DEFINITION This framework document and forecast considers the long-term future of urban transportation. Framework documents, developed by Dr. Peter Bishop, chair of the M.S. program in Futures Studies at the University of Houston, are a document development tool used by some foresight professionals. They include resources for current assessment, forecasting, scenario development, community expertise, and further research. They facilitate the collection of a broad and balanced set of inputs to a basic forecast, the section in yellow below, one of several potential products of the framework document.

My forecast involves the expected construction, circa 2030±10 years, of our first underground automated highway systems (UAHS) in a high density urban environment, and their high probability post 2030 as a developmental attractor for solving urban transportation gridlock problems in our wealthiest cities worldwide in the 21st century. In support of this forecast, the framework document outlines such topics as progress in tunneling technologies, automated highway systems, smart cars, and zero emission vehicles. It also briefly considers technological, economic, political, and social issues relevant to underground automated highway systems and related infrastructure (underground parking systems, access and egress systems, and other underground structures and amenities) for urban environments.

Dongshan Tunnel in Anshui, China, opened 2008. Blue and white LED starlight lighting improves driver orientation.

SUMMARY The construction of underground automated highway systems (UAHS) may significantly increase the safety, speed, aesthetics, and capacity of goods and human transport in our largest and highest density cities in coming decades. When combined with underground parking structures at source and destination, such systems promise to increase metropolitan traffic capacity and throughput by at least another order of magnitude in their presently conceivable deployment, eventually halving or thirding today's average urban commute times, and reducing surface transportation architecture, noise pollution, and visual blight through the selective takeback of some of our most valuable surface architecture currently dedicated to surface transportation. Significantly more than an order of magnitude of additional transportation real estate is available for use underground, and such development can be done in a way that has either a negligible or positive effect on urban aquifers. UAHS will underpass today's heavily congested surface roads and greatly improve public accessibility to popular destinations, as well as facilitate substantially greater goods traffic from edge-of-city distribution centers to urban shopping and industrial areas. Their emergence depends on continued progress in several enabling technologies, including: 1) further improvement in automated tunnel boring, excavation, and shoring systems, 2) advancement in intelligent vehicles (IV's) and automated highway systems (AHS), and 3) development of ultra low and zero emission vehicles (ULEV's and ZEVs) which can navigate underground networks without buildup of polluting emissions.

Largest tunnel boring machine (TBM) to date. 15.7m diameter, Sparvo, Italy, 2011.

Assuming these enabling technologies continue to improve at historic rates, I would presently forecast that construction on the first underground corridors for AHS networks will begin circa 2030 in our largest and wealthiest cities, as that is about the time we are likely to have cheap and plentiful tunnel boring machines (TBM's), a limited surface-level AHS network in HOV lanes in a few cities, and a significant percentage (≥ 40%) of hybrid, ultra low, or zero emission vehicles in deployment. Underground automated highways promise unique benefits in visual and auditory aesthetics, urban space utilization, efficient and sustainable transportation, and automating a significant fraction of the urban commute for city inhabitants. While aerial automated transportation systems might one day offer even more scalability and lower construction cost, I propose that significantly more difficult technical problems, saturating need for urban transportation, and the superior environmental, aesthetic, and safety factors of underground vs. aerial transport will keep UAHS the primary priority in urban areas over the entirety of the twenty-first century. These systems will enable rather than reduce city densities and some forms of urban sprawl, but at the same time should significantly increase the quality of life and tax base within the world's leading cities. At present they appear to be a developmental attractor for mid-21st century urban transportation. While many cities may resist them, I would expect the overwhelming majority to implement them once they reach a certain size, density, and wealth threshold during the latter half of this century.

