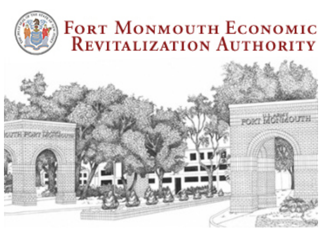
Intelligent Transportation Systems:
Automated Highways, Autonomous Vehicles, aTaxis & Personal Rapid Transit



Alain L. Kornhauser

Professor, Operations Research & Financial Engineering
Director, Program in Transportation
Faculty Chair, PAVE (Princeton Autonomous Vehicle Engineering
Princeton University

September 18, 2012

CS 402

PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

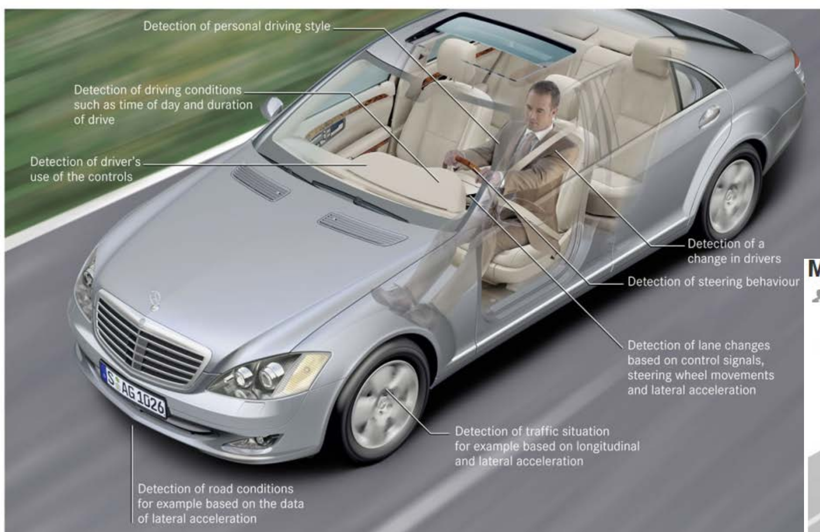
Intelligent Transportation Systems

- Coined by Fed DoT in early ‘90s to include:
  - ATMS **(Adv. Transp. Management Systems)**
    - Intelligent Traffic Control Systems and Value Pricing Systems (EZ Pass mid 80s)
  - ATIS **(Adv. Transp. Information Systems)**
    - Turn-by-Turn GPS Route Guidance Systems (‘97 CoPilot Live)
  - ARTS **(Adv. Rural Transp. Systems)**
  - ATS **(Automated Transit Systems)**
    - Automated People Movers and Personal Rapid Transit (Ficter ‘64, W. Alden ’71, WWU ‘75)
  - AHS **(Automated Highway Systems)** (1939 World’s Fair, RCA-Sarnoff late 50s*, R.Fenton ‘72 OSU)
    - Autonomous vehicles
      - * VK Zworykin & L Flory “Electronic Control of Motor Vehicles on Highways” Proc. 37^{th} Annual Mtg Highway Research Board, 1958

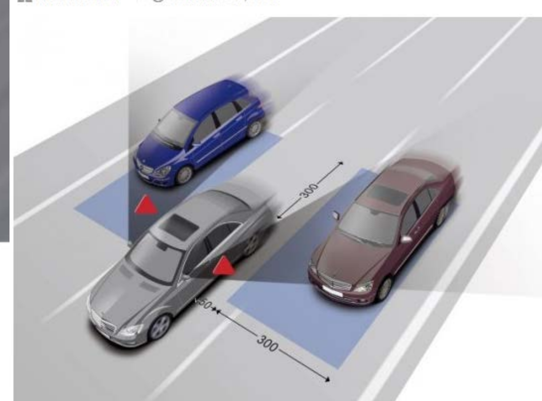
Intelligence (aka Automation) in the current Automobile

- Self-parking systems video (1st version Toyota '03; US '06) MB Park Assist
- Lane Departure Warning Systems
  - Continental LWDS; Bendix AutoVue LDWS; Ford Driver Alert; Bosch Lane Departure and Lane Keeping Support; Continental Driver Assistance Systems
- Frontal Impact Warning Systems Volvo video
- MBML350 Safety Features *; Mercedes Benz ; MB Lane Keeping Assistance; MB Active Lane Keeping Assist YouTube*
- MB Attention Assist YouTube;

Attention Assist:
How the Mercedes driver assistance system detects tiredness

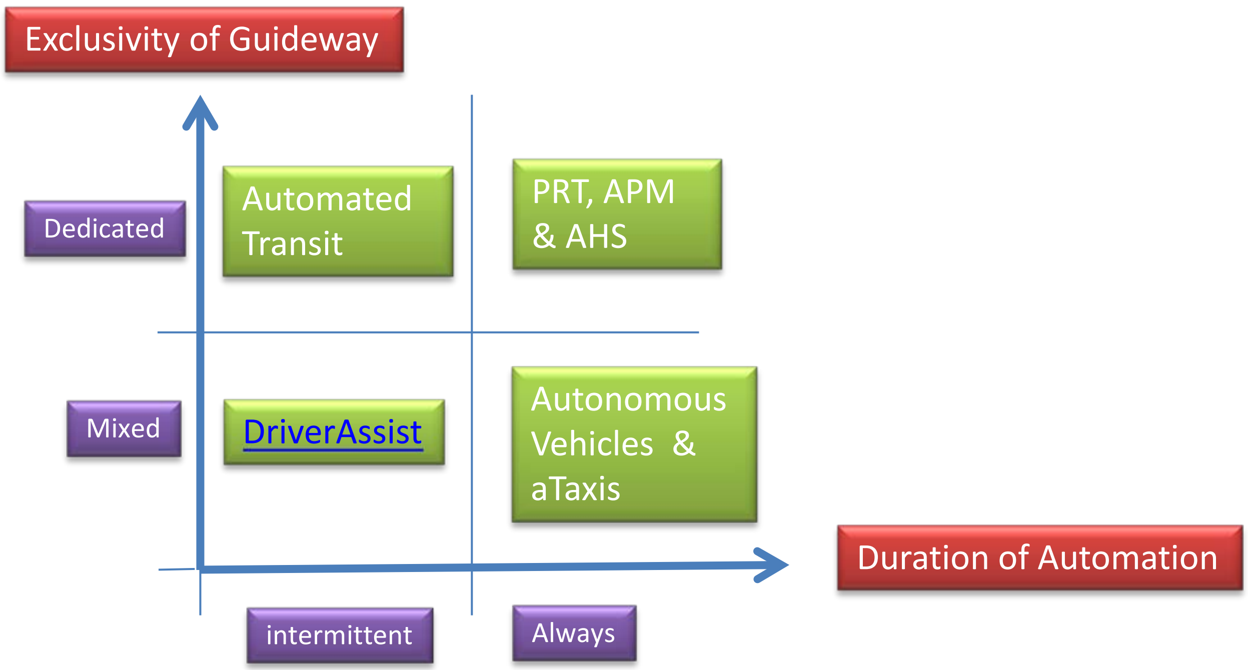


Mercedes-Benz TecDay – Blind Spot Assist
Muamer Hodzic | November 12, 2008



Lane-departure warning system: steering wheel vibrations warn the driver if he or she is veering out of the lane

What's Next:
Lateral & Longitudinal Vehicle Control



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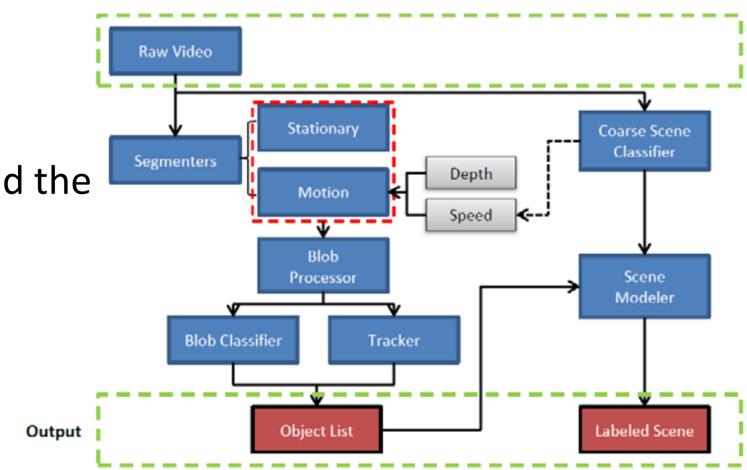
Conceptually, the Vehicle Control Problem is basically:

- “Simple”
  - Feasible region is a flat plane with boundaries and the environment is somewhat well structured.

