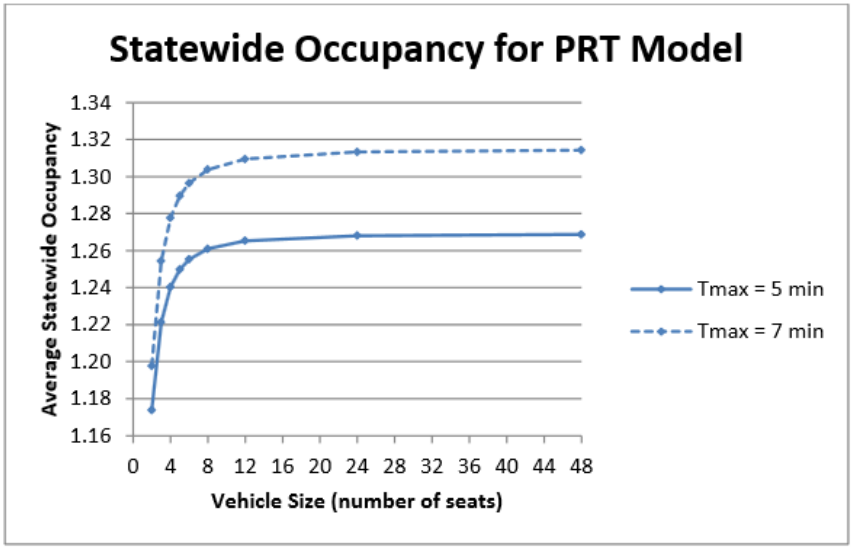


Figure 35: Statewide Occupancy for PRT Model Given Variable q_{max}

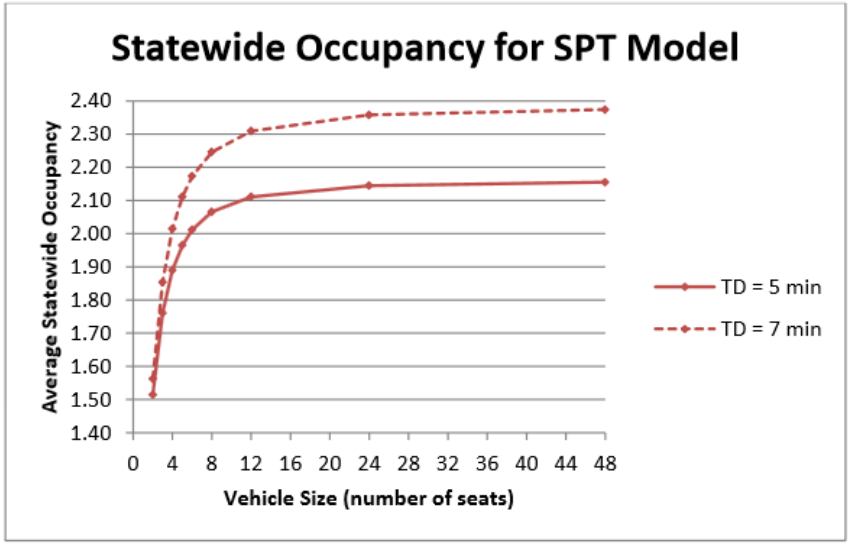


Figure 36: Statewide Occupancy for SPT Model Given Variable q_{max}

State-wide automatedTaxi (aTaxi)

- Serves essentially all NJ travel demand (32M trips/day)
- Shared ridership potential:

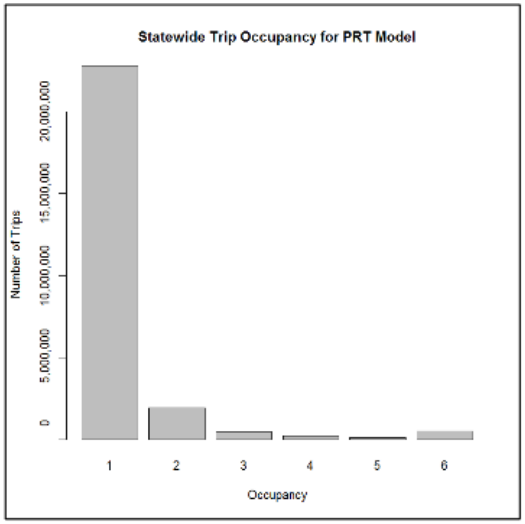


Figure 37: Histogram of Taxi Trip Occupancies for $(q_{max} = 6)$; $(t_{max} = 5)$ in PRT Model

