Outline

Define the problem
Examine technologies:
   Autonomous vehicles
   Personal rapid transit (PRT)
   Energy optimized vehicles
System design
Prototype implementation
US is world's 3rd largest oil producer
Commuting Energy

Americans drive 3 trillion miles annually.
Trips to the workplace account for 22.5% of US personal travel.
65% of miles are classified as urban.
This proposal could replace up to half of those urban miles (1T miles).
The energy savings would be 3M barrels of oil per day. This is 15% of US petroleum usage.
The carbon savings would be 146,000 metric tons per day. This is 12 trains of 100 cars of coal.
How Americans get to work

88% drive a car or light truck
  – 76% drive alone and 12% carpool.
4.7% use public transportation
2.9% walk
3.3% work at home
1.2% use bicycle or motorcycle.

http://www.census.gov/population/www/socdemo/journey.html
Low ridership makes cars more efficient than buses in US

<table>
<thead>
<tr>
<th>Transport mode</th>
<th>Average passengers per vehicle</th>
<th>Efficiency per passenger mile (BTU/Mile)</th>
<th>Efficiency per passenger mile (mpg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorcycles</td>
<td>1.2</td>
<td>1,853</td>
<td>66.9</td>
</tr>
<tr>
<td>Transit rail</td>
<td>24.4</td>
<td>2,638</td>
<td>47.0</td>
</tr>
<tr>
<td>Commuter rail</td>
<td>34.2</td>
<td>2,577</td>
<td>48.1</td>
</tr>
<tr>
<td>Cars</td>
<td>1.57</td>
<td>3,514</td>
<td>35.3</td>
</tr>
<tr>
<td>Personal trucks</td>
<td>1.72</td>
<td>3,947</td>
<td>31.4</td>
</tr>
<tr>
<td>Transit buses</td>
<td>9.1</td>
<td>4,315</td>
<td>28.7</td>
</tr>
</tbody>
</table>

Energy consumption at 30 mph (kcal/km/person)

- 11: Commuting HPV
- 30: Bicycle
- 112: Train & riders
- 120: Car & 5 riders
- 539: Car & driver (38 mpg)

D.G. Gordon & J. Papadopoulis, Bicycling Science, 3rd ed, MIT Press, 2004. The HPV is an order of magnitude energy improvement over good solutions. It represents two orders of magnitude better energy use compared to many cars on the road today.
Optimize the System

Automobiles do well on an interstate trip with the whole family and luggage.

Cars are suboptimal for getting to work.

Average US car weighs 4000 lb.

Average US male weighs 190 lb.

This talk explores what can be done by designing urban travel for maximum energy efficiency.
Objectives

- Improve energy efficiency by 10x to 30x.
- Eliminate all tailpipe emissions.
- Increase freeway lane capacity by 8x.
- Reduce traffic accidents by 20x to 40x.
- Eliminate congestion.
- Use existing infrastructure.
- Same performance as light rail at a fraction of the cost.
Vehicle math

- Power = $K_1 \times V + K_2 \times V^3$

- Power (W) is what is needed to hold the speed against rolling resistance and air drag.

- Assume smooth level surface and no wind.

- For a car, rolling resistance is dominant until 35 mph.

- For a light vehicle, air drag takes over at 12 mph.

Energy to overcome rolling resistance

\[ \frac{dW}{dt} = C_v/\eta \sum m \cdot g[C_R + s/100 + a/g(1 + m_w/\Sigma m)] \]

- \(C_v\): Speed of vehicle
- \(\eta\): Overall mechanical efficiency of transmission
- \(\Sigma m\): Total mass of vehicle, rider and baggage
- \(g\): Gravitational acceleration
- \(C_R\): Coefficient of rolling resistance
- \(s\): Upslope (%)
- \(a\): Vehicle acceleration
- \(M_w\): Effective rotational mass of wheels
Energy to overcome aerodynamic drag

\[ \frac{dW}{dt} = 0.5 \frac{C_v}{\eta} C_D A \rho (C_v+C_w)^2 \]

- $C_v$: Speed of vehicle
- $\eta$: Overall mechanical efficiency of transmission
- $C_D$: Aerodynamic drag coefficient
- $A$: Frontal area of vehicle and rider
- $\rho$: Air density
- $C_w$: Headwind
DARPA Grand Challenge

- Military contractors gave limited results.
- 1st race: March 2004, 229 km; No finisher.
- 2nd race: Oct 2005 (desert dirt roads) 5 finishers.

RoboCars need more development

- Not robust.
- Need to satisfy regulators.
- Technology is much easier if the roadway cooperates.
Autonomous cars are coming

Cruise control and collision avoidance systems are getting more sophisticated.
Expect to see a self-driving car in 10 years.
Opportunity for a new urban transportation mode

Ultra-light single occupancy autonomous vehicles.
Vehicles link electronically for families and shoppers.
Public and private vehicles mix.
Operates as a rail-less Personal Rapid Transit (PRT)
Autonomous vehicles are already here

- Trains to satellite terminals at airports.
- Commuter trains in Europe.
- Elevators & escalators.
- Factory automation.

Photo shows the autonomous commuter train in Lille, France. Trains run on 2 minute headways at peak times.
Personal Rapid Transit (PRT)

Fully autonomous vehicles on a reserved guideway.

Small vehicles.

Nonstop service using most direct route.

Off-line stations.

On demand access.
Slow PRT implementation

- Designed in the 1970's.
PRT problems

- Network is too dense.
- Limited capacity due to following distances and rail switching speeds.
- Congestion in stations.
- Need new infrastructure.
- Visual impact.
- Need for emergency access.

http://www.lightrailnow.org/facts/fa_prt001.htm
Human Powered Vehicles

• An HPV has hit 82 mph on level ground with only human power.

