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Self-driving Tricycles

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Abstract: Bicycling can be promoted by proper infrastructure design. However, much of the urban developed world is burdened by decades of automobile-based design. Changing the infrastructure is a major undertaking. A more realistic approach may be to change the bicycle.

There are practical reasons that inhibit bicycling, such as inclement weather, hills, and clothing that is inappropriate for exercise. These can be mitigated by HPV designs that protect against rain and provide an electric helper motor for hills. Status is a more important factor; people feel more important when they replace their bike with a car. We therefore propose creating a high technology bicycle that can be viewed as a step up from a car.

Self-driving cars are evolving rapidly. Google has driven its autonomous cars more than 500,000 km in California traffic. The Mercedes S-class may be capable of driving itself today, but laws stand in the way. A large connected vehicles demonstration is in progress in Ann Arbor, Michigan. Sophisticated Intelligent Transportation Systems (ITS) are in place in Japan. Europe has demonstrated the SARTRE project, where a semi-autonomous road train drove 190 km on Spanish freeways.

Full self-driving equipment currently costs thousands of dollars, and may seem inappropriate for a bicycle. There are two methods that can integrate bicycles into urban ITS systems of the 21st century.

1) *A simple device such as a smart phone can broadcast the cyclist's position and velocity to other vehicles. Alternatively, automotive radar systems are capable of detecting bicycles and pedestrians.*
2) *The cycle itself can become self-driving and safely blend with motor vehicles.*

This paper presents designs for the second option.

If road vehicle automation can make traffic accidents rare, a bicycle is almost as safe as an SUV and can mix with big vehicles on city streets. We have built a self-driving recumbent electric tricycle, with a total materials cost under $5000 for vehicle, motor, batteries, sensors, actuators, and electronics. This vehicle is purely electric, with a choice of manual drive-by-wire from a joystick or full autonomous operation from microprocessors. Future designs could be hybrid electric / human power. A hybrid human powered vehicle (HHPV) could form the backbone of an urban transportation system and offer faster and more convenient service than a car, bus or train. Urban transportation could be based on electric vehicles getting 0.25 L/100 km (1000 mpg) equivalent, and run entirely on renewable energy. A 10 kg lithium battery would provide sufficient power. Range anxiety would disappear, since a light battery can be swapped in less time than it takes to fill a gas tank. The bank of discharged batteries provides a buffer for storing wind and solar energy.

We stand at a historic cusp, where the transportation systems serving our cities may be on the verge of changing drastically. In the US, it is possible that bicycle mode share will increase significantly beyond the current 1%. But even if other cities can reach the 38% share of Copenhagen, 62% of people will not be cycling. This paper is directed to non-bicycle users, and attempts to use technology to make their journey as energy efficient and non-polluting as possible.

Various factors inhibiting bicycle use have been identified among people who bicycle to work frequently or occasionally [1]. These include:

- Weather: Rain, temperature and wind
- Distance and the need to work at multiple locations
- Need to wear business attire and desire to avoid perspiration

Pleasant weather has a positive effect on bicycle usage. Women cyclists are often concerned about [2]

- Safety
- Being able to carry daily items
- Need to fix hair on arrival

The health advantages of cycling outweigh the risks [3]. However, one might conjecture that people who never commute by bicycle perceive cycling as a risky activity. Various programs have been undertaken to encourage cycling and reduce traffic congestion. There are at least 100 bike-sharing programs operating in 125 cities worldwide [4].

Adverse cycling factors can be mitigated by Human Powered Vehicle (HPV) designs that protect against rain and provide an electric helper motor for hills. Status is a more important factor; people feel more important when they replace their bike with a car. This is particularly evident in China, where an increasingly prosperous middle class has replaced bicycles with cars [5]. As this trend accelerates in China, India and other developing countries, the unsustainable pressure on global resources intensifies. We therefore propose creating a high technology bicycle that can be viewed as a step up from a car.

Reducing one's carbon footprint is often presented as a sacrifice, settling for something that is less fun and less convenient. On the other hand, efficient technologies such as electric or hybrid cars are often depicted as too expensive for the average person to afford. Our goal is to devise a mode of urban transportation that is more convenient, faster, safer, and less expensive than any alternative. This mode will also be the most environmentally benign; people will choose to have a low carbon footprint for non-altruistic reasons.