1.5. System Diagram



- “Challenge”
  - to properly identify and tag the boundaries and the objects in some neighborhood of the vehicle

- Longitudinal and Lateral control problems:
  - Have velocity vector be **Tangent** to a centerline between feasible lateral boundaries and don’t hit anything

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PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

- Focus on Intelligent Vehicle Control Systems for Automated Transit Systems (Personal Rapid Transit)

  - extensive research on control and management systems for large fleets of vehicles in a large interconnected dedicated network of guideways and stations
  - area-wide network design for large-scale implementations
    - state-wide PRT

- for Automated Highways (Personal hands-off & Feet-off vehicles operating on conventional roadways)

DARPA GRAND CHALLENGE

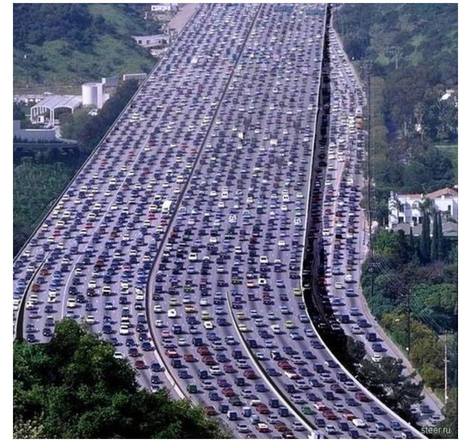
  - participation in DARAP Autonomous Vehicle Challenges
    - focus on stereo vision-based systems for sensing local environments
      - » dynamic depth mapping, object identification and tracking, road edge identification.
    - robust control in the presence of substantial uncertainty and noise

  - Evolution to autonomousTaxis concept of Area-wide Public Transit

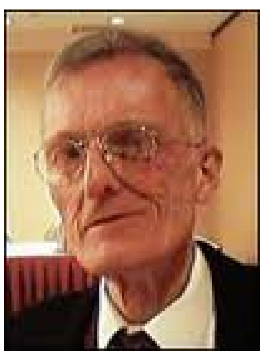
PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

Starting in the late 60s…

Some thought that: **“The automation & computer technology that took us to the moon could now revolutionize mass transit and save our cities from the onslaught of the automobile”**



Donn Fichter “Individualized Automatic Transit and the City” 1964



PRT

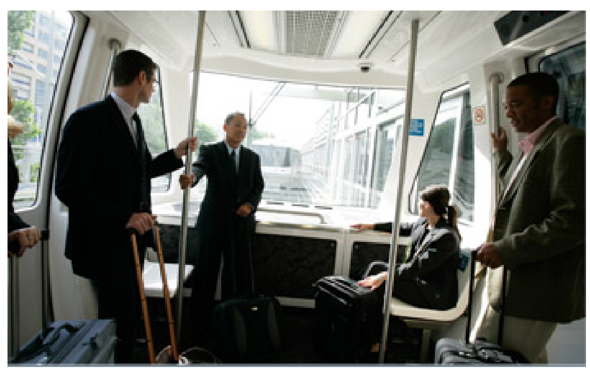
Westinghouse Skybus Late 60’s-

APM

APM

Automated People Movers

Now exist in essentially every Major Airport and a few Major Activity Centers



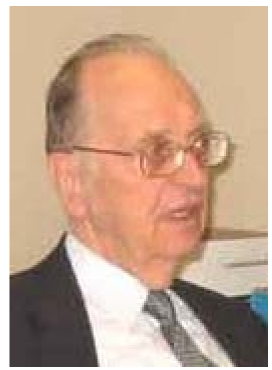
PRT

Personal Raid Transit

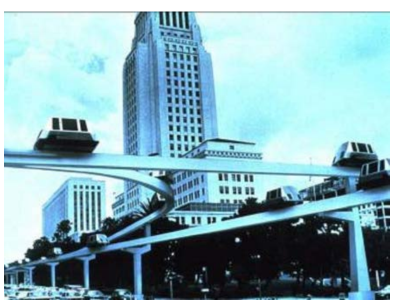
Starting in the early 70's, U of Minnesota became the center of PRT research focused on delivering auto-like ubiquitous mobility throughout urban areas

William Garrard

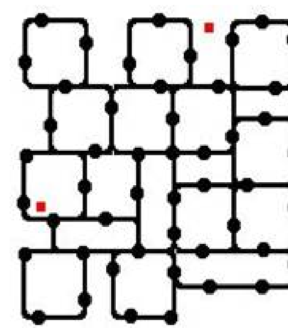
J. Edward Anderson



Alain Kornhauser



- Since Demand very diffuse (Spatially and Temporally):
  - Many stations served by Many small vehicles
    - (rather than a few large vehicles).
- Many stations
  - Each off-line with interconnected mainlines
    - To minimize intermediate stops and transfers
- Many small vehicles
  - Require more sophisticated control systems,
    - both longitudinal and lateral.



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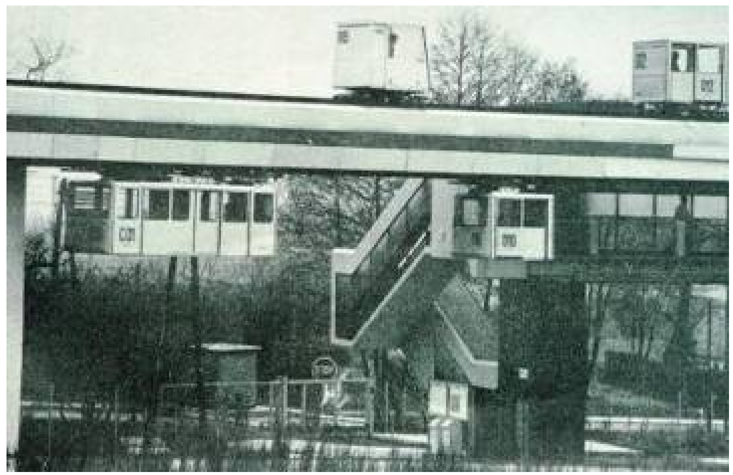
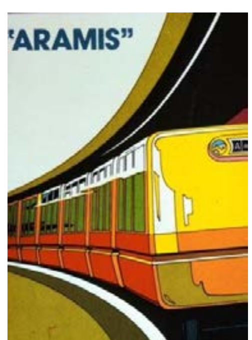
PRT

Personal Raid Transit

Some early test- track success…





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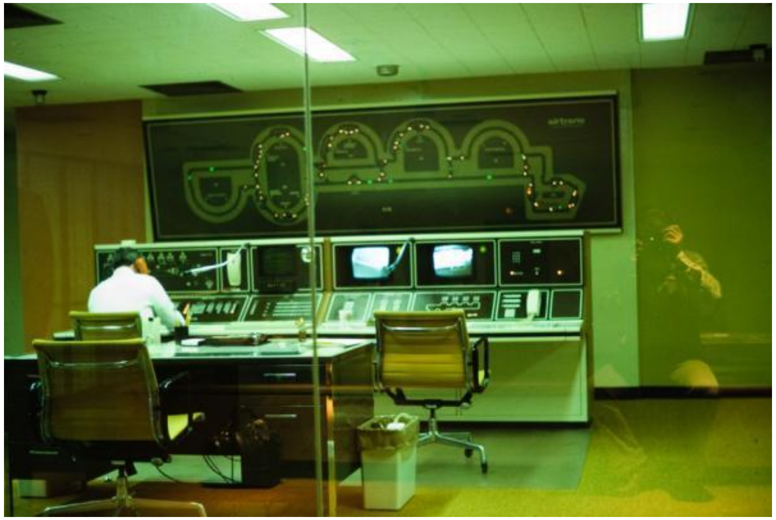
PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

