Title

How We Can Have Safe, Clean, Convenient, Affordable, Pleasant Transportation Without Making People Drive Less or Give Up Suburban Living

Authors
Delucchi, Mark
Kurani, Ken

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HOW WE CAN HAVE SAFE, CLEAN, CONVENIENT, AFFORDABLE, PLEASANT TRANSPORTATION WITHOUT MAKING PEOPLE DRIVE LESS OR GIVE UP SUBURBAN LIVING

Mark Delucchi

with

Ken Kurani

illustrations by Jayoung Koo

Institute of Transportation Studies
University of California
One Shields Avenue
Davis, CA 95616

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WHAT'S THE PROBLEM?

We complain about suburban sprawl and gridlock on the highways, yet many of us live in single-family homes, and most of us drive automobiles. We bemoan the loss of "community," yet choose to live in faceless suburbs. We think we want more "livable cities," but are unwilling to sacrifice the perceived benefits of a suburban lifestyle to have them, preferring to visit cities as tourists rather than live in them.

For decades, city planners, transportation planners, and policy analysts have struggled to reconcile what we say we want with what we actually choose. By and large, they have failed. Around the world, car use has grown unabated. When people get wealthy, they buy cars[1] and live in bigger homes further away from central cities. In an era of rapidly expanding personal mobility, cities have been constructed and reconstructed for fast, heavy motor vehicles. Nothing short of outright prohibition or economic catastrophe—not high gasoline prices, not better public transit, not better zoning—has stopped this trend.[2]

The result is a host of seemingly intractable problems: unacceptable congestion and fatalities on streets and highways, environmental degradation, ugly infrastructure, social fragmentation and insularity, and cultural impoverishment. Unable to stop the fundamental transportation and land-use forces at work, people have tried to mitigate at least some of the undesirable consequences of our present system. There have been some notable successes: emissions of urban air pollutants from new, well-maintained cars are dramatically lower than emissions from cars 30 years ago, and in recent years the number of motor-vehicle related deaths annually has stabilized, in large part due to tougher drunk-driving laws, greater use of seat belts, and improved vehicle design. However, we still face serious environmental concerns such as global climate change, economic and environmental problems associated with oil use, appalling death and injury on the highways, rising traffic congestion, undeniably ugly transportation

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[1] Gardenshire and Sermons (1999) conclude that poor households in the US convert increases in income into automobiles even faster than do non-poor households.

[2] Something close to an economic catastrophe – the recent global recession – may have contributed to what may have been a short-lived, minor decline in VMT. In 2008 the Brookings Institution reported that the decades long trend toward increasing national vehicle miles traveled (VMT) flattened out in 2004 and turned down in 2007 for the first time since 1980. Although the authors do not demonstrate a cause of the decrease, they do open the report with a mention of a "combination of gas price fluctuations, economic stress, energy concerns, and public financing woes" (Puentes and Tomer, 2008). Interestingly, an updated look at the same FHWA data as used by Brookings shows that despite the severe economic recession, which continued after Brookings published its report, national VMT began to rise slightly again in 2009 and to-date in 2010 (Federal Highway Administration, 2010). Although the month-to-month increases in annualized national VMT starting in November 2009 are small compared to the historical rate of increase dating back to the 1980s, they are increases nonetheless, and during a period of high unemployment and great anxiety about the economy – which we believe illustrates the great power of the forces pushing car ownership and use in the U. S. (Any reader wanting some context for the size of the overall problem this report addresses need only consider that we are talking about a problem for which an increase on the order of one *billion* miles VMT is a comparatively "small".)

infrastructure, and increasing social fragmentation, which many blame on automobile-driven suburban sprawl (see Burchell et al., 2002).[3]

Is there anything we can do?