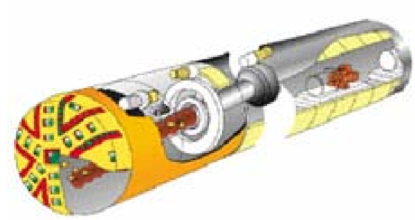
CURRENT ASSESSMENT

-- Current Conditions

- There are annually about 41,000 automobile-related fatalities a year in the U.S., and about 120,000 a year in Europe. Auto fatalities are the leading injury-related cause of death among people aged 15-44 years worldwide. 1.2 million people died and 39 million were injured in motor vehicle accidents in 1998. [11]
- Ninety percent of today's accidents are caused at least in part by human error. About 70 percent of today's accidents are caused predominantly by human error. Another 20 percent have some kind of component of human error that helped cause the accident. [10]
- Pedestrians and bicyclists are particularly vulnerable groups, making up 45% of all road deaths in the United Kingdom in 1996, 30% in Denmark, and a low of 17% in France.
- "Average travel speeds on the crowded commuter corridors near large U.S. cities drop to about 36 miles per hour at rush hour, leading annually to some 5 billion collective hours of delay and estimated productivity losses of $50 billion nationwide." [9]
- According to Worldwatch, the world's cities take up 2% of Earth's surface yet account for 78% of carbon emissions. Making their transportation networks more efficient would be a major benefit.
- Underground metro transport has gained important market share in large cities (notably New York, London, and Paris). Use of public transport by urban residents of major cities varies from a low of 7% in Los Angeles to a high of 83% in Mexico City. [2]
- Kansas City has 20 million square feet of industrial parks in old underground quarries under the city. Toronto and Montreal have extensive retail space beneath their downtowns. [8]
- Underground transportation of "fluid bulk goods" (electricity, water, sewer, natural gas, crude oil) is already a healthy and growing infrastructure in major cities. Microtunneling, or "trenchless technology" (installing and rehabilitating underground utility systems with minimal surface disruption) is a rapidly growing industry with many new publications and conferences.
- Countries like the Netherlands, Switzerland, Taiwan, Japan, and the U.S. are all presently engaged in extensive, multi-year, megascale underground tunneling projects. A few recent U.S. projects, such as Boston's 2.5 mile "Big Dig", have been boondoggles, but others, such as Alaska's Anderson Memorial Tunnel, have won engineering awards and come in ahead of time and under budget. In general, European and Asian countries seem better at deploying this technology at present.

Northbound entrance to the Tip O'Neill Jr. Tunnel, Boston, MA. Boston's "Big Dig" (2000-2006) was a slow (best internat'l teams and tech excluded), minimally automated, poorly managed, amazingly expensive ("cost plus" contracts) tunelling project. A big lesson for the future.

- Recent costs for underground construction and reinforcement ("mining, tailings disposal, and lining") of roadway tunnels have fallen as low as $1.50/cubic foot for the 11.5 km Flam-Gudvangden tunnel in Norway in 2002. Recent costs per cubic foot have been as much as 100X higher for other projects, such as $150/cubic foot for the Madrid Metro extension. Ideal geology, greater contractor experience, more automation, lower finishing requirements, and smaller size for a roadway vs. Metro tunnel all contributed to the low Norway figure [8].



- "The latest TBMs can slice corridors 40 feet in diameter through almost any kind of terrain, including sand, at rates of up to 20 feet per hour. They can dig horizontally, vertically, even in spirals. High-speed conveyors suck the tailings out of the hole, while a robotic rig automatically snaps sheets of lining in place like huge Lego pieces." [8]
- Partial Zero Emission Vehicles (PZEV's) run on gasoline but have to meet California's Super Ultra Low Emission Vehicle (SULEV) tailpipe standard, which is 90% cleaner than the average new 2004 automobile. PZEVs emerged as a result of California's Zero Emission Vehicle (ZEV) mandate, begun in 1990. The California Air Resources Board lists 90 gasoline-fueled car models that meet the ultra-low emission vehicle (ULEV) standard for the 2002 model year and six that meet the Super Ultra Low Emission Vehicle (SULEV) standard, with more expected to be added in 2003. [15]

-- Stakeholders

- Construction and tunnelling industry and unions
- Autonomous highway system and smart car engineers
- Zero emission vehicle developers
- Third party automobile electronics manufacturers (AHS car interiors)
- University research departments
- Sustainability advocates
- Urban planners
- City, state, and federal politicians
- Law enforcement (AHS's must be significantly safer, so they promise to free up major law enforcement resources from current traffic accident and control duties).
- City businesses, major traffic destinations, urban core.
- City-dwellers

-- History

- "In 1990, the California Air Resources Board mandated that by 1998, 2 percent of autos produced and sold in California must be zero-emission vehicles (ZEV's). That mandate was weakened in 1996 and instead automakers were required to produce and sell 10 percent ZEVs by 2003. The mandate was further weakened in 1998 when CARB agreed to only require 4 percent of the total car sales to be "pure ZEVs." The remaining 6 percent of the ZEV mandate could be met by "super, ultra low-emission vehicles (SULEV's)" and hybrids." [16]
- The U.S. Dept. of Transportation spent $50 million on AHS research from 1991 to 1997. This culminated in Demo '97, a National Automated Highway System Consortium demo in San Diego, CA, involving eight automation-equipped cars demonstrated a number of technology innovations, including:
  -- Lane keeping and close headway maintenance (platooning) at up to 65mph.
  -- Automated lane changing.
  -- Obstacle avoidance by both swerving and stopping.
  -- Simultaneous operation with heterogenous platforms, including buses.
  These AHS-equipped cars ran a total of about 8,000 miles, carried 4,000 passengers, and had no safety incidents. Interestingly, vision based technologies were as reliable as other sensing technologies such as magnetic markers. A subsequent budget crunch at DOT, combined with industry pressure for a shorter-term focus on safety caused the National AHS Consortium to be defunded even given these substantial achievements. Automated Highway System (AHS) and Automated Vehicle Guidance (AVG) initiatives continue to progress in Japan, the Netherlands, Germany, and other countries. [9]
- A 1997 German study looking for ways to reduce the environmental impact of urban goods shipments was one of the first to seriously consider automated underground shipment systems, showing their interest with sustainability-conscious planners. [4]
- Underground structures are known to be generally more earthquake-resistant than surface structures. With fluidized bed construction they can ride on "lakes" of gravel and be highly resistant to subsoil shifts. Example: 1995 Kobe Earthquake in Japan, which caused severe damage to the Kobe City Hall, but no damage to the underground shopping mall below it. (See picture below).