Korea has the worst traffic accident rate of any developed country. They have set the goal of bringing traffic fatalities to zero by 2030, while doubling highway capacity and halving greenhouse gas emissions [6]. Road vehicle automation can achieve these outcomes. Once such a system is in place, vehicle size and energy consumption can further shrink to the point that automated vehicles bear a strong resemblance to human powered vehicles. Cars would see bikes even when the drivers don't, and the car would not let the driver hit the bike. Thus bicycles will be safe in mixed traffic, even without infrastructure modifications.

This argument does not detract from the desirability of planning bicycle friendly infrastructure. However, automation does not figure in many thirty-year transportation plans, and its advent may be as disruptive as the Internet. Few people could foresee the ramifications of the Internet thirty years ago.

There are a number of factors driving a transportation revolution [7]:

- high price of oil
- concern for climate change
- concern for urban pollution
- concern for sustainability
- avoidance of international conflict over energy resources.
- improved electric vehicles
- autonomous road vehicles
- congestion

The automobile does best on the open road, and there is a perception that it is well matched to the US because of the wide open spaces. However, 65% of US Vehicle Miles Travelled (VMT) are urban, and most trips are short; 88% of Americans drive alone to work, and few regularly use their cargo-carrying capacity [8, 9]. Thus it is appropriate to concentrate on urban travel, where traffic often stops or slows. Typical urban car speeds are given in Table 1. It is seldom possible to achieve an average speed of 50 km/h (30 mi/h) or greater on an urban trip. The data from Yakima show that even in a small town, travel speed is less than posted speed during peak periods [10]. Most of the roads in this study were posted for either 35 or 30 mph, with slower measured speeds on the 30 mph sections.

Table 1. Typical urban car average speeds

Location	**Mi/h**	**km/h**	**Notes**
U.S. average commute	28	45	Average trip length is 12 mi.
U.S. EPA city fuel rating	19	31	City driving cycle assumes 43% stopped or decelerating [11]
Japan city fuel rating	15	24	52% stopped or decelerating [11]
Mumbai, India	5-19	8-30	Minimum and maximum average speed [12].
Yakima, WA, USA	23.86	38.48	Average of 44 segments posted for 35 mph during PM peak.

Transit doesn't do better. Typical light rail speeds are given in Table 2. When one considers wait times and the last km from the station to the true origin or destination, the performance is worse than tabulated. Bus lines are often indirect and infrequent.

Table 2: Typical urban light rail average speeds

Location	**Mi/h**	**km/h**	**Notes**
Seattle, USA	22	35	Downtown to airport is 15.5 mi, scheduled in 38 minutes plus 5 minute average wait time [13].
Vancouver, Canada	28	45	Does not include wait times
Tokyo, Japan	16	26	Marunouchi line from Kasumigaseki to Ikebukuro travels 10.8 km in 25 minutes
New York City, USA	17.4	28.1	Average subway scheduled speed [14]
Chicago, USA	29.2	47.1	Average scheduled speed [14]
Washington, DC, USA	29.5	47.6	Average scheduled speed [14]

City bicycle speeds can be competitive with other modes; other papers at this symposium deal with how to make the bicycle a more frequent choice. The question addressed in this paper is: how to offer improved transportation options to the non-cycling public that are environmentally benign.

A good place to start is Personal Rapid Transit (PRT), an idea that has been explored since the 1960s. PRT is characterized in [15] as

1. Fully automated vehicles capable of operation without human drivers.
2. Vehicles captive to a reserved guideway.
3. Small vehicles available for exclusive use by an individual or a small group, typically 1 to 6 passengers, traveling together by choice and available 24 hours a day.
4. Small guideways that can be located above ground, at ground level or underground.
5. Vehicles able to use all guideways and stations on a fully coupled PRT network.
6. Direct origin to destination service, without a necessity to transfer or stop at intervening stations.
7. Service available on demand rather than on fixed schedules.

Figure 1. PRT system at Masdar.