DFW AirTrans PRT
Was built and operational for many years




Morgantown 1975

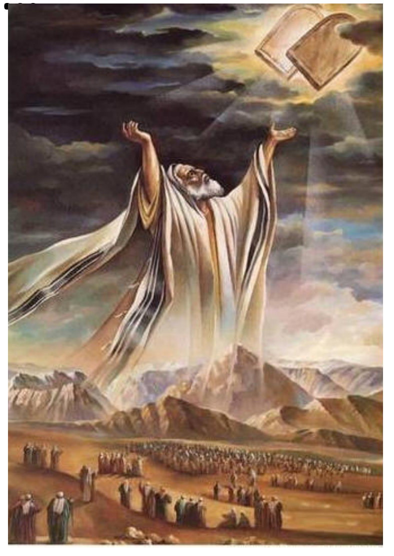
Video1 Video2

– About 40 years ago: Exec. Director of APTA*
said to me:

"Alain: PRT is the transportation system of the future…

And Always will be!!!"

Well after 40 years…..



…are we finally approaching the promised land???

**American Public Transit Association*

Today…

Morgantown 1975

Remains a critical mobility system today & planning an expansion

And Today…

- Masdar & Heathrow are operational

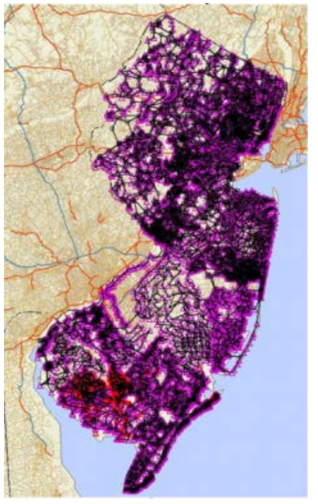
Video

Video

So Let's Consider Going...

From: **the Paved State**

Back to: ***the Garden State***



Mobility without Personal Automobiles

for New Jersey

So…

- Premise:
  - NJ in 2012 is very different from NJ in 1912

- A look at what might be NJ's Mobility in 2112
  (or before)

Looking Back

- let's look at the automobile:

Daimler, 1888

- In the beginning, it takes a while

Central Ave. Caldwell NJ c. 1912

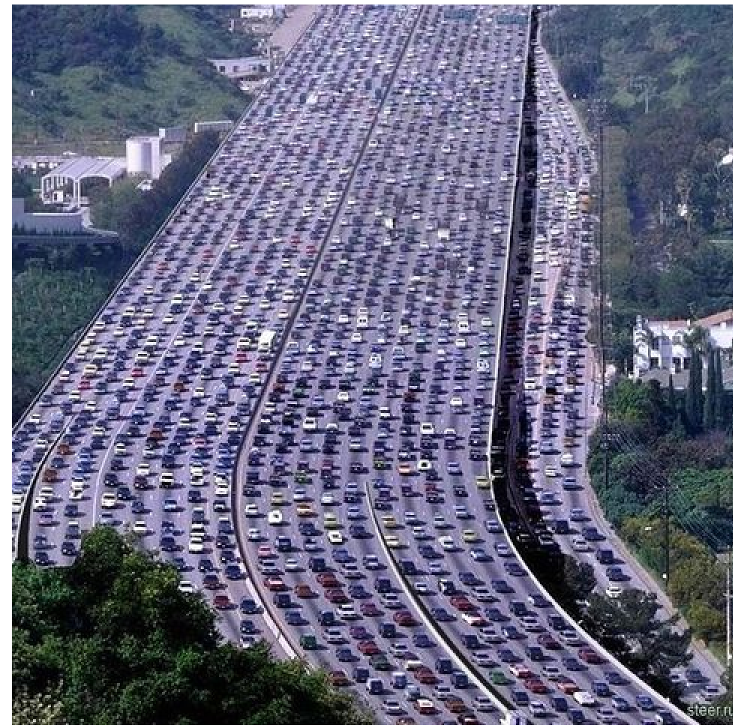

Bloomfield Ave., Caldwell, N. J.

Bloomfield Ave. & Academy Rd. c. 1912 Before it was paved

Muddy Bloomfield Ave. c. 1912

Muddy Main St. (Rt. 38) Locke, NY. c. 1907

Finally:

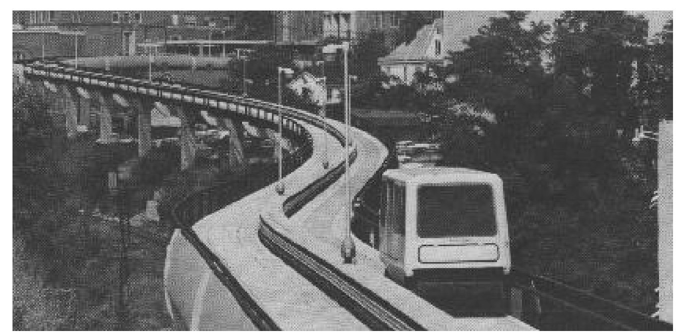


Automobile Congestion - present

Starting to Look Forward

Daimler, 1888

Morgantown, 1973



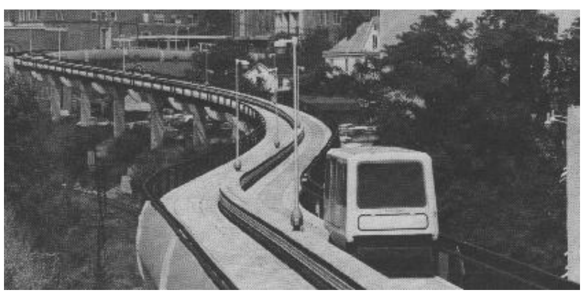
So…

1888

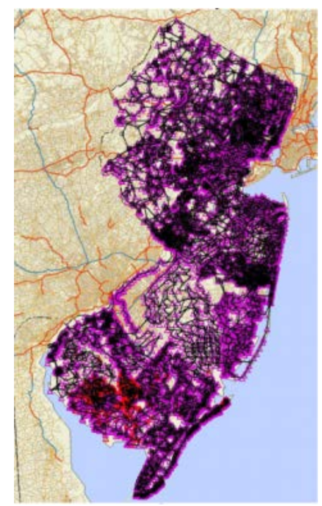
1908

1988

1973



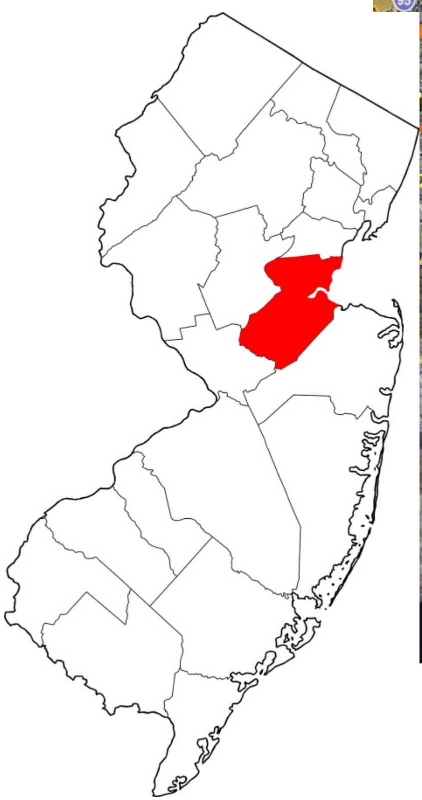
2073

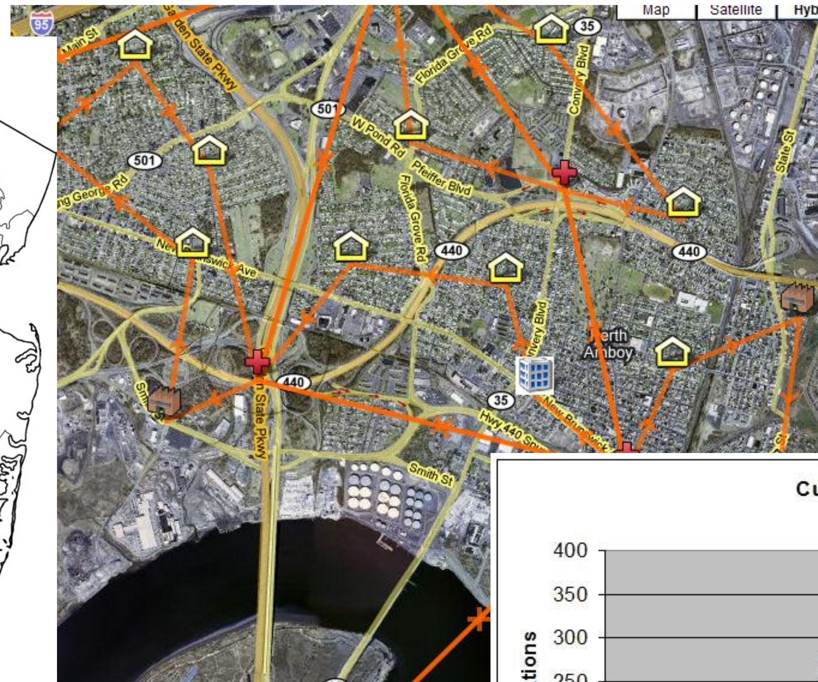


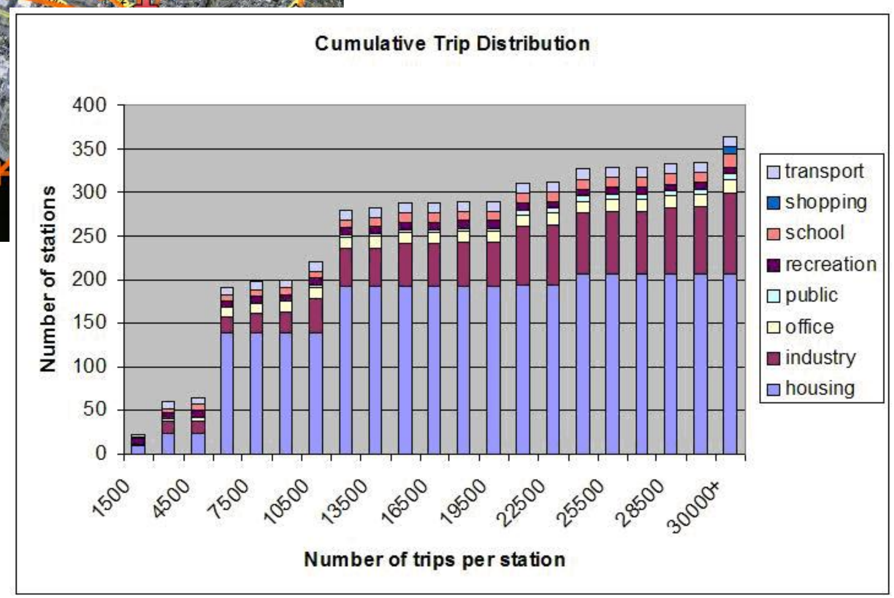
What might it take for PRT to provide essentially ubiquitous mobility for New Jersey?

- For the past 6+ years this issue has been addressed by my Transportation Systems Analysis Class
- Address the question: Where to locate and interconnect PRT stations such that ~90% of the trip ends in New Jersey are within a 5 minute walk.
- After assembling a database of the precise location of trip end, students layout and analyze a statewide network.

Middlesex County



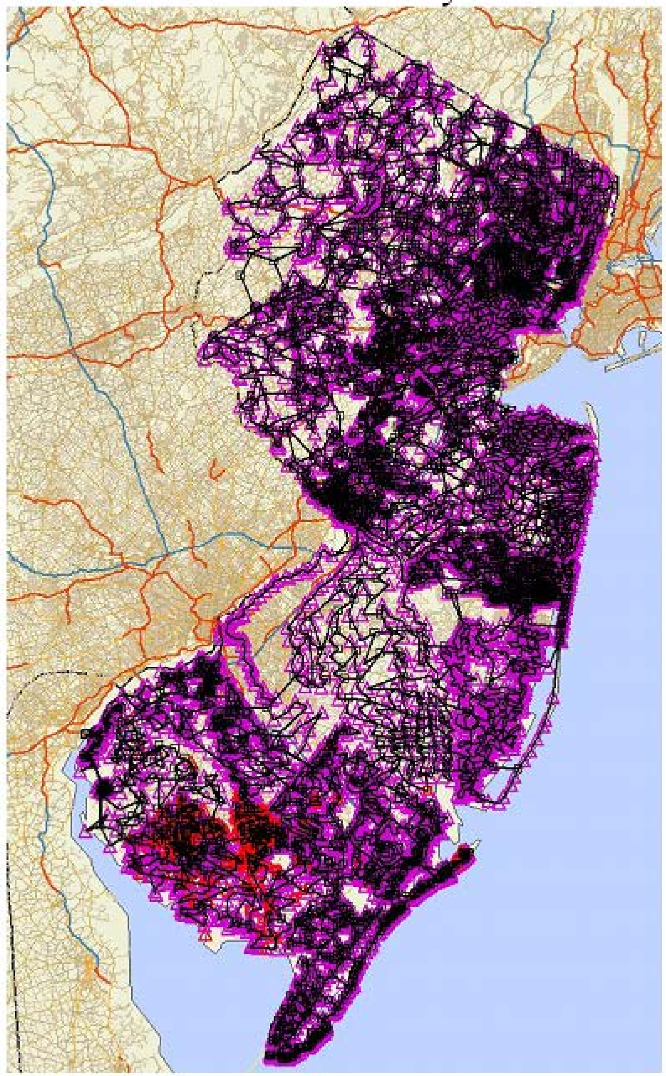




AUTONOMOUS
VEHICLE
ENGINEERING

Princeton University

Personal Rapid Transit (PRT)
for
New Jersey



http://orfe.princeton.edu/~alaink/PRT_Of467F07/PRT_NJ_Orf467F07_FinalReport.pdf

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PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

County	Stations	Miles	County	Stations	Miles
Atlantic	191	526	Middlesex	444	679
Bergen	1,117	878	Monmouth	335	565
Burlington	597	488	Morris	858	694
Camden	482	355	Ocean	540	1,166
Cape May	976	497	Passaic	1185	1,360
Cumberland	437	1,009	Salem	285	772
Essex	595	295	Somerset	568	433
Gloucester	412	435	Sussex	409	764
Hudson	467	122	Union	577	254
Hunterdon	405	483	Warren	484	437
Mercer	413	403	**Total**	**11,295**	**12,261**