- Jet-fan ventilation was approved in the late 1990's and was allowed in the last section of the Central Artery (Big Dig) project in Boston. This eliminates the need for separate longitudinal ducting and saves 10-20% on tunnel construction costs.

-- Constants

- Few cities which have had underground metro systems in use for a substantial time regret the choice to build that system and to place it underground near and adjacent to the city center. [2]
- The heat of ambient earth is around 57 degrees in mid-latitudes. That constancy keeps underground heating and air conditioning costs low.
- One rule-of-thumb for transit has been that a fixed rail mass transit system becomes viable for city populations over 1 million people. In the first decades of their use, UAHS might only be viable for very

large cities, or for smaller cities with unique density, affluence, mobility, and social diversity.

FORECAST

-- Cycles

- Economic cycles influence the ability to finance high capital projects such as underground tunnel networks. One would expect the long term financing required to emerge in countries at the peak of their economic health. If sufficient attention is not given to political and economic fluctuations, megaprojects may be abandoned when support weakens, as with the Superconducting Supercollider Project in Texas, abandoned in 1993 after $2B of a projected $11B had been spent.
- Present highway usage follows predictable peak/off-peak cycles limited by population size. Unmanned ground vehicles (UGV's) might expand the number of vehicles in a city, but as with current city parking and freeway metering their use would very likely be carefully regulated to ensure lack of congestion on AHS networks.

-- Trends, Extrapolations

- Automobile use and enjoyment continues to rise as new interior features make personal automobiles a more attractive investment. AHS's promise the merger of the best of mass transit and personal vehicular use in one heterogenous electronic routing system.
- The use of the single-occupant car has continued advance against all efforts to induce both public transit and carpooling behavior. "Transit trips are now less than one in 50 person trips in U.S. urban areas, the latest hard number being 1.8 percent for 1990. Far from increasing as predicted by transit advocates, transit has been losing ground despite taxpayer support that covers all its capital and half its operating costs." [14]
- U.N. demographers estimate half the world will live in cities by 2007. Nearly all population growth for the foreseeable future will occur in urban areas, with most of this in developing nations.
- "The number of megacities (population over 10 million) is rapidly increasing, with almost all the growth in the developing world. In 1950, there was only one megacity in the world, New York. Today (2002), there are 17." The megacity trend bypasses Europe, where population is shrinking. [5]
- The oft-quoted cost ratio for surface vs. elevated vs. underground transportation costs was 1:3:6 in the 1990's. Median ratios from a 1995-1998 report from 30 cities in 19 countries were approximately 1:2:4.5. There is evidence this ratio is continuing to drop for underground construction. [2]
- Cut-and-cover tunneling has become increasingly difficult in urban areas due to traffic and construction delays. Fortunately, shield tunneling has made significant progress during the 1990's, and now permits safe and cost-effective construction even in very soft water-bearing ground. [3]
- Surface land cost in large cities has been skyrocketing in recent years, and may continue to do so as the plethora of social options in megacities continue to make them more desirable than other living areas. The cost of using surface land for new highway construction projects is already prohibitive.
- Fred Hapgood: "A Moore's Law for TBMs would claim the number of TBMs working at any given time doubles every decade. There were maybe 5-6 in the early 1960s, 10-15 in the early 1970s, 25-30 in the early 1980s, 50-60 in the early 1990s, and around 125 in 2003. Will the curve continue? Will there be 250 in 2015, 500 in 2025, and 1000 in 2035? Why not?"

-- Plans

- The National Intelligent Transportation Systems Program Plan of 2002 [12] has the following 10 year goals:
  -- Safety. Reduce transportation related fatalities 15% by 2011, saving 5-7,000 lives.
  -- Security. Better protect against natural and man made disasters.
  -- Economy. Save at least $20 billion per year by enhancing national traffic throughput and capacity.
  -- Access. Improve availability of traffic system information for all users.
  -- Energy. Save one billion gallons of gasoline each year and reduce emissions in proportion.
  Funding incentives of $101-$122 million/year have been provided for this process since 1998.
- Public plans for underground construction, tunnel boring machine construction, intelligent vehicle deployment, and hybrid, ULEV, and ZEV vehicle development may also exist, but were not evident in my initial search of this space.