Acknowledging that there have been many efforts to plan towns and transportation systems to better accommodate walking, bicycling, small vehicles, and other modes that can mitigate the impacts of automobile use (see the discussion later in this report), we take what we believe is a distinctive approach: the complete separation of high-speed, high-mass vehicles from low-speed, low-mass vehicles on a city-wide scale. Instead of having a single road system that serves everything from 50 lb. children walking at 2 mph to 150,000 lb. trucks traveling at 65 mph, we propose to plan new towns with two separate road systems, segregated according to the mass and speed of the modes. Cut points of 25 mph top speed[4] and 1000 to 1200 lb. maximum curb weight will distinguish low-speed, lightweight modes (LLMs) from fast, heavy vehicles (FHVs). LLMs include any mode of transport under the mass and speed limit: pedestrians, bicycles, pedicabs, mopeds, motor scooters, motorcycles, golf cars, minicars, and so on.[5] FHVs range from the conventional cars, trucks, and vans we drive every day to the tractor-trailers that deliver most of the goods we buy. As we delineate later, the physical infrastructure of the LLM network can range from an undifferentiated narrow lane that handles all LLMs (where traffic volumes are very low) to a multi-lane roadbed for motorized traffic with a paved bicycle path and an unimproved pedestrian path alongside (where traffic volumes are high). FHV roads will be similar to present conventional roads.

With this new plan for a dual transportation infrastructure, we propose to design new communities that are accessible, safe, clean, and cohesive.

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[3] Congestion. Everywhere in the country traffic congestion has increased dramatically since 1982 (Schrank and Lomax, 2003, 2007). The annual cost of congestion increased from about $15 billion in 1982 to $45 billion in 1995 and $78 billion in 2005 (2005 $, 437 urban areas) (Schrank and Lomax, 2007).

Accidents. For the last 15 year, more than 40,000 people have died in motor-vehicle accidents in the U. S. ever year. Reductions in the fatality and injury rate per VMT, due to reduced involvement of alcohol, increased use of seat belts, improved vehicle safety, and other factors, have been roughly balanced by steadily increasing VMT (Blincoe et al., 2002; Starnes, 2008).

Oil use. Motor-vehicle energy use and petroleum use has been increasing since 1970 because VMT has increased steadily while fuel use per mile has declined only modestly. Since the mid-1990s, petroleum use has increased with VMT, which implies that fuel-use per mile has remained constant (Davis et al., 2008). With increasing oil use come all of the attendant economic and environmental problems, such as energy insecurity, water pollution, and climate change. For example, oil-importing "energy-security" costs have increased since the 1990s because of increasing petroleum use, increasing oil imports, higher oil prices, and more regional conflicts over oil (Leiby, 2007).

[4] Note that the maximum speed limit is a design or technology limit, not an enforcement option: the LLMs are to be constructed so that they are incapable of exceeding the maximum allowable limit. This requirement already has been implemented in the recent regulations governing the safety and speed of "low-speed vehicles" (Federal Register, 1998).

[5] We will not address the motive-power of motorized LLMs just yet; but as we delineate our transportation/land plan, it will become apparent that there is much to be gained from electric-drive LLMs.

Our approach is distinctive at several levels. First, we are start by accepting that many people want to live in single-family homes, in relatively low density, and to be auto-mobile. We design a town that accommodates those preferences, yet at the same time offers qualitative improvements in safety, esthetics, travel pleasure, infrastructure cost, social organization, pedestrian space, and so on. Second, in order to accomplish this we separate travel according to kinetic energy of modes. Finally, we develop a particular land use and transportation infrastructure layout that accomplishes what we want.

A NEW TRANSPORTATION/LAND USE SYSTEM

We propose that it is possible to build *new* communities and transportation systems that accommodate the strong preferences for auto-mobility and single-family homes, yet at the same time are much safer and cleaner, more pleasant and more socially integrated than other commonly proposed transportation and planning measures.

Key to our proposal are two ideas: first, *virtually all that is undesirable with our present land-use transportation system stems from the presence everywhere of fast-moving heavy vehicles (FHVs).* FHVs are dangerous, consume a lot of energy and materials (and hence pollute a lot), and require an extensive, expensive, unsightly infrastructure. They cut a wide swath through communities, crowding out people, places, and other forms of transportation. Yet most of us depend on FHVs to provide invaluable and indeed irreplaceable services, and so within current infrastructure designs, FHVs must have access to all places. This conflict between the need to have FHVs accessible to all, and the problems of having FHVs everywhere, can be resolved if—and this is the second idea—*every place within a community (every household, every business, every public place) has direct access to two completely independent travel networks: one for FHVs, and the other for LLMs,* with the additional requirement that nonmotorized traffic be separated from motorized traffic on the LLM network where traffic volumes are high.