Bottom Line

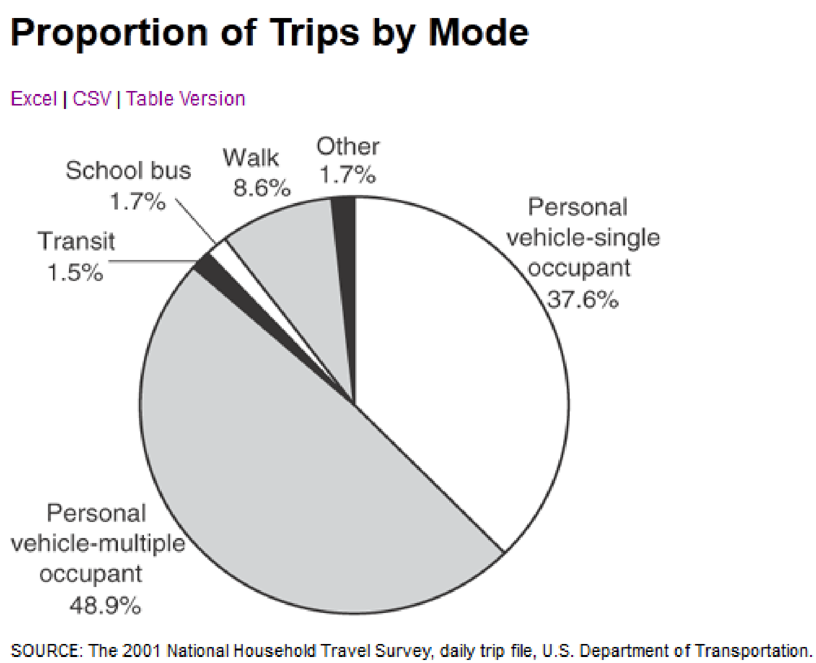
Element	Value
PRT Trips per day (90%)	26.51M
Peak hour trips (15%)	3.98M
Fleet size	530K
Fleet Cost $B	$53B @ $100K/vehicle
Stations	11,295
Station Cost	$28B @ $2M/Station
Guideway	12,265 miles
Guideway Cost	$61B @ $5M/mile
Total Capital Cost	$143B

What the APTA guy was telling me was…

- Final Region-wide system would be really great, but…
- **Any great final system MUST evolve from some great initial system and be great at every step of the way, otherwise…**
- It will always be ***"a system of the future"***.
- The ***dedicated grade-separated guideway infrastructure*** requirement of PRT may simply be too onerous and risky for it to ever serve a significant share of the urban mobility market.

While there are substantial challenges for PRT..

– All other forms of Transit are today **hopelessly uncompetitive** in serving anything but a few infinitesimally small niche markets.



http://www.bts.gov/publications/highlights_of_the_2001_national_household_travel_survey/html/figure_06.html

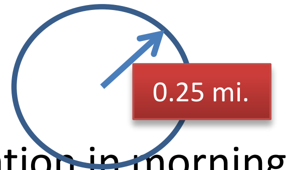
Current State of Public Transport…

- **Not Good!:**
  – Serves about 2% of all motorized trips
  – Passenger Miles (2007)*:
    - 2.640×10^{12} Passenger Car;
    - 1.927×10^{12} SUV/Light Truck;
    - 0.052×10^{12} All Transit;
    - 0.006×10^{12} Amtrak
  – Does a little better in "peak hour" and NYC
    - 5% commuter trips
    - NYC Met area contributes about half of all transit trips
  – Financially it's a "train wreck"

http://www.bts.gov/publications/national_transportation_statistics/2010/pdf/entire.pdf, Table 1-37

Transit's Fundamental Problem…

- **Transit is non-competitive to serve most travel demand**
  - Travel Demand (desire to go from A to B in a time window ΔT)
    - A & B are walk accessible areas, typically:
      - Very large number of very geographically diffused {A,B} pairs
    - ΔT is diffused throughout the day with only modest concentration in morning and afternoon peak hours



- **The Automobile at "all" times Serves…**
  - Essentially all {A,B} pairs demand-responsively within a reasonable ΔT
- **Transit at "few" times during the day Serves…**
  - a modest number of A & B on scheduled fixed routes
  - But very few {A,B} pairs within a reasonable ΔT
- **Transit's need for an expensive driver enables it to only offer infrequent scheduled fixed route service between few {A,B} pairs**
  - But… Transit can become demand-responsive serving many {A,B} if the ***Driver*** (aka ***Intelligence***) is made ***cheap*** (aka ***artificial***)
  - If it is really ***Intelligent*** then it can utilize the existing roadway infrastructure.

Intelligent Transportation Systems

- Coined by Fed DoT in early '90s to include:
  - ATMS **(Adv. Transp. Management Systems)**
    - Intelligent Traffic Control Systems and Value Pricing Systems (EZ Pass mid 80s)
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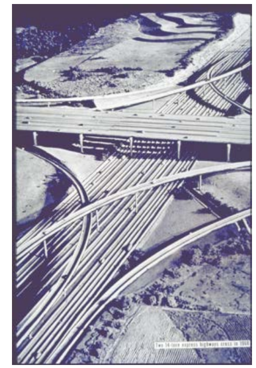
    - Autonomous vehicles
      - * VK Zworykin & L Flory "Electronic Control of Motor Vehicles on Highways" Proc. 37th Annual Mtg Highway Research Board, 1958

Evolution of AHS Concept

- GM Futurama @ 1939 World's Fair



- Zworykin & Flory @ RCA-Sarnoff in Princeton, Late 50s*

* VK Zworykin & L Flory "Electronic Control of Motor Vehicles on Highways" Proc. 37th Annual Mtg Highway Research Board, 1958

- Robert E Fenton @ OSU, Early 70s*

* "A Headway Safety Policy for Automated Highway Operations" R.E. Fenton 1979

Evolution of AHS Concept

- AHS Studies by FHWA in late 70's and mid 90's

2004	2005	2007
DARPA GRAND CHALLENGE	DARPA GRAND CHALLENGE	DARPA URBAN CHALLENGE

2005

DARPA GRAND CHALLENGE

2007

BRIDGING THE GAP DARPA 1958 2008 50 YEARS POWERED BY IDEAS

URBAN CHALLENGE

Link to Presentation Not Easy Old House 2005 2007

The DARPA Grand Challenges

Defense Advanced Research Projects Agency

- **DARPA Grand Challenge**
  Created in response to a Congressional and DoD mandate: a field test intended to accelerate research and development in autonomous ground vehicles that will help save American lives on the battlefield. The Grand Challenge brings together individuals and organizations from industry, the R&D community, government, the armed services, academia, students, backyard inventors, and automotive enthusiasts in the pursuit of a technological challenge.

- **The First Grand Challenge: Across the Mojave, March 2004**
  Across the Mojave from Barstow, California to Primm, Nevada :$1 million prize. From the qualifying round at the California Speedway, 15 finalists emerged to attempt the Grand Challenge. The prize went unclaimed as no vehicles were able to complete more than 7.4 miles.

- **The 2005 Grand Challenge**
  Multi-step qualification process: Site Visits, NQE – Semifinals, GC final event
  132 miles through the Nevada desert. Course supplied as list of GPS waypoints. October 8, 2005 in the desert near Primm, NV. Prize $2 million.