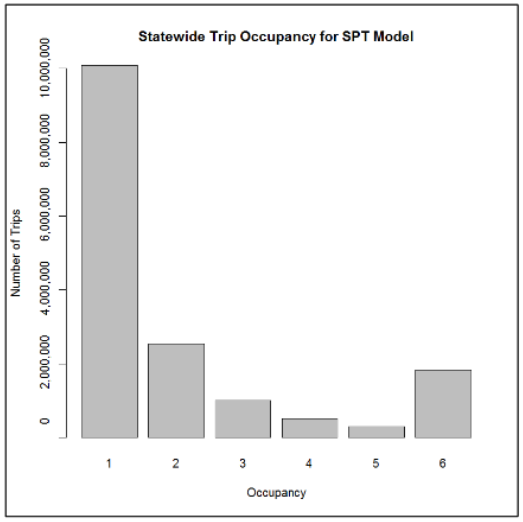


Figure 38: Histogram of Taxi Trip Occupancies for $(q_{max} = 6)$; $(t_{max} = 5)$ in SPT Model

State-wide automatedTaxi (aTaxi)

- **Fleet size** (Instantaneous Repositioning)

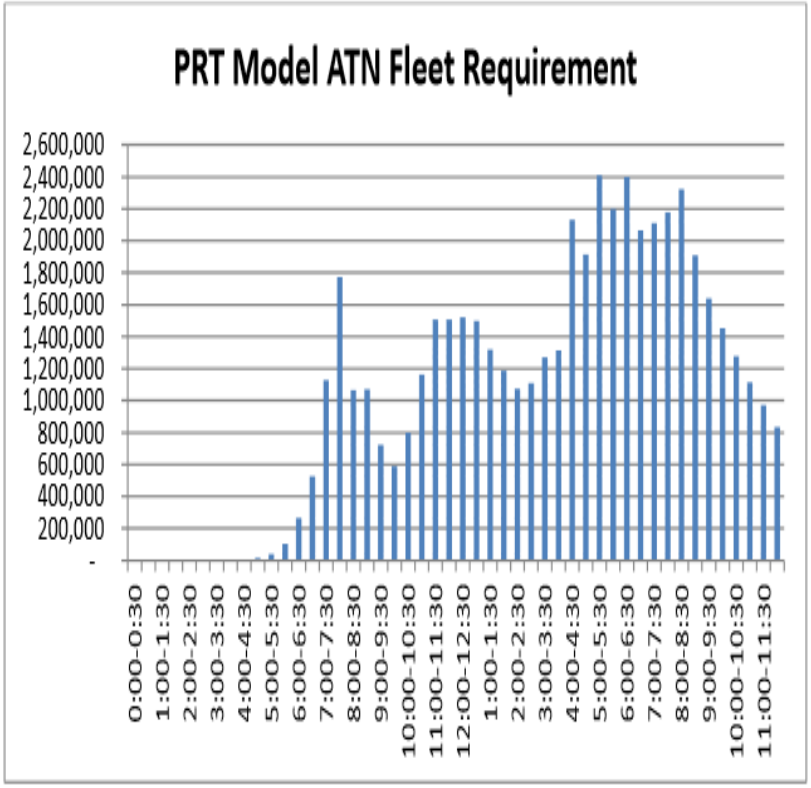


Figure 39: Vehicles Required at 48 Time Steps in PRT Model Assuming Instantaneous Repositioning