While there are currently 130 driverless train systems in operation worldwide, there are only three operating PRT systems [16]. The three PRT systems include the rail system that has been operating in Morgantown, WV since 1975, though it is based on larger vehicles. The other two systems have been recently constructed and are based on vehicles running on dedicated, paved guideways. They are located at London's Heathrow Airport and the environmental city of Masdar, UAE, shown in Figure 1. The tire marks evident in the picture result from precisely following the same path. PRT vehicles were often envisioned as traveling on light elevated rail guideways. Their proponents argued that these light-weight guideways would be inexpensive to construct, but the cost of constructing a city-spanning network has worked against the idea. The failure of PRT to win widespread acceptance can be attributed to several factors:

- An up-front investment is needed to build an entirely new infrastructure.
- Captive vehicles are plagued with the last and first km problem of system access.
- Traffic planners are reluctant to commit to a system that has not already been demonstrated elsewhere at the same scale.
- Supporting technology was not readily available in the 20th century.

Some futurists talk of 100 mi/h cars; such a goal is not desirable and would only exacerbate sprawl. Sustainable transportation requires that we look at present transportation demands, and build an improved system serving those needs. Moving people from true origin to destination at an honest 50 km/h (30 mi/h) average speed in the city is a major improvement, and it is achievable through automation. Automation presents two paradoxes:

1. Trip times can be substantially shorter despite lower maximum speeds.
2. Fewer highway lanes can carry more traffic.

The first effect is the result of going from origin to destination in a reserved lane with no stops. The second effect comes from increased highway capacity when automated vehicles are operated in platoons.

The energy needed to move a vehicle is the sum of energy to overcome rolling resistance and energy to overcome aerodynamic drag. Lower maximum speeds lead to more efficient energy usage in two ways. Drag energy is proportional to the cube of speed, so doubling the speed requires eight times more energy. Rolling energy is directly dependent on speed, so when speed doubles, this part of energy only doubles; however frequent accelerations require more energy. Thus the PRT paradigm of no stops between origin and destination uses energy efficiently.

Energy to accelerate or to overcome rolling resistance is proportional to the mass of vehicle and passengers. A 1682 kg (3700 lb) vehicle carrying an 86 kg (190 lb) man has 10 times as much rolling resistance as a 91 kg (200 lb) vehicle carrying the same rider.

As vehicle mass goes down, the relative importance of overcoming wind resistance increases. For cars, energy to overcome rolling resistance is greater until 55 km/h (35 mi/h); at higher speeds aerodynamics dominates. For bicycles, the cross-over point comes at 20 km/h (12 mi/h) [17]. Highly efficient light vehicles must have small frontal area and be carefully streamlined. When streamlined ultra-light vehicles are operated at reasonable speeds, and avoid unneeded accelerations, fuel efficiencies of 0.25 L/100 km (1000 mi/gal) equivalent are possible. [18].

Energy consumption at 50 km/h (30 mi/h) is shown for various vehicles in Figure 2 [17]. A single occupancy automobile getting 6.6 L / 100 km (38 mi/gal) requires 31 kW (42 hp). When the vehicle is loaded with five people, efficiency improves to 7 kW/person, rivaling a diesel commuter train's 6.5 kW/person. Anyone capable of moving a bicycle at 50 km/h is expending 1.7 kW. Aerodynamics makes an HPV even more efficient, requiring only 0.64 kW (0.86 hp). This true regardless of the power source, be it human, gasoline, or electric. In the US, a tricycle with a 0.75 kW electric motor is legally a bicycle.