-- Basic Forecast

- Digging transportation networks underneath our largest cities will offer us a major new advance in our matter-, energy-, space-, and time-efficiencies of social interaction. Increasing such social computational efficiencies may be the primary purpose guiding city structure.
- Smart cars and intelligent transportation systems stand to significantly reduce annual automobile fatalities. Automated highway systems and improved passenger safety systems in AHS-equipped automobiles may cut fatality percentages dramatically, perhaps even below 1/5 of their present rate in early deployments, particularly if they are initially run at slower speeds (e.g., max 50 mph) than manual driving.
- While the present 41,000 automobile-related deaths a year in the U.S. are presently tolerated as the necessary cost of current technology, this annual loss represents perhaps our leading source of what Richard Rhodes calls “structural violence” (unavoidable risk to life, unlike personal health choices) in the developed world. As soon as our aboveground AHS networks show significant reductions in this fatality rate, there will be a public groundswell to increasingly expand their use. Only UAHS offers the scalability to allow both continued city density increases and increasing AHS use in our leading cities.

- In the controlled environment of underground tunnels, which allow additional grids of wall and roof sensors, one would expect AHS safety to be even greater than on AHS surface roads. We may choose to offset some of this additional safety margin by operating at higher speeds in underground networks.
- AHS systems will save at least 50% on fuel efficiency by converting stop and go to relatively continuous driving [4]. Further energy efficiencies can be achieved due through regenerative braking systems, platooning (drafting), streamlining, and other refinements.
- U.C. Berkeley PATH simulations estimate that AHS would double or triple conventional highway capacity. Using embedded roadbed sensors, HOV lanes might be upgraded to AHS lanes at a cost as low as $10,000/mile, versus the millions of dollars per mile involved in their initial construction. AHS are networks thus not necessarily expensive, just a lot more intelligent than current navigation technologies. They are much more about dramatic safety increases than about capacity increases.
- Adding AHS capacity to a single inside lane of a three-lane (one way) corridor, which would be its most likely surface implementation, will thus cause only a 66% increase (from three to five effective lanes), assuming AHS triples average capacity per lane. But were we to also excavate an additional eight lanes (one way) for an underground AHS corridor that would expand us from three to twenty-nine effective lanes: a 9.7X capacity increase. That is a transportation system capable of supporting a whole new level of social complexity, and there is plenty of space for that and more under any city.
- Our tunnel boring machine (TBM) technologies have been rapidly and dramatically improving since 1994's completion of the Chunnel, the $21 billion, 31-mile rail tube that connects France and Britain. Today TBMs are highly automated, with robotic systems that lay tunnel linings, with robotic shotcrete tunnel support systems, and with semi-automated waste rock and muck transport systems. Tomorrow, most of the human operators may even remain above ground, tele-operating excavation systems away from the danger of the rock face. Costs for digging are dropping dramatically as well with the 2002 Flam-Gudvangden tunnel in Norway (in ideal geology) coming in at $1.50/cubic foot. Considering the spiraling cost of surface land, and the increased desire of city dwellers to be insulated from the noise, visual blight, and inconvenience of construction, I predict underground transportation projects will become more cost-competitive every year forward by comparison to surface transportation projects in high density urban environments.
- One important cost savings may occur when single-lane surface AHS networks exist in a metropolitan area. Such networks could be used by unmanned ground vehicles (UGVs) to autonomously ship out waste rock from excavation sites. Trucking excavated rock, dirt, and muck (“spoil” or “tailings”) offsite can be a large fraction of construction cost. With UGV disposal trucks this cost may be substantially reduced.
- Over the next two decades we will see increasingly intelligent new-model vehicles with lane departure warnings, adaptive cruise control, collision avoidance systems, road condition communication features, and other navigational advances. Perhaps circa 2025 we may expect our first pilot automated highway system (AHS) lanes on the highways of a few pioneering cities. As the surface network and safety record grows, converting to AHS-ready cars will be increasingly compelling, as 21st century multi-taskers can simply do a lot more with the autopilot engaged than they can when their hands, feet, eyes and brains must attend to the road. For the first decade or so drivers may be required to remain in their seats in case of need for manual override, and be allowed to nap upright, but with in-car entertainment and IT technologies this will still allow significant and compelling new freedoms to the driver.