- **The 2007 Urban Challenge**
  Nov. 2007; 60 miles in an urban environment. Lane keeping, passing, stop-signs, K-turns “driving down Nassau Street”. Range of Prizes

Prospect Eleven & 2005 Competition

the making of a monster

2005 Grand Challenge

Objective

- Enrich the academic experience of the students

Constraints

- Very little budget

Guiding Principles

- Simplicity

Homemade

"Unlike the fancy "drive by wire" system employed by Stanford and VW, Princeton's students built a homemade set of gears to drive their pickup. I could see from the electronics textbook they were using that they were learning as they went."

http://www.pcmag.com/slideshow_viewer/0,1205,l=&s=1489&a=161569&po=2,00.asp

Fall 2004


GMC

Fall 2005

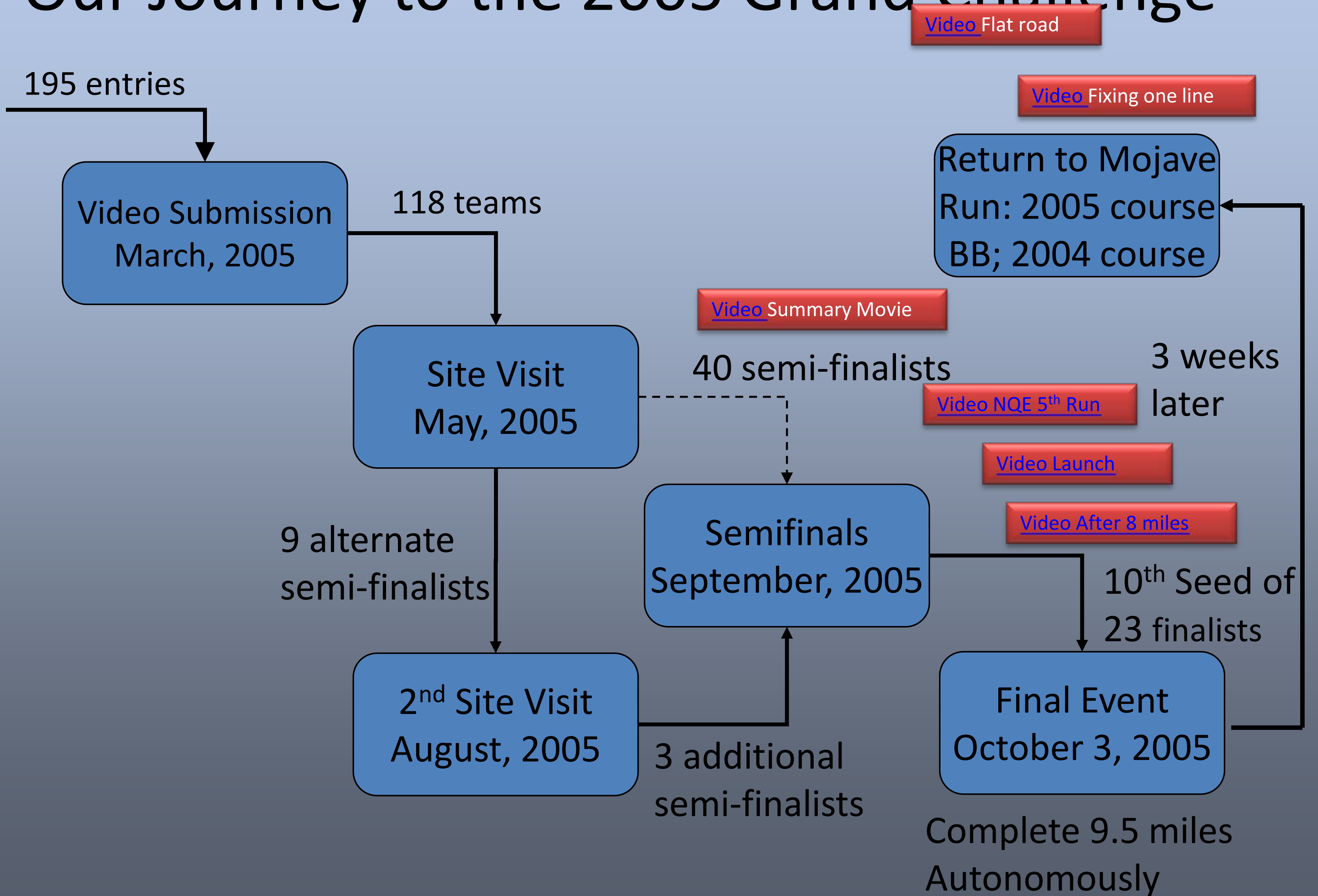

26
WBA
COLEMAN
GMC
41
PROSPECT ELEVEN

It wasn’t so easy…

Pimp My Ride

(a video presentation)

Our Journey to the 2005 Grand Challenge



[Link to GPS Tracks]

Achievements in the 2005

DARPA GRAND CHALLENGE

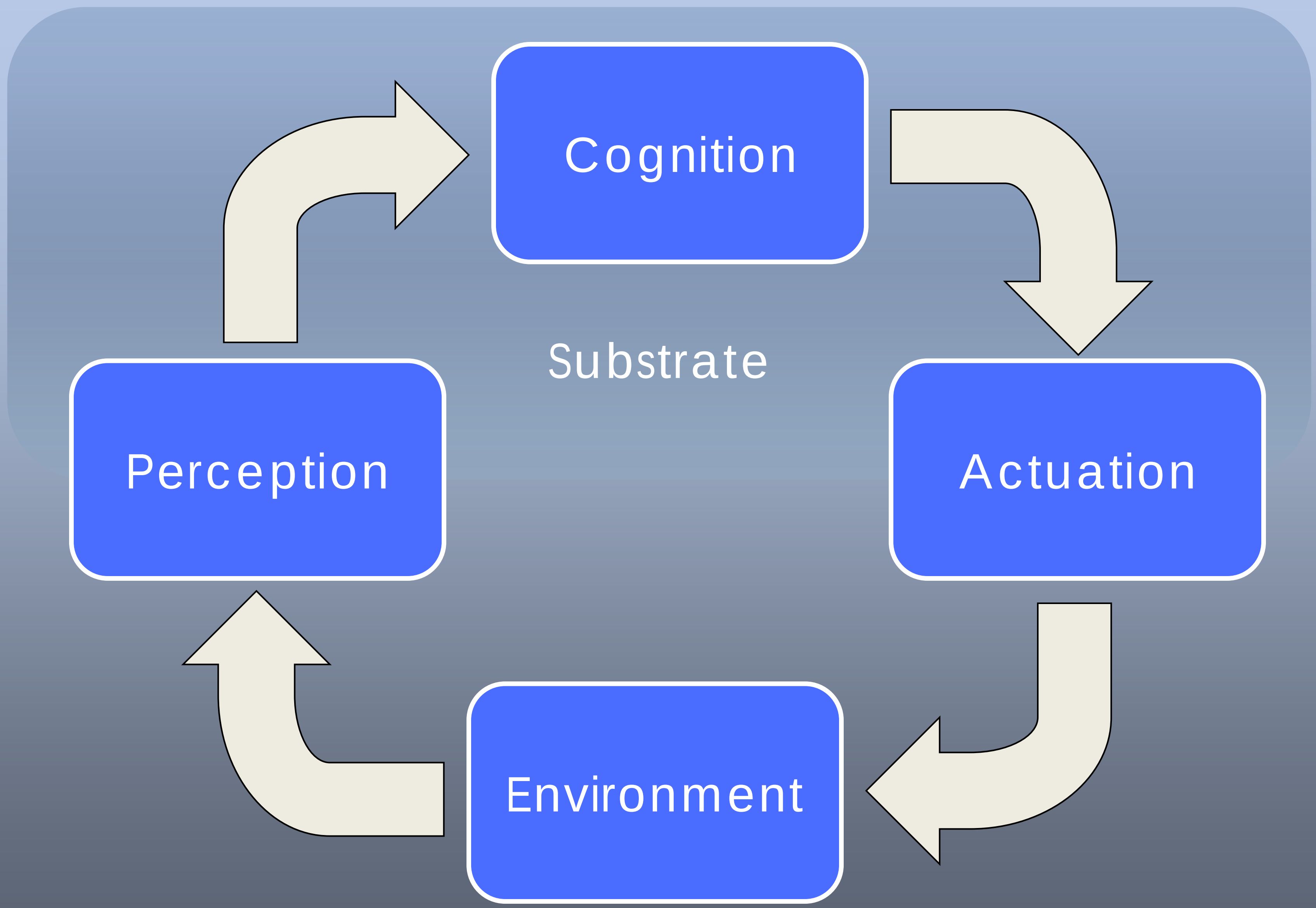
Participation in the 2007

URBAN CHALLENGE

2007

- Semifinalist in the 2007 DARPA Urban Challenge
- Stereo and Monocular cameras, along with RADAR
- Homebrewed State Estimation system