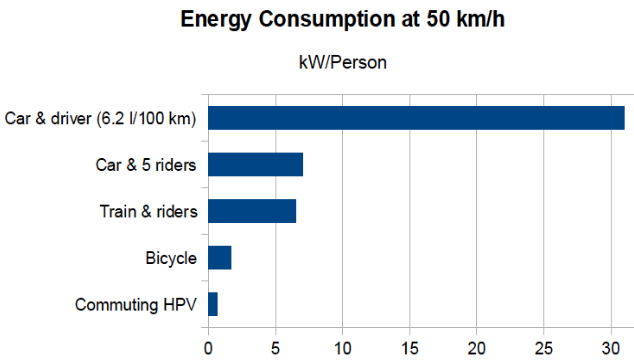

Figure 2. Energy Consumption

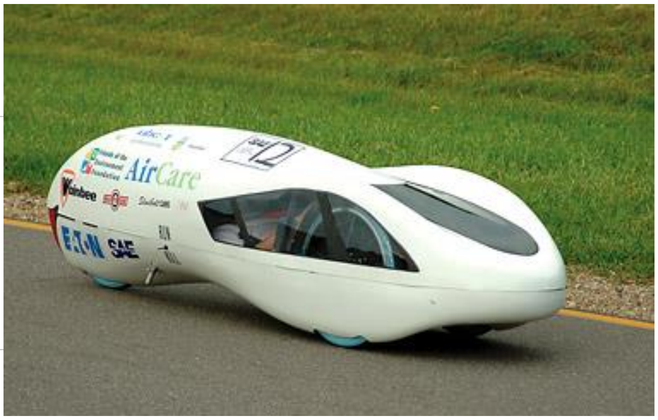

Figure 3. UBC vehicle at SAE competition

Experimental vehicles modeled on the HPV have achieved remarkable performances on the track, though these are not practical vehicles. Students at the University of British Colombia built the vehicle shown in Figure 3 for the Society of Automotive Engineers (SAE) supermilage competition; it achieved 0.075 L/100 km (3145 mi/gal) at low speed [19]. An electric vehicle travelled 100 km (62 miles) in one hour, equivalent to 0.11 L/100 km (2200 mi/gal) [20].

It has been pointed out that the posted speed limit may have little to do with actual speeds [21]. A side effect of vehicle automation is that speed limits become real. The speeds at which automated vehicles are operated must be set to conform with driver expectations of the proper speed. There is a danger that legalism and fear of liability will lead to unrealistically low speeds, which will drive away riders. The system's operating speed is set by the government. The speed should be fast enough to attract riders, but slow enough to optimize energy use.

Today, cars that drive themselves or offer extensive Driver Assistance Systems (DAS) are picking up where PRT left off. Automated bus docking systems have been demonstrated. DAS may provide automatic parking, Adaptive Cruise Control (ACC), lane departure warnings, or collision avoidance systems. An ACC system detects the distance and speed of the closest in-lane vehicle ahead and modifies following speed. Better traffic throughput is achieved by Cooperative Adaptive Cruise Control, in which a platoon of vehicles shares information [22].

Google has driven its autonomous cars more than 500,000 km in California traffic and expects to have its system on the market within five years [23]. The Mercedes S-class may be capable of driving itself today, but laws stand in the way [24]. Most of the world's motor vehicle codes are based on the Vienna Convention on Road Traffic, a 1968 UN treaty. It states “Every moving vehicle or combination of vehicles shall have a driver”.

A large connected vehicles demonstration is in progress in Ann Arbor, Michigan [25]. The one-year Safety Pilot involves 2,836 communicating vehicles, and is scheduled to conclude on August 18, 2013. Sophisticated Intelligent Transportation Systems (ITS) are in place in Japan [26], which is evaluating whether to implement highway road trains by the early 2020s. Europe has demonstrated the Safe Road Trains for the Environment (SARTRE) project, where a semi-autonomous road train drove 190 km on Spanish freeways [27]. In a road train, the lead vehicle is professionally driven, and the following vehicles are under automated control. Volvo was part of the consortium in the SARTRE project, and has set the goal that none of its vehicles will be involved in crashes.

An isolated autonomous vehicle will improve safety, but it will do little to relieve congestion. The system-wide improvements occur when automated vehicles communicate with each other, and operate in platoons. Driving in closely-spaced platoons can increase highway capacity by a factor of three to eight [28]. It follows that one or more freeway lanes should be reserved for automated cars and buses; otherwise manually driven vehicles would insert themselves and snarl the lane. An HOV lane could be repurposed for automatic operation, minimizing the infrastructure costs. Even when the automated lane operates at a fraction of its capacity, it can divert enough vehicles from the manually driven lanes to increase the manual freeway capacity, despite the lost lane.