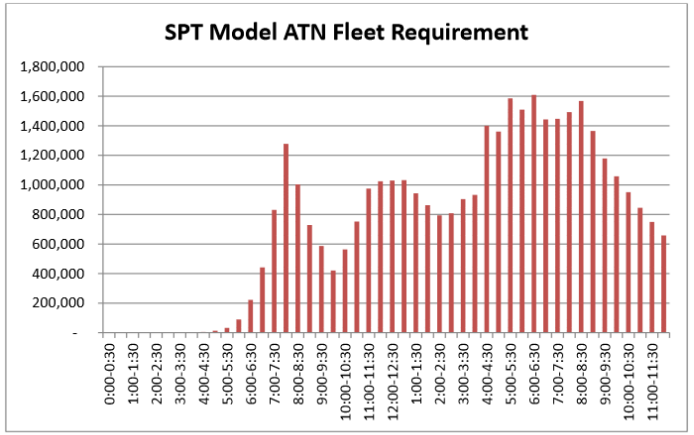


Figure 40: Vehicles Required at 48 Time Steps in SPT Model Assuming Instantaneous Repositioning

State-wide automatedTaxi (aTaxi)

- Abel to serve essentially all NJ travel demand (32M trips/day)
- Shared ridership allows
  - Peak hour; peak direction: Av. vehicle occupancies to can reach ~ 3 p/v and eliminate much of the congestion
  - Essentially all congestion disappears with appropriate implications on the environment
  - Required fleet-size under 2M aTaxis (about half)
    - (3.71 registered automobiles in NJ (2009)

Discussion!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Thank You

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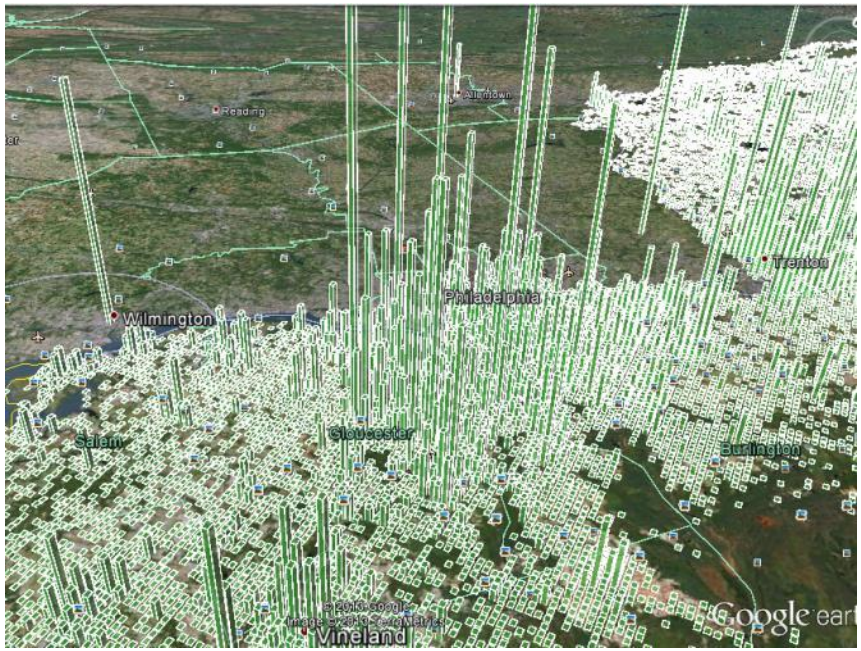