- "A driver electing to use an automated highway might first pass through a validation lane, similar to today's high-occupancy-vehicle (HOV) lanes. The system would determine if the car will function correctly in an automated mode, establish its destination, and deduct any tolls from the driver's credit account. Improperly operating vehicles would be diverted to manual lanes. The driver would then steer into a merging area, and the car would be guided through a gate onto an automated lane. An automatic control system would coordinate the movement of newly entering and existing traffic. Once traveling in automated mode, the driver could relax until the turnoff. The reverse process would take the vehicle off the highway. At this point, the system would need to check whether the driver could retake control, then take appropriate action if the driver were asleep, sick, or even dead." [9]
- One optimistic projection by the National Academy of Engineering, the one most likely if present trends continue, forecasts that by 2025 50% of all new vehicles shipped in the United States will be hybrid, about 10% will be hydrogen fuel cell, and about 40% will be conventional. From that point forward both hybrids and conventional autos are expected to shrink in market share, and by 2040 almost all new vehicles shipped in the U.S. will be hydrogen fuel cell.
- By 2030 a wide variety of ultra low emission and zero emission vehicles (ULEV's and ZEV's) will be on

the market. Hybrid, electric, natural gas, and hydrogen automobiles will be able to operate in ZEV mode for long distances underground, and many new gasoline-using cars, SUV's and trucks will be available in ULEV and perhaps even ZEV configurations. Tunnel ventilation technology will likely have advanced to the point that ULEVs will be able to travel long distances underground without inordinate expense for emissions ventilation of the tunnel.

- It seems likely that only AHS-equipped, ZEV's or ULEV's will be allowed underground. After an initial safety-conscious stage of reduced maximum speeds (perhaps 50 mph), I would expect some cities to increase their AHS allowed speed limits on inside lanes to speeds above their manual driving speed limits. By that point, average transit times might be halved or cut in third by comparison to today's surface driving options.
- Underground parking lots and rapid deployment emergency vehicles are key components to the urban UAHS. If a driver goes to sleep and doesn't wake up in time to take over the controls when she reaches her destination, she'd be automatically routed to an underground lot. In our increasingly space-conscious future, many city dwellers might pay rent to store their cars permanently in underground megalots, freeing up their residential garage space for extra living room. Such lots would also lease space to car co-ops and car rental agencies.
- As above-ground parking infrastructures go underground in coming years, some fraction (10%? 15%?) of surface roads and highways might be rezoned and reclaimed by cities as greenbelt, bringing walking, biking, and beauty back to some of our most blighted urban environments. One of the selling points of Boston’s Big Dig to its citizenry was the 40 acres of new park created in the Charles River Basin.
- With good management, we can even envision nature trail networks emerging on a small fraction of reclaimed and lesser-used surface streets in our more foresighted metropoli, linking the city’s parkland as a chain of emerald islands, and providing recreation and low speed urban transportation for that increasing fraction of urbanites who would like the option to use human-powered bicycles, electric bicycles, and other low-speed electrics, such as Segways, for local commutes. Cruising through the greenery at a computer-governed 15 to 20 mph, getting a workout if one wants, and enjoying the view seems like a highly socially and politically desirable future for urban and community planning.
- When considering the green future promise of UAHS we can consider Leuven, arguably the most pleasant town in Belgium, where almost all city car parks are located underground due to special historical circumstances. This has allowed them to make many of the main, high-density streets pedestrian only, the ideal for a livable city. A ring and spoke design and a network of one way streets near the core further simplifies aboveground traffic flow.

- Consider also Switzerland's aesthetic for underground entrances, as seen in the Mont Russelin tunnel on the A16 highway below:

ALTERNATIVE FUTURES

-- Potential Events, Wildcards

- The economics of underground AHS may not be compelling with four-lane subsurface corridors, but may require six-, eight-, or ten-lane one-way corridors to provide congestion-free commuting in many cities. This may delay AHS network deployment until tunnel boring machines with this capacity have become commonplace. By the mid-1990's three lane TBMs were common. Four-lane TBM's have since been used in Japan and six-lane are planned in France.
- It is not clear to what extent polluting vehicles can be economically allowed in underground tunnel networks. In some Japanese road tunnels exhaust air is cleaned and reused at various points in the tunnel, using electrostatic precipitators. Should air scrubbing and circulation technology advance even faster than hybrid, electric, and hydrogen vehicle market share in the next three decades, it possible that even low-

emission fossil fuel vehicles (LEV's) will be allowed in underground AHS networks, which should further increase their economic attractiveness and early adoption.