Thus road vehicle automation works best when the automated vehicles are in separate lanes. This in turn simplifies the technology for automation, removing the need for expensive radar or lidar systems to detect unforeseen events. If the vehicle always operates on fixed routes, these can be digitally mapped accurately, and the odometer and compass are sufficient to determine position. An occasional GPS fix or landmark can reset odometer drift. Low cost laser or sonar rangefinders can determine the distances to neighboring vehicles. Adjacent vehicles can be in wireless communication. Every tenth of a second, they can share current positions, velocities, and planned maneuvers; most unexpected behavior goes away.

An automated road vehicle in a reserved lane satisfies most of the characteristics of PRT. The only exception is that the vehicle need not be captive to the guideway. It may exit the automated system, and turn control over to the driver. Such a vehicle is called “dual mode”. It eliminates the first and last mile problems of public transport, but can benefit from automation for the middle portion of the ride.

There are technical issues on safely transitioning between manual and automated modes, and in certifying that a vehicle is fully capable of automated operation, and has not been tampered with. Such security can be designed into hardware systems. A dual mode vehicle attempting to enter an automated system would be electronically queried for credentials, established at the vehicle's last inspection. These credentials can include enforceable limits on vehicle dimensions, weight, emissions and fuel efficiency.

Driver assistance systems that rely on operator intervention during a crisis may fail if a driver is unresponsive; after all, one of the attractions of self-drive is being able to do other things, including sleeping. It is preferable to depend entirely on automation, and prohibit direct driver intervention. Otherwise, a nervous driver might panic at the tight spacing, slam on the brakes, and collide. The corollary is that a dual mode vehicle must be drive-by-wire, with no mechanical controls.

When the computer is operating all vehicles in a lane, there should be no collisions. Motorcycles would be almost as safe as trucks. Bicycles could join the stream if they can keep up and take orders from the traffic control computer. Human powered vehicles have reached 130 km/h (82 mi/h) [29]; with a suitable aerodynamic fairing and a third wheel for balance, a bicycle can run with the big boys. In order to strictly follow instructions from the computer, such a cycle would need to have automated propulsion, steering, and brake systems. It is possible to build a hybrid human / electric powered vehicle in which the rider pedals to charge one battery, while a separate battery powers the vehicle. Electronics can be built to swap the traction battery and charging battery at the right time.

There is a critical opportunity within the next several years to design automated lanes and vehicles. If this opportunity is missed, automated vehicles will just be improved automobiles; they can be much more. A smoothly operating system requires not just the travel lane, but a lane for exiting from the middle of platoons or merging onto the end of one. Right of way scarcity makes it desirable that an automated lane be half the width of a standard lane, thus allowing conversion of an existing lane into both an automated travel lane and a transition lane. This in turn dictates that automated vehicles should not be much wider than one meter; wider vehicles may be possible, since computer drivers tolerate narrow lanes better than human drivers.

Thus an automated vehicle might look like a HPV powered by a small electric motor. It might carry two passengers, either seated in tandem or side-by-side. These vehicles could be electronically or mechanically coupled to form a larger vehicle traveling as a unit. Such a modular vehicle adapts to the size of the group and their cargo as needed. When operated on city streets as a road train, the vehicles link together to form a modular bus [30].

Self-drive can be far more than an improved automobile. Automated road traffic produces an entirely new transportation mode offering

- Convenience of the automobile
- Public access of the bus
- Size of the motorcycle
- Energy efficiency of the bicycle
- Safety of the train
- No congestion

A highly aerodynamic light vehicle traveling at modest speeds requires little energy. An electric urban vehicle could be powered by a 10 kg lithium battery [31]. Light batteries enable refueling by battery swap. The swapped out batteries can be recharged at any time of the day or night, particularly those times when wind or solar power is available. Thus urban transportation from renewable, non-polluting power is feasible. Since the vehicles are automated, the riders need not be concerned with battery charge; the vehicle will stop at a refueling station when needed. Most trips to the refueling station will be done by riderless vehicles.