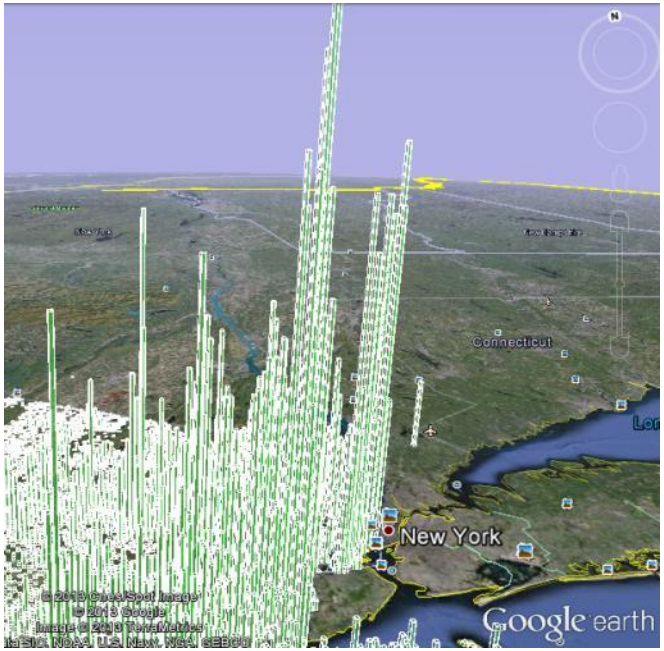

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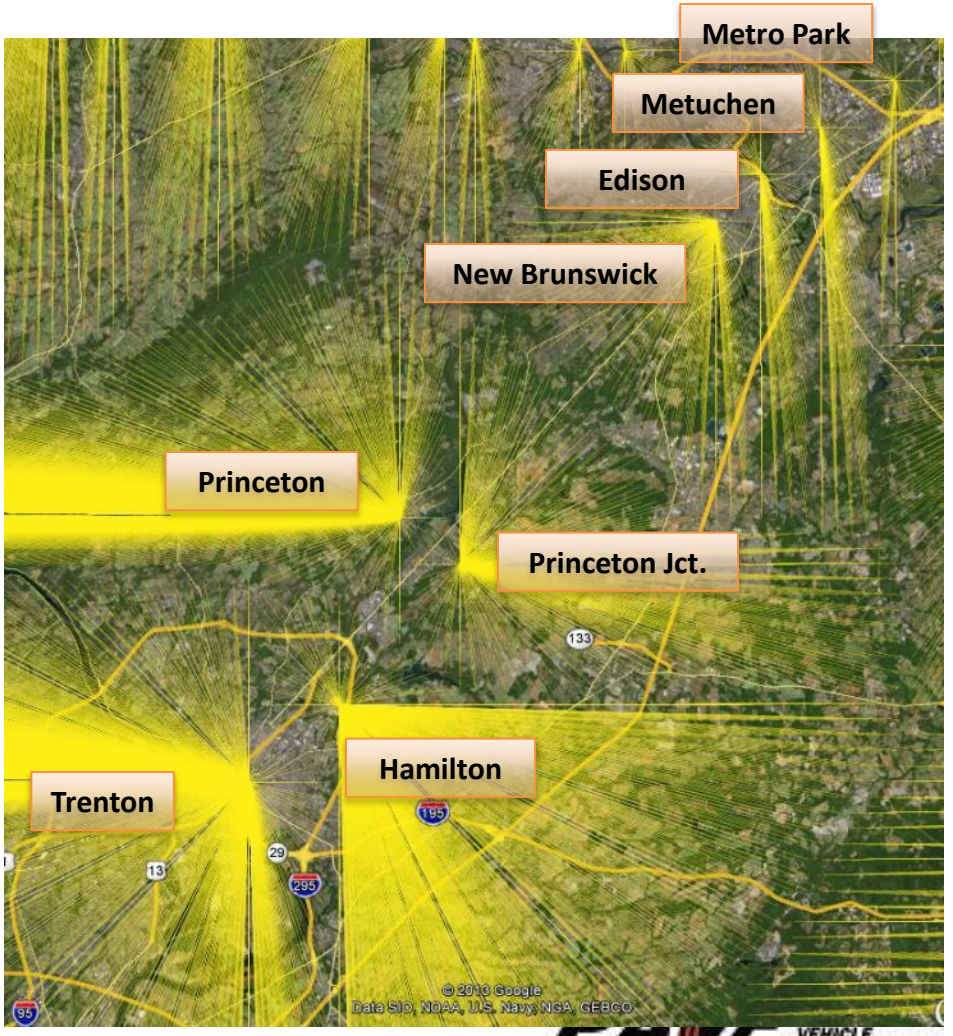
PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