- If global warming or the PPMV of atmospheric CO2 continues to climb in coming years, our use of fossil fuel vehicles might become politically unsustainable. An early, rushed conversion to lower carbonization fuels (natural gas, etc.) or zero emissions transportation systems (e.g., nuclear generation feeding electric or hydrogen vehicles), occurring while it was still not cost-competitive with hybrid or ZEV fossil fuel technology could shift priorities away from UAHS in the near term and substantially delay the emergence of the networks. This seems unlikely within the next 20 years but may be an important consideration later in the century.
- Corruption and incompetence in construction, as occurred in Boston's $14.6 billion, ten-lane Central Artery/"Big Dig" Tunnel, may continue to give large scale projects a bad name. Bechtel-PB was awarded the Central Artery contract on a cost-plus basis, meaning the more trouble they encountered the more they were paid by the Feds and the state. The state is now suing for cost overruns and waste. To further complicate matters, leaks have recently sprung in a few sand-rich areas due to inadequate construction methods. In a recent poll, more Bostonians said that for the cost the Big Dig project was a mistake (40%) than supported it (33%). [13] Eliminating cost-plus contracts and working only with contractors that have superior quality and time-performance records for tunneling projects seems necessary, as does minimizing traffic disruption during construction, another major problem with the Boston project. Aboveground AHS networks and UGV's for removing waste rock at night might help greatly with congestion in such projects.
- Safety requirements in earthquake prone cities (Los Angeles, San Francisco) may delay UAHS systems vs. alternative locations, as the recommended spacing for pullout and evacuation facilities may be cost prohibitive at first. As automated emergency machinery improves, the cost of recommended safety facilities may drop. On the other hand, the ever-increasing value of human life in all developed societies may counteract this, restricting most of the first-generation urban UAHS networks to developing and newly affluent nations like China, Korea, and India.
- A revolution in tunnel construction methods might involve using TBM-elevators for digging tunnels in multiple independent sections rather than from only two ends. Laser guidance and ventilation systems have already advanced to the point where this may be practicable. Given the proliferation and interchangeability of TBMs for urban tunnelling, having eight TBMs and associated machinery working simultaneously on one project might allow a 4X reduction of tunnel construction time. This innovation may become practical as the price of TBM's continues to drop.
- As national security issues continue to advance, governments may outlaw private underground structures below a certain depth, and declare eminent domain on all land deeper than a prescribed depth. This would give city managers unrestricted access to a large volume of building space below high density living areas without need for right-of-way acquisition cost.

-- Issues, Dilemmas, Choices

- Government funding for AHS has been uneven. As mentioned, the US Dept. of Transportation terminated its support of the National AHS Consortium in 2000 after a successful feasibility demo in San Diego in 1997, citing a need to refocus on shorter-term transportation priorities.
- Underground construction costs fall with time as technologies and productivity improve, but the costs of new underground transit systems may not reflect this due to higher standards of amenity and safety. Such standards are socially determined choices that are significantly stricter in some cultures.
- Tunnels can advance anywhere from 4 to 80 meters/day depending on the geology and automation of the tunnel boring machines. Sinkage and water seepage are other potential problems that determine the cost of support needed. Tunnels can be automatically waterproofed and supported with robotic shotcreting systems. Financing, political and legal issues, geology, city structure, safety standards, finishing requirements, tunnel boring machine automation level, experience of the construction team, AHS sophistication, ZE vehicle availability, and motivation of the stakeholders are among the factors that will determine which early AHS networks are early successes and which are not.
- A major choice for politicians involves the degree of privatization of the network. Allowing toll tunnels, dynamic pricing, and electronic toll systems would significantly accelerate the development of certain sections of the network, and bring greater competition into the industry. Oversight would be needed to ensure adequate public benefit and accountability of private ventures.
- Another significant design choice is the height of the tunnels. A 1992 French commission made Recommendations on Reduced Height Urban Tunnels (RECTUR), which recognized three height choice standards for tunnels:
  -- Six foot seven (2.0m), which covers 85 percent of vehicle types in the Paris region excluding minibuses in which passengers can stand, and all existing emergency vehicles;
  -- Eight foot ten (2.7m), which allows most ambulances and the minibuses;
  -- Eleven and a half feet (3.5m), which allows urban buses and most fire equipment, but not heavy trucks or long-distance coaches.

Standardizing to a smaller tunnel height would allow the development of a larger urban network, but would also require downsizing automated trucks if they were to be allowed in the underground network. Car/truck separation or integration is another political choice to be faced.