What exactly would this dual-transportation network and community look like, and what advantages would it have over present transportation and land-use plans? In this paper, we delineate our plan and its general advantages, compare our plan with similar ideas in the planning and transportation literature and in the real world, review the impacts on transportation problems, and discuss the economics. We conclude with a discussion of whether people will live in towns like we propose and use LLMs. We recognize that while we discuss the basic ideas in terms of a fully formed city, ultimately the success of the principles that guide our design will depend on solving the problems of how to build such cities one sub-division at a time and, perhaps—and certainly more problematically—how to retrofit existing cities.

The plan

We design a city with two universally accessible but completely independent transportation networks: one for LLMs and the other for FHVs. The LLM and FHV travel networks are accessible to everyone and provide access to everywhere, but are separated physically and *never intersect* or even touch. We emphasize that the two networks are completely separated everywhere such that there is no possibility of physical interaction between FHVs and LLMs.[6] In our view, any possibility of such interaction would immediately and unacceptably increase the risks to the occupants of LLMs and reduce the convenience to all users. And there must be *two* universally accessible networks—an FHV as well as an LLM network—because FHVs perform many valuable functions, and few people or businesses will want to be in a community where the use of FHVs is restricted.

In contrast to multi-modal solutions, in which users must shift themselves and any baggage, cargo, and personal belongings back and forth between multiple travel modes in a single trip, this dual infrastructure design creates two complete, distinct systems with alternative temporal, spatial, and social sensibilities. Like pedestrian malls or downtown areas in which cars are sometimes banned, the LLM system creates a less harried lifestyle space. But better than such piece-meal efforts, the LLM network is accessible to everyone and to fully featured motor vehicles,[7] and thus is a complete and convenient new lifestyle infrastructure—one that is functionally equivalent to the current automobile and road system, but with few of the undesirable features. In fact, we will argue that within the overall town plan we propose, the LLM network actually is more convenient by any measure than is a conventional single street system in a typical suburb.

Experience and common sense tell us that people will use an LLM network only if it is obviously more convenient and safe than the FHV network. For it to be maximally convenient and safe, it must directly connect everyone to everything without ever crossing or even touching the FHV network. But, as we noted, the FHVs also must have access to everywhere, because they provide services that are at least occasionally highly valued, e.g., higher passenger and cargo capacity, that the LLMs cannot.

How can we design two street systems to be co-extensive yet non-intersecting?
In abstract geometric terms, the solution is two parallel radial/ring networks: a system of LLM streets radiating outward from the town center, interlaced with a system of FHV roads radiating inward from a circumferential outer beltway. As we shall see, not

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[6]By contrast, *within* the LLM network the separate bicycle and pedestrian paths do intersect the motorized LLM roads. (It is not possible—in two dimensions—to have three completely non-intersecting but universally accessible networks on a surface. The cost of building in the third dimension, i.e., having all motorized and non-motorized LLM intersections and collocations be grade-separated is assumed to be too expensive, too land-consuming, too great an impediment to travel, and too visually blighting to be feasible.) At most of these intersections the bicycle and pedestrian paths can cross the motorized LLM roads at grade because motorized LLMs will have so little kinetic energy —as little as 1/20th the kinetic energy of conventional FHVs -- that they will pose relatively little threat to non-motorized LLMs at intersections. Where traffic volumes are so high that cyclists and pedestrians might be uncomfortable crossing at grade, bicycle and pedestrian tunnels can be provided.

[7]A fully featured LLM is a mini-car that is just like a conventional FHV except that it is smaller and slower and unlike a sparse golf-cart like vehicle: it has a completely enclosed cabin, full and comfortable seats, adequate leg room and storage space, air conditioning and heating, entertainment systems, a smooth quiet ride, good handling, power steering, power braking, power windows and door locks, a responsive and reliable motor, an attractive design, and robust construction. In our cost analysis we estimate the cost of an LLM mini-car with all of these features.

only does this system provide two universally accessible yet completely separate travel networks, it generates what many consider to be an ideal small town, with a commercial town center, high density residential living immediately outside the center, and low-density living further out. This transportation plan thus provides the social and commercial benefits of having a coherent center while accommodating as much low-density development as people want.