It is not enough to invent a superior transportation mode; we must consider implementation. Any system requiring an entirely new infrastructure will be stillborn. How does the first self-drive vehicle get onto the road? Nevada has been touted as the first state to legalize autonomous vehicles. In fact, what they have done is to require that an experimental autonomous vehicle have two people on board monitoring it; don't expect to get driverless pizza delivery in Nevada. How much testing will be required to convince authorities that automated vehicles are safe? Is there any test program that can anticipate all possibilities? Even if there is, if the vehicle has evolved over time, how can we be certain that the current version is still safe on all tests? How can politicians be motivated to change motor vehicle codes? Who will be liable if something goes wrong?

As mentioned above, the first automated vehicles on the highway are likely to form a road train, following a vehicle with a driver. This technology could be brought to city streets to form a modular bus [30]. The bus would consist of small pods. The main bus would not stop at bus stations; pods would accelerate as the bus approached, and join onto its rear. Any pod could exit the train from the middle, with the other pods forming up to fill the gap. The public pods would belong to the transit agency and initially only operate with the modular bus.

Once a city begins to operate modular buses, it is a small step to route them on dedicated busways or HOV lanes. If there are no other vehicles in these lanes, there may be no need for the human-driven lead vehicle. The system would evolve into a PRT-like system operating on converted lanes. The paradigm is similar to light rail in that the city provides both the vehicles and the lanes.

Such a pod-based transit system might add elements of vehicle-share. The city could purchase dual mode pods, and allow people to drive then after leaving the automated system. Once such a system has proven itself, it could admit privately-owned dual mode vehicles.

The Elcano Project has built a prototype for an ultra-light dual mode autonomous vehicle, shown in Figures 4 and 5 [32, 33]. It is built on a standard tadpole recumbent tricycle, modified to be an electric bike. Total cost of components is under $5,000, including the mechanical chassis, electronics, sensors, and actuators. Derailleurs, sprockets, and chain are replaced by a hub motor powered by lithium batteries. A standard e-bike controller responds to the throttle. The operator uses a joystick to control the vehicle. A heavy duty servo steers the front wheels. A second servo pushes the dual cable brake lever to activate disk brakes on the front wheels. A similar system could be used to control an automobile; the tricycle steering is Ackerman, and the servos provide enough thrust and robustness. It is possible to use regenerative braking from the electric motor to charge the battery.

Figure 4. Elcano unloaded; seat removed

Figure 5. Elcano with rider

The machine was originally built to compete in the Seattle Robotics Society's Robo-Magellan contest for outdoor autonomous robots [34]. The contest requires each robot to navigate to latitude and longitude points that are revealed only at the start of the race. The project is named after Juan Sebastian Elcano, the first European to sail around the world. Ferdinand Magellan never returned from his journey; he was killed in the Philippines. Elcano managed to bring 18 survivors back to Spain. The open source code and electronics of the Elcano Project is designed to make completion of Robo-Magellan easy. The first prototype vehicle satisfies the 50 pound (23 kg) weight limit and four foot (1.2 m) dimensional limits of the contest when the boom is removed.

A micro-computer controls the prototype vehicle. An operator uses a joystick: up to accelerate, down to brake, left or right to turn. The computer interprets these motions, and sends appropriate signals to actuator controllers. The next phase is to replace the operator with a set of small computers. Custom electronics have been designed and fabricated to make the systems robust. A second prototype vehicle is being configured by the Computer Software and Systems Department of the University of Washington, Bothell. Dr. Folsom will direct his Embedded Systems class to complete the software for autonomous operation starting in Fall, 2013. The Elcano Project is cooperating with other groups interested in making self-driving vehicles. A suitable simulator is being developed at Rutgers University. The Elcano design is also compatible with the USARsim simulator, which is designed for a wide variety of robots, including automated road vehicles. Use of a simulator enables research by groups not having access to a physical vehicle.

Automotive radar and lidar systems cost thousands of dollars; the Elcano self-driving cycle omits them. In a group of vehicles, a less well-equipped vehicle can increase its knowledge of its location and surroundings by communicating with vehicles with better sensors [35]. The present design is based on an inexpensive sensor suite:

- Global Positioning System (GPS) receiver.
- Inertial Navigation Unit (INU) which provides a digital compass and tilt sensor.
- Cyclometer, measuring odometry from the wheel.
- Modified optical mouse, which gives two-dimensional optical odometry.
- Sonar range finders, which can detect obstacles.
- Digital camera to find lane markings, vehicles or landmarks.
- Digital map of intended route.