-- Ideas, Perspectives, Proposals

- There may be social resistance to automated highway systems that impedes their early adoption. Safety perceptions may be similar to the first elevators a hundred years ago. It took several public demonstrations to change public perception of their safety, including one where Mr. Otis of the Otis Elevator Company cut the elevator cable while suspended 45 feet above ground to demonstrate that the safety brake held. Many comparable demonstrations will be required for AHS to become popular.
- Demo '97 trials with AHS drivers showed that older adults were actually more trusting of AHS technology than younger drivers, so no "age division" is expected in adoption of AHS technology.
- The government and public may rightly fear that automated systems will initially make us worse drivers. It seems likely that for at least the first decade of their use these systems will require drivers to remain behind the wheel in case of emergency. It also seems reasonable to mandate that such systems should educate humans to be better drivers than in previous eras even when AHS systems are not engaged. In other words, such systems may need to have good driver education features, and a proven ability to make us better drivers when AHS features aren't being used.
- Will the fact that there is no "real" scenery underground be of concern to tomorrow's drivers? Most UAHS-ready cars will come equipped with extensive electronic entertainment and IT systems as well as wireless connections to the outside world. Drivers will be likely to be engaged in a number of productive pursuits, including napping, that would all make the lack of scenery irrelevant. Those who preferred scenery could project detailed simulations or live webcams of the surface environment they were passing under, giving them the same option to jump off and change destination spontaneously as with surface driving. Given present trends in augmented reality display technologies, by 2030 such views would likely be more informative than those available to today's surface drivers.
- International Tunneling Association commentary:
  "Tunnels provide safe, environmentally sound, fast, and unobtrusive urban mass transit systems"
  "City traffic tunnels clear vehicles from surface streets, traffic noise is reduced, air becomes less polluted, and the surface street areas may be partially reused for other purposes."
  "Underground car parks in city centers leave room for recreation areas above ground"
  "Multipurpose utility tunnels are less vulnerable to external conditions than surface installations and cause insignificant disturbance aboveground when installed equipment is repaired or maintained."

-- Key Uncertainties

- Who will handle the liability for fatalities in early AHS systems? Who can be sued? Resolving liability issues will take significant political insight and may be a major stumbling block until a system is successfully created in an innovative country. (Issues, Dilemmas, Choices)
- It is possible that early AHS systems might reduce the average accident rate to lower than 1/5 previous rates. Yet even a quintupling of safety may not be enough for adoption in several societies. Those societies able to accept a measurable and declining level of "normal accidents" caused by these complex technologies will be able to realize the safety benefits of UAHS early. Those who unrealistically expect perfection from their machines will labor under their less efficient and more accident-prone manual systems until they change their mindsets, or until accident rates finally drop to miniscule levels, which may take an additional decade or two of advancement in AHS technologies. (Ideas, Perspectives, Proposals)
- Early public failures in AHS systems in a pioneering city may reduce public confidence and set back the field significantly in its early years. (Potential Events, Wildcards)

-- Alternative Scenarios

- Elevated skyways, such as monorails, are likely to gain increasing acceptance in some cities as one element in a plurality of transportation options, as they become increasingly quiet, energy efficient, and to some extent at least, aesthetically appealing. Both high speed elevated rail and mag-lev installations are making steady advances, and both now offer peak operating speeds of 250 mph (likely to be the maximum for some time to come). Such systems remain mass rather than personal transit however, removing both travel environment customizability and door-to-door efficiencies. They will likely only be used in a few high density corridors, and unless they are to become a visual blight, are not likely to even double a city's current traffic capacity, much less improve it by an order of magnitude. Nevertheless, monorails seem particularly attractive as city showpieces, traveling over the most beautiful areas of each city, as extensions for existing mass transit networks, and as adjuncts to high density tourist attractions, such as Disneyland or Las Vegas.

- Mass transit will likely continue to advance at low rates in urban environments, but given the many consumer disadvantages such inflexible networks, and the lack of need for modest mass transit efficiencies in a world of accelerating automobile efficiencies, conventional mass transit may remain close to its historic 2% or less of person trips in U.S. urban areas. At the same time, mass transit may proceed by decree in some of the more centrally-planned or socialist economies, such as France. Today's urban citizens, more mobile and insulated than ever, seek the highly personalized environments that intelligent vehicles offer. AHS systems deliver both synchronous linked (mass transit) and unlinked (personal transit) in one heterogenous network. Therefore while urban core mass transit will certainly advance in coming years, I expect it to remain a small percentage of person trips going forward.

- The development of robust distributed autonomous 3D air traffic control software for vehicles, combined with a new, safe and environmentally sound form of aerial power that did not produce greenhouse gases might lead to unmanned aerial vehicles (UAVs) outcompeting AHS networks early in their development. UAV's are certainly more scalable and require significantly less construction cost. However, it seems reasonable to expect that 2D, low-speed AHS control software will be safer much earlier than 3D, high-speed UAV control systems. Furthermore, environmentally sustainable (zero emission or electric) ground transport will be achieved far earlier than sustainable air transport. Increasing UAV transport also adds significant visual and noise blight, even if the safety and social acceptance issues can be addressed, which are far from clear. Finally, we must note that cities do not have a need for infinite transport scalability. They all saturate both the goods (Buckminster Fuller's "etherealization" trend) and the energy [6] that they consume per capita, in all developed countries. Therefore, gaining an order of magnitude greater urban transportation density through UAHS, while halving average transportation times, quintupling safety, and otherwise increasing livability may be sufficient to the needs of our megacities for several generations.