Figures 1a to 1d illustrate the concept. Figure 1a shows the road scheme, Figure 1b shows the road scheme and general land-use classifications, Figure 1c shows roads and all buildings, and Figure 1d shows roads, buildings, and landscaping. In all Figures, FHV roads are light gray and LLM streets are dark gray.

The entire town lies within an outer, high-speed beltway for FHVs. A central LLM road rings the commercial and civic center of the town. (As we shall see, the town center, like the neighborhood areas around the center, is accessible to FHVs as well as to LLMs.) Neighborhoods, accessible everywhere by FHVs and LLMs, lie between the outer FHV beltway and the central LLM ring. The LLM streets all radiate outward from the LLM ring road around the town center, and the FHV roads radiate inward from the FHV beltway around the entire town. (The LLM street system includes separate bicycle and pedestrian paths in some places.) Note that the two networks service every individual location but never intersect.

The town center (the area inside the central LLM ring road) contains most of the shops, schools, offices, churches, civic buildings, inter-city transit stations, and other commercial and retail spaces in the town. The radial LLM streets feed into the central ring road and provide direct, LLM-only access from all neighborhoods to all areas in the town center.

On the outside of the central LLM-ring road the residential neighborhoods begin, with high-density multifamily dwellings closest to the town center and large-lot single-family homes furthest. This traditional pattern of decreasing density is repeated along each LLM “branch” radiating out from the LLM ring road. Again, the two networks serve all households, but never intersect—every property has access to an LLM road in one direction and an FHV road in another. Each major radial “branch,” comprising one major LLM/FHV pair, functions socially as a neighborhood, with a neighborhood park, neighborhood school, public gardens, and a few neighborhood shops. Figure 2 shows a neighborhood branch in more detail.

Every home, business, and public area—indeed, every place within the town— either “faces” the LLM community network and “backs” onto the FHV network, or else borders one of the road systems (LLM or FHV) and shares a driveway that leads to the other system (see the detailed residential-area plans of Figure 4 and especially Figure 5). The FHV roads that radiate inward from the outer high-speed beltway interlace with but never touch the LLM streets that radiate from the town center. The idea is to have the FHV roads remain on the “backs” of housing units, rather like service alleys, and the LLM streets to be on the fronts, like community paths and streets. Private driveways connect both of the networks with private garages or parking areas. (This can be done by having two garages or parking areas; one garage or parking area that opens on two sides; or a driveway that splits in two and loops to both networks.) Figures 4 and 5 show details of single-family residential streets, including garages and driveways. Figures 1a-1d and 2 show the multi-family housing area around the town center.

The FHV roads have two main functions: to provide households direct access, via the outer beltway, to *outside* of the town, and to provide persons and goods movers from outside the town direct access to the inner civic, commercial, and service core of the town center, via two or three FHV roads that penetrate all the way to the town center.[8] These penetrating FHV roads go underneath the central LLM ring road and come up into roads and parking on the "back" side of all of the businesses, offices, schools, and so on.[9]

By contrast, the main function of the LLM streets is to provide access *inside* the town, especially to and from the town center, via the central LLM ring road.

The FHV network and the LLM network thus complement each other functionally: the LLM network is designed mainly for trips within the town, and the FHV network is designed for all other trips. Of course, it is possible to use the FHV network for any within-town trip, but the system is designed so that within-town trips generally are safer and more convenient via the LLM network. It also is possible to extend a few LLM streets under or over the high-speed FHV beltway to connect with the LLM network of a neighboring town, although this generally will make for relatively long travel times by LLM. Figures 7a and 7b show a plan with three towns, two of them sharing a segment of FHV outer beltway, and Figures 8a and 8b show the shared outer FHV-beltway commercial-corridor section in more detail.[10] (We have not shown an LLM road connecting the two plans, but it is easy to imagine the two radial LLM roads in Figures 8a and 8b connecting in the shared FHV-beltway commercial-corridor area.)