Prospect12_TestRun


Cognition
Substrate
Perception
Actuation
Environment

Perception

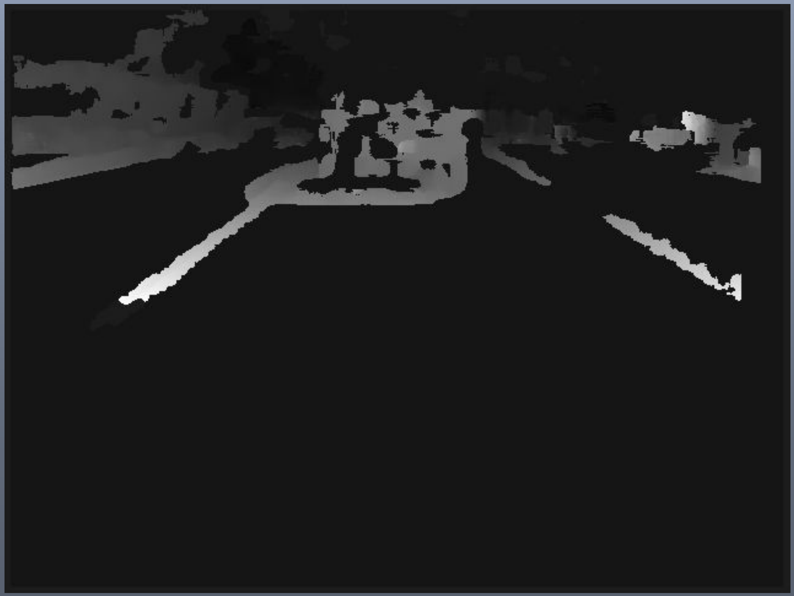
Monocular VISION

Lane
DETECTION

StereoVISION

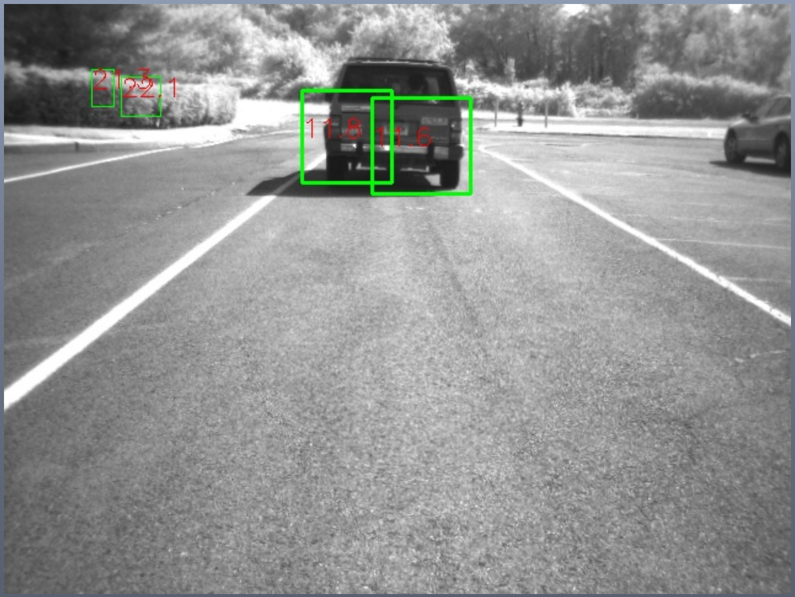
Obstacle

DETECTION



Obstacle

DETECTION

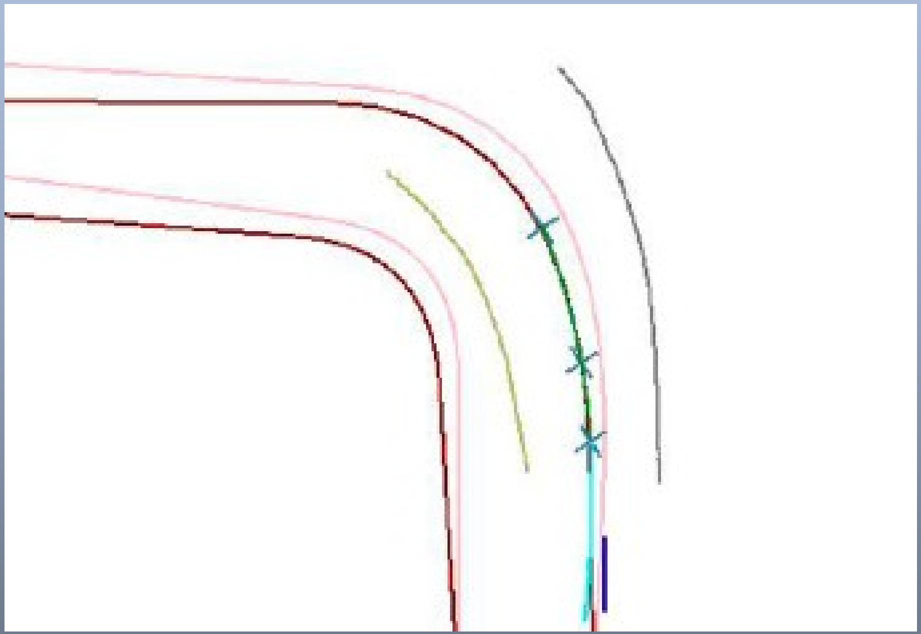


Precision GPS

MEMS IMU

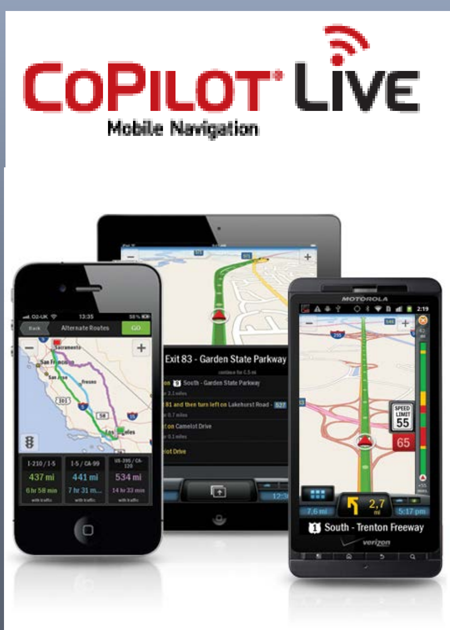
Sensor

FUSION



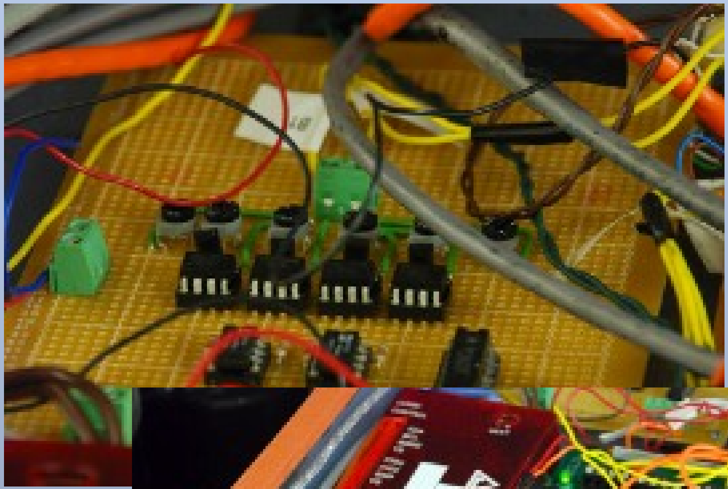
Cognition

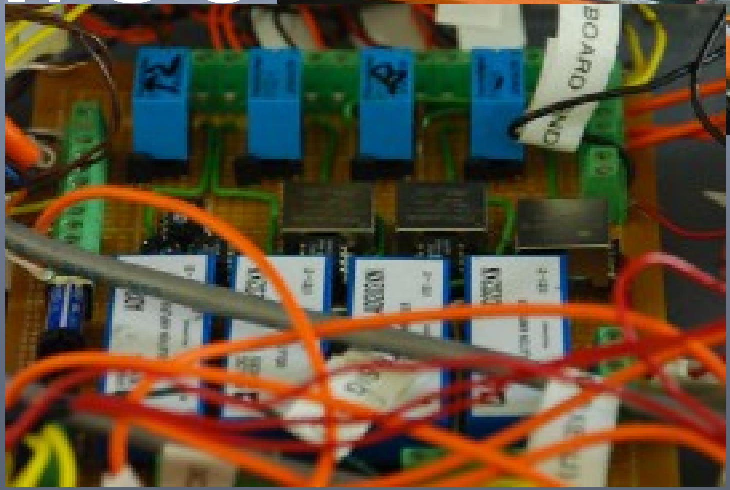
Global and Local
NAVIGATION



Actuation

Home-brewed ELECTRONICS





Mechanical
ACTUATORS

Substrate

Quad-core

PROCESSING

Today..