System organization is given in Figure 6. There is a break between the low level micro-controller (designated C2) that spins the wheels and points the steering, and the higher level processors that find route and position. The prototype demonstrates low level control; an alternate micro-controller and actuators could handle any other vehicle ranging from a radio controlled toy car to a full sized car. The higher level functions are independent of the vehicle.

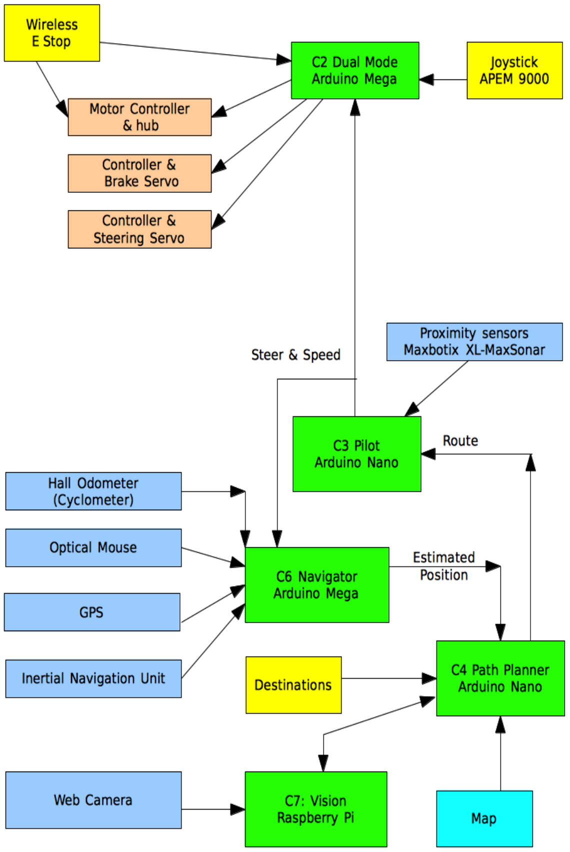

Figure 6. Architecture

The higher level navigation is performed by three separate processors, operating continuously:

1. A localization processor (C6) reads sensors and forms the best estimate of current position and heading.
2. A route finder (C4) reads a digital map of the area, inputs the current location, and selects the best path to the destination.
3. A pilot (C3) directs the vehicle to follow the next segment of the route, deviating around any obstacles that it finds.

Additional processors (C7) may be assigned to high information sensors, such as a camera. Communications with other vehicles would need an additional processor.

Alternately, all these tasks could be implemented on a single computer or smart phone. We have instead chosen to distribute the tasks among small processors to assure real-time availability without depending on an operating system. The hardware separation of computing tasks enforces modular design.

The production vehicle is envisioned to add an enclosed shell, providing superior aerodynamics and protection from the weather. The shell needs to be designed for easy entry and egress. It must provide proper ventilation, all weather visibility, and avoid solar overheating.

The goals of the Elcano Project are:

- Make autonomy available to non-specialists.
- Produce an experimental vehicle and electronics costing less than $5,000 total. A fully enclosed road-worthy production vehicle should cost less than $10,000.
- Generate public demand for road automation.
- Encourage high fuel efficiency (1000 mpg / 0.25 L/100 km) through ultra-light automated vehicles.
- Set standards for cooperative automation using a scalable distributed Traffic Management System.

The long term vision is not a single self-driving vehicle, but a collection of such vehicles that communicates with each other. Automatic vehicles can take instructions from a roadside Traffic Management Computer that manages a section of roadways. These computers would link together to form a distributed, scalable Traffic Management System; such a system can reduce congestion.

Conclusion

Autonomy changes the very nature of urban transportation. Its potential for safety is widely recognized. Less evident is its potential to break transportation's automobile fixation. When accidents become rare, vehicles of all sizes can safely mix. Vehicles can become modular and miniature, with additional carrying capacity added only when needed. Small vehicles require an order of magnitude less energy, breaking oil dependency, removing range anxiety from electric vehicles, and enabling sustainably powered transportation.

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