-- Leading Indicators

- Megacity growth, density, and wealth.
- The pace of commerce and public activity in our largest, densest, and wealthiest cities.
- The cost of surface land.
- The environmental and sustainability ethic of city dwellers and city managers.
- Availability of city, state, and federal finance for megaprojects.
- The degree of congestion on surface streets.
- Public demand for surface greenery and noise reduction.
- Tunnel boring machines size, efficiency, and automation.
- Automated lining, excavating and reinforcing technologies (e.g., robotic shotcrete).
- Ultra low and zero emission vehicle progress and market share.
- Intelligent vehicle and automated highway system safety and efficacy.
- Compelling things to do (other than driving) in IT-equipped cars.
- Intelligent vehicles that educate us to be better-than-average drivers in manual mode.

INFORMATION SOURCES

-- Experts

Richard Bishop is a leader for intelligent vehicle activities at ITS America. Bishop Consulting supports clients in research and business development within the intelligent vehicles and vehicle-highway systems arena, providing services in partnership development, system applications, industry trend analysis, and business strategy. He lectures as an expert in intelligent vehicle and vehicle-highway systems, and is a contributor to industry trade publications.

Jack Burke has spent nearly 60 years in the underground construction and mining industries. In 1988 he formed Jack Burke and Associates, consultants on surface and underground construction. Jack is also a technical contributing editor for *Tunnelling and Trenchless Construction* and *Tunnel Business Magazine*.

Fred Hapgood is a technical writer and futurist with a long term interest in researching trends and possibilities in underground construction.

Ben Knight is vice president of research & development at Honda R&D Americas, Inc. He is responsible for planning and implementation of Honda's environmental product efforts and programs for both gasoline and alternative fuel vehicles, including Honda's U.S. Fuel Cell Vehicle (FCV) program. Honda makes many low emission vehicle (LEV) sedans, coupes, minivans, and light trucks, as well as a growing number of ultra low emission vehicles (ULEV's) (Civic, Accord, Insight) and one zero emission vehicle (EV Plus).

Alan C. Lloyd was chairman of the California Air Resources Board from 1999 to 2004, when he became secretary of the California Environmental Protection Agency. Dr. Lloyd was the 2003 Chairman of the California Fuel Cell Partnership and is a co-founder of the California Stationary Fuel Cell collaborative. He is a past chairman of the U.S. Department of Energy Hydrogen Technical Advisory Panel (HTAP).

Peter Samuel is editor and publisher of *Toll Roads News* and a North American correspondent for *World Highways* and *Intelligent Transportation Systems International* magazines of London. He has a degree in economics from the University of Melbourne.

Steven Shladover is deputy director of the Partners for Advanced Transit and Highways (PATH) Program at U.C. Berkeley.

Mike Smith is a mining engineer with 35 years management experience in mining, underground construction, manufacturing, marketing, and publishing, together with associated publicity. He has managed mines of coal, copper and gypsum. He has also run mining equipment manufacturing and marketing concerns, and has launched two successful tunnelling magazines. For the last 15 years, he has worked closely with the world's largest manufacturers and contractors in the mining and tunnelling industries. During this time he has attended every significant conference and exhibition, and has undertaken assignments in 40 countries. He runs Tunnelbuilder.com, a leading industry portal.

Chuck Thorpe is director of the Navlab group in the robotics institute at Carnegie Mellon University. Since 1984 the Navlab group has built a series of 10 robot cars, from minivans to full-sized passenger buses. The research is funded by the Defense Advanced Research Project Agency (DARPA) for building off-road scout vehicles, and by the U.S. Department of Transportation for traffic safety and automated highways.

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Fuel Cell Today. Accelerating the commercialization of fuel cells for electricity generation.
IEEE Intelligent Transportation Systems Society. Advancing the theoretical, experimental, and operational aspects of electrical engineering and information technologies as applied to ITS.
Intelligent Transportation Society of America (ITS America). A membership based nonprofit established in 1991 to coordinate the development and deployment of ITS in the United States.
International Tunnelling Association. Leading international organization championing the improved use of underground space.
Partners for Advanced Transit and Highways (PATH). A division of the Institute of Transportation Studies at U.C. Berkeley, in partnership with Caltrans.
Tunnelbuilder.com. Leading industry portal for services to the tunnel building industry. (Mike Smith).
Tunneljournalists.com. Technical and photojournalists with experience covering the tunneling industry
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