GENERAL ADVANTAGES OF THE PLAN

The system of outward radiating LLM streets interlaced with inward radiating FHV roads minimizes the number of expensive grade separations needed to completely avoid at-grade crossings: at only two or three places do the FHV roads need to go under

[8] Note that "FHV road" is not synonymous with "high-speed road." Only the outer beltway and the two or three FHV roads that penetrate to the town center have speed limits posted higher than 25 or 30 mph. The radial roads that intertwine with the LLM network are all low-speed routes that happen to provide access to large, heavy vehicles *capable* of high speeds, but limited by conventional enforcement to speeds typical for residential areas

[9] The FHV roads may connect within the town center, so that all of the town center is accessible from any FHV road that goes into the center (Figure6a), or each FHV road into the center may provide access only to one sector of the center, to prevent people from using the FHV network to travel through the town center to the other side (Figure 6b).

[10] It probably is desirable to have a greenbelt between the outer FHV beltway and the ends of the LLM residential streets, to buffer the residential areas from the noise and unsightliness of the beltway, and to delineate community boundaries. Figures 1b, 2, 7b, 8a, and 8b show this greenbelt buffer.

the central LLM ring road and enter the town center.[11] And, as mentioned above, at a few places the LLM streets may make a grade-separated crossing of the outer FHV beltway and connect with the LLM network of the adjacent town. Any other basic geometry—particularly a grid—would require *many* more under- and over-crossings in order to maintain complete physical separation between the networks. Such grade-separated crossings increase the cost of the infrastructure dramatically and introduce new safety problems of their own, e.g., reduced sight-lines at over-crossings, flooding in undercrossings, abrupt speed changes on up-slopes and down-slopes, and so on. And, we emphasize again that in our view the FHV and the LLM networks must be completely separate, with no possibility of any physical interaction of FHVs and LLMs, in order for the LLM network to be used fully as an alternative transportation system. Our plan geometry achieves this with minimum cost and maximum safety.

The general plan gives rise to appealing town characteristics:

- Stores, offices, schools, civic buildings, churches parks, inter-city transit stations, and so on, are in the center of town (Figures 6a and 6b) and neighborhood centers (Figure 3) not sprawled disjointedly over a suburban landscape. This coherent social and commercial geography *identifies* the town and neighborhoods.

- High-density multi-family housing units are around the core (Figures 1a-1d and 2), and provide convenient pedestrian, bicycle, and other LLM access to the town center for those who prefer higher-density, more urban living.

- So-called "big-box" retailers can locate along the outer beltway (Figures 8a and 8b) and thus be easily accessible to people in the community without disrupting the look, function, and feel of the town itself.[12]

- Major residential LLM branch roads function as neighborhood accessneighborhoods, with small neighborhood parks, elementary schools, and some shops in a neighborhood center (Figure 3). This smaller scale of organization provides a more perceptible sense of place, because people can locate themselves, socially and

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[11] We speak specifically of FHV undercrossings to avoid the visual and noise blight of large overcrossings. Still, local sub-surface soil and water conditions might argue against the construction of subterranean road sections. In these cases, overcrossings might be the preferred design; these overcrossings might carry either the FHV or LLM network, where the choice is subject to local conditions.

[12] At the same time, these retailers currently profit in part from shifting a portion of the transportation cost of products—hardware, office supplies, toilet paper, pet food, or whatever—to households. Thus big-box stores are part of a pattern of suburban sprawl that reinforces perceived need for big-box SUVs to haul big-box purchases. While we have no proof to offer yet, it seems plausible that within the land use and transportation system we lay out in this paper, smaller retailers will be able to compete based on convenience for some of the business that they now lose to the big-box stores.

geographically, first within the town, then within a neighborhood, and finally on a street.

- Even though the quantity and quality of suburban single-family homes are not restricted by policy, the transportation system integrates the resultant "suburbia" with the rest of the community and creates a coherent town.

- Unlike conventional street systems, which divide and separate communities and generally do not promote a pleasant street life, the LLM network—safe, clean, quiet, pleasant, and convenient—facilitates access, promotes interaction, and integrates the town, helping to create the sort of "unified street space" advocated by some urban designers and town planners (e.g., Southworth and Ben-Joseph, 2004b).[13]

We note that the transportation system and the urban form go hand-in-glove: given an interpenetrating radial-arm system with an inner ring road (for LLMs) and an outer beltway (for FHVs), it makes no sense to have the major non-residential (and non-neighborhood) destinations anywhere but the center. (This is obvious from inspection of Figures 1a-1d.) By contrast, a sprawling grid does not have a functional center, and hence allows fragmented, non-integrated development patterns typical of most suburbs: indistinguishable tracts of housing interspersed with strip malls.