• Streamlining is essential.

• Optimized for minimum energy consumption.

http://www.ihpva.org/Records/
Why HPV sales low

- Few off-street paths.
- Expensive.
- Heavy.
- Less maneuverable than bicycle.
- Ventilation problems.
- Little cargo capacity.
Electric Bicycles

- An electric helper motor is commercially available for bicycles.
- If < 20 mph, legally a bicycle in US.
- May be treated as moped elsewhere.
- 2 wheelers are most of world's electric vehicles.
- Biggest market is China.

http://www.ebikes.ca/
http://www.bionx.ca/
http://www.evsolutions.net/
High fuel efficiency

• In 1980, Douglas Malewicki built a car weighing 230 lb empty.
• It achieved 157 mpg at 55 mph using a 2.5 hp engine.
• The design uses HPV concepts.

http://www.canosoarus.com/03CalifCommuter/CalCom01.htm
Maximizing fuel efficiency

- The UBC supermileage student team used a vehicle similar to an HPV but with a gasoline engine to get 3145 mpg at SAE supermileage event in June, 2006.

This is by no means a practical vehicle, but it indicates that 100 mpg is not an ambitious target.
Electrathon

High school students build and race electric vehicles.

Power from 50 lb of lead-acid batteries.

Winners cover 40 mi in an hour.
The Cogηeta solution

- Build a people-mover based on personal pods.
- Includes a fleet of public, autonomous SOVs.
- Repurpose freeway lanes for autonomous pods and prevent entry of ordinary vehicles.
- All pods are under computer control when on dedicated paths.
- Private pods use manual control on streets.
- There are stations at each entry / exit ramp.
Are the pods safe?

With no driver control, would expect similar safety to autonomous trains.

Autonomous commuter trains have operated in Lille, France since 1983 and Vancouver, Canada since 1986.

Estimated Lille accident rate for motor vehicles is 29x autonomous rate.
## 1995 accident rates

<table>
<thead>
<tr>
<th></th>
<th>Deaths / 10,000 km</th>
<th>Injuries / 10,000 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lille autonomous train</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Vancouver autonomous train</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>All automated systems</td>
<td>0.00025</td>
<td>0.063</td>
</tr>
<tr>
<td>US motor vehicles</td>
<td>0.0107</td>
<td>1.270</td>
</tr>
</tbody>
</table>
# Lille accident rates

<table>
<thead>
<tr>
<th></th>
<th>Deaths</th>
<th>Injuries</th>
<th>M passengers</th>
<th>Injuries / M passengers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lille metro, 2006</td>
<td>0</td>
<td>2 (estimate)</td>
<td>86</td>
<td>0.023</td>
</tr>
<tr>
<td>Lille motor vehicles, 2007</td>
<td>103</td>
<td>3407</td>
<td>5100</td>
<td>0.668</td>
</tr>
</tbody>
</table>
High capacity

- Estimated lane capacity is 11,500 people / hour.
- Exceeds the 2,300 for a freeway car lane.
- It is less than the 15,000 for bus rapid transit and the 50,000 of a subway.
- Two or more pod lanes would fit in the space required for a lane of cars.

This is based on the assumption that vehicles are 3m long and travel bumper-to-bumper at 40 kph. We assume that at maximum capacity, there is one platoon every 30 seconds with a 4 second gap between platoons.

Capital costs

The abandoned BNSF rail line near Seattle is being acquired by local government.

A consultant estimated costs per mile and per station. Paths and stations for a 12 mile line would cost:

- Commuter rail: $198M to $371M
- Autonomous pods: $39M to $97M.
  - Does not include cost of replacing 6 grade crossings.

By contrast, Link light rail extension to UW is budgeted at $1.9B.
30 mph not fast enough?

• A commuter train that hits 50-60 mph peak speeds only averages 25 mph when you count stops.
• Commuter rail is slower than this when you include passenger wait times.
• In congested traffic, cars may average only 10-20 mph.
• With no stops, a low speed vehicle is faster than a high speed one with stops or congestion.
Can it go faster?

- Yes, but fuel consumption goes up.
- System capacity is proportional to speed.
- Safety becomes more critical at higher speeds.
The Elcano Project

Build a vehicle demonstrating low cost autonomy.
Build more vehicles.
Build a control system that demonstrates the personal people mover.
Move to a commercial system.
Deploy a campus scale system.
Deploy city scale systems.
Software Architecture

Diagram showing the architecture of a system with components such as E Stop, Motor 1, Motor 2, SRS Controller, Hall Odometer, Optical mouse odometer, GPS, Navigator, Visual Odometry, Obstacle Detection, Pilot, Path Planner, and RNDF / MDF.
Components

Motor controller: Execute gamebot commands.

Pilot: Generate commands to follow a cubic arc at a set speed profile.

Navigator: Find current location and heading.

Camera monitor: Pick lane following, visual odometry and obstacle avoidance from smart camera.

Path planner: Generate arcs and speeds for requested trip.
Emphasis on Software

Vehicle specific behavior belongs to the motor/steering controller.

Gamebot interface:
  DRIVE {Speed ComandedSpinSpeed}
  {FrontSteer ComandedSteerAngle}

Open source simulator: USARSIM

Localization from digital maps (RNDF), lane following and odometry.

Main AI is vehicle independent.
Autonomy is 1st step

Making an autonomous vehicle is a 6 month project.
Real technical challenge is to safely control several vehicles.
Marketing the system is a major challenge.
Getting Involved

http://sourceforge.net/projects/urbanchallenge/
tyler@tfolsom.com
Engineers
Software developers
Artists and graphic designers
Business people
Letters of support from potential customers and partners