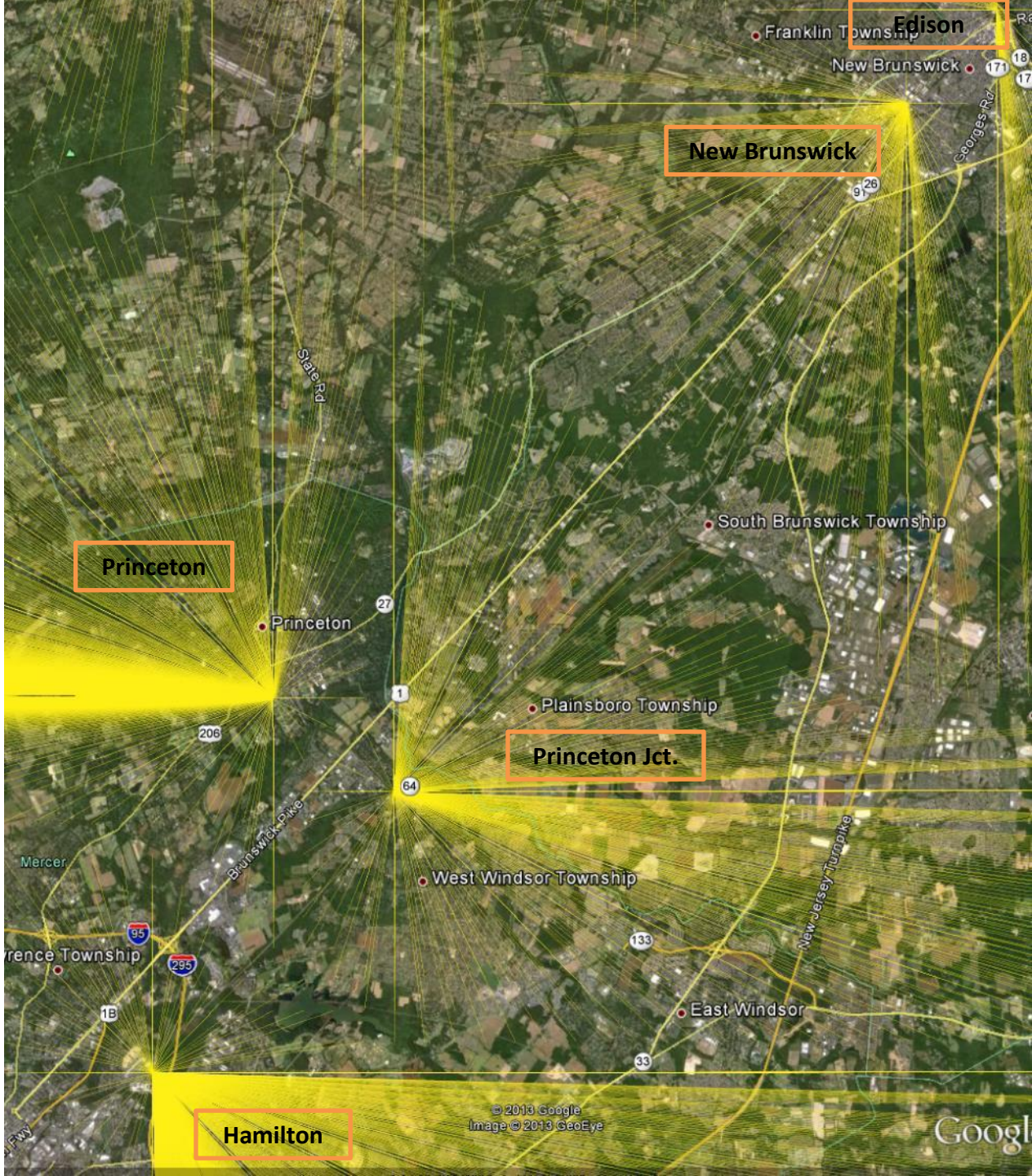
"Manhattan Customer-shed" Regions
for
NJ Transit Train Stations

Yellow Lines connect 0.25 mi^2 areas to nearest NJT Train Station

where Distance is a "Manhattan Metric" = $|\Delta x| + |\Delta y|$



“Manhattan Customer-shed” Regions for NJ Transit Train Stations



Yellow Lines connect 0.25 mi^2 areas to nearest NJT Train Station

where Distance is a “Manhattan Metric” = $|\Delta x| + |\Delta y|$

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