- Continuing to work on Prospect 12
- Vision remains our focus for depth mapping, object recognition and tracking
- Objective is to pass NJ Driver's Test.

Evolved Since the DARPA Challenges..

- "Bus 2.0" GPS-based (Steering/Lateral-control) Driver Assistance System in Twin Cities
  - Provides lateral-control assistance to buses operating on narrow freeway shoulders

- Autonomous Buses at La Rochelle (CyberCars/Cybus/INRIA)
  http://www.youtube.com/watch?v=72-PlSFwP5Y
  - Simple virtual non-exclusive roadway
    - Virtual vehicle-based longitudinal (collision avoidance) and lateral (lane keeping) systems

Princeton University

Evolved Since the DARPA Challenges..

From the Stanford team…

Feet off
Hands off

Google Team: ~50 People ~ $15M/yr (chump change)

PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

Addressing the fact that…

We really don't want to drive…

Addressing the fact that…

We aren’t that good…

>90% crashes involve human error

Google’s :

Estimated Safety Benefits

- Analysis based on NHTSA [DOT HS 810 767 Pre-Crash Scenario Typology for Crash Avoidance Research]
- For Highway relevant scenarios
  - –71% fewer crashes
  - –65% fewer injuries
  - –81% fewer fatalities

[More on Google: Levandowski Presentation]

Google is demonstrating that…

The way to really get STARTED is to concentrate the intelligence in the Vehicle

and be Robust to the infrastructure

Prove the concept in "one" vehicle, then replicate

Beginning to see a response by the vehicle manufacturers…

2013MB ML-Class Active Lane Keeping
and JamAssist is coming (video)

The 1st Showroom Taste of Hands-off, Feet-off

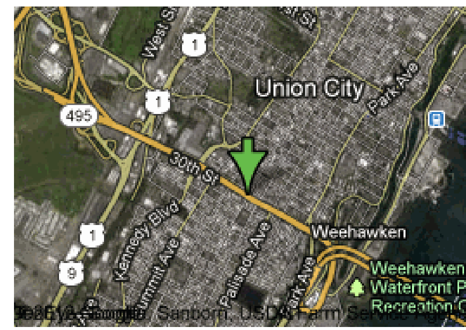
Next may be: Daimler's "6D" vision:

Initial Demonstration
Transit-based Driver Assistance

- "Bus 2.0" GPS-based (Steering/Lateral-control) Driver Assistance System in Twin Cities
  - Provides lateral-control assistance to buses operating on narrow freeway shoulders
  - Based on high precision GPS

Opportunity for a Substantive Extension of Transit-based Driver Assistance

- Specific: **"495-viaduct" Counter-flow Exclusive Bus Lane (XBL)** URL
  - Currently:
    - Fleet of 3,000 buses use the XBL leading to the Lincoln Tunnel & 42nd Street PA Bus Terminal.
    - Unassisted practical capacity: 700 busses/hr (5.1 sec headway)
  - By adding Intelligent Cruise Control with Lane Assist to 3,000 buses…
    - e.g. Daimler Benz Distronic Plus with Traffic Jam Assist
  - Could achieve sustained 3.0 second headways
    - Increases practical throughput by 50%
    - from 700 -> 1,000 buses/hr; 35,000 -> 50,000 pax/hr
    - Increased passenger capacity comparable to what would have been provided by $10B ARC rail tunnel.



PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

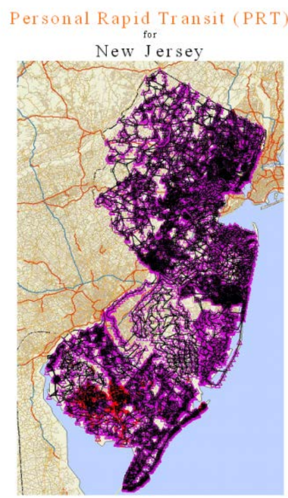
Initial Demonstration of Autonomous Transit

- Autonomous Buses at La Rochelle (CyberCars/Cybus/INRIA) http://www.youtube.com/watch?v=72-PlSFwP5Y
  - Simple virtual non-exclusive roadway
    - Virtual vehicle-based longitudinal (collision avoidance) and lateral (lane keeping) systems

PAVE PRINCETON AUTONOMOUS VEHICLE ENGINEERING

Far-term Opportunities for Driverless Transit

- Recall: NJ-wide PRT network
- Objective: to effectively serve essentially all NJ travel demand (all 30×10^6 daily non-walk trips)
  - Place "every" demand point within "5 minute walk" of a station; all stations interconnected; maintain existing NJ Transit Rail and express bus operations)
- Typically:
  - ~10,000 stations (> $25B)
  - ~10,000 miles of guideway (>$100B)
  - ~750,000 PRT vehicles (>$75B)
  - Optimistic cost: ~$200B

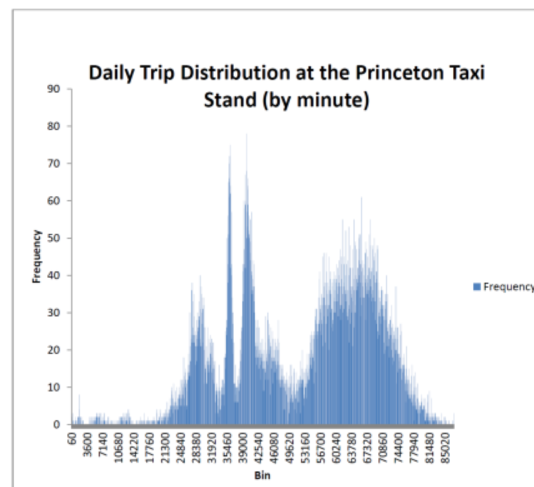


Far-term Opportunities for Driverless Transit

- Biggest Issues
  - How to get started
  - How to evolve
  - Cost & complexity of guideway
- What if ????
  - autonomousTaxi (aTaxi) served passengers from curb-side aTaxi stands
  - Offered on-demand service between aTaxiStands using existing streets
- Ability to get started
  - With a few aTaxis from a few aTaxiStands
- and evolve to
  - ~10,000 aTaxi stands
  - ~750,000 aTaxis
  - Offering
    - peak hours: stand2stand shared aTaxi service
    - else: stand2stand shared services and door2door premium service

State-wide autonomousTaxi (aTaxi)

- Ability to serve essentially all NJ travel demand in
  - sharedRide mode during peak demand
  - premium door2door mode available during off peak hours
- Shared ridership allows
  - Av. peak hour vehicle occupancies to ~ 3 persons/vehicle in peak directions
  - Essentially all congestion disappears with appropriate implications on the environment
  - Required fleet-size under 1M aTaxis
    - (3.71 registered automobiles in NJ (2009)



Thank You