The plan we propose provides the social benefits of organized development and low-impact transportation while providing the widest possible range of travel and lifestyle choices—including unrestricted suburban living and auto-mobile travel.

Size and growth of towns

The size of our proposed new town and transportation system is limited ultimately by the maximum acceptable travel time on the LLM network from the outer ends of the LLM radial streets to the city center. As we show next, this constrains the town to a maximum diameter of about 4 miles. A town of this size will accommodate 50,000 to 100,000 people.

The 4-mile maximum diameter keeps travel times on the LLM network reasonable. If for safety reasons the LLMs are built so that they cannot exceed 25 mph (a point we address later), then an average 1.0 to 1.5- mile trip into the center will take about 5 minutes and a trip across town will take about 10 minutes. These are similar to travel times for comparable purposes on present suburban road networks.[14] Moreover, we

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[13] Southworth and Ben-Joseph (2004b) write that "the core idea is that the street is properly a physical and social part of the living environment, to be used simultaneously for vehicular movement, social contacts, and civic activities….Pedestrians, children at play, bicyclists, parked cars, and moving cars all share the same street space. Even though it seems these uses conflict with one another, the physical design is such that drivers are placed in an inferior position." Our plan realizes this idea by creating a network and vehicle system that ensures that vehicles do not conflict with the other uses.

[14] The travel times are likely to be similar, in spite of a technological limit of 25 mph for LLMs versus a posted limit of 25 to 45 mph in conventional suburbs, because LLMs can travel at close to the 25 mph maximum most of the time, whereas FHVs on a conventional suburban road often are stopped, moving

expect that many people would be willing to use bicycles at least occasionally for trips of two miles or less on a convenient, safe cycling network.[15] For these reasons, we propose that the radial LLM streets (and adjoining bicycle and pedestrian paths) generally should not exceed 1.5 miles in length. If the town center has an 0.5-mile radius, the result is town of no more than 4 miles in diameter.

Figure 2 illustrates a complete radial section of the LLM and FHV networks from the outer FHV beltway to the service core in the center of town along one LLM/FHV neighborhood branch. With a maximum 4-mile diameter, the whole community (which certainly does not have to be precisely circular, but which we are analyzing as an approximate circle for convenience) has a maximum area of about 13 square miles. At relatively high suburban commercial and residential densities, this accommodates as many as 100,000 people—probably the upper limit for a single town/transport-network. At cozier dimensions and lower densities, the plan would accommodate

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much more slowly than the posted speed limit, or taking relatively circuitous routes. There are several reasons for this:

- Major intersections in a conventional street system usually have traffic lights, which can result in considerable delay, whereas major intersections in the LLM network are well suited for roundabouts, which as discussed elsewhere in this report result in relatively little delay.
- Minor intersections in a conventional street system often have stop signs, which also significantly reduce overall trip average speed. In many cases, traffic planners use stop signs to control vehicle speeds on local and collector roads. However, in an LLM network such speed control is unnecessary because the vehicles are unable to exceed the safe speed of 25 mph. Thus, the LLM network does not need stop signs for speed or safety-related purposes. Yields signs, which again result in comparatively little delay, can be used where it is important to indicate right-of-way.
- Local and collector streets in conventional suburbs sometimes have a variety of “traffic calming” or traffic-flow measures, such as speed bumps, curved or narrowed roads, one-way streets, and closed roads. These measures generally reduce average speeds or increase trip distance and thereby increase trip times. By contrast, the LLM network needs no such traffic-calming or flow measures, because the vehicles themselves are “calm” by design and the radial/feeder street system makes it very unlikely that unanticipated large flows will develop on residential streets. (Such problems of unanticipated large flows can develop on grid networks, because of the universal connectivity of a grid, but not on our radial/feeder system.)

In sum, the inherently safe and efficient design of the vehicles and the streets in our system obviates the need for traffic lights, stop signs, traffic-calming measures, and traffic-flow measures, all of which serve to inconvenience motorists and increase trip times. These advantages of the LLM network cancel any advantage of traveling at relatively high speed (more than 35 or 40 mph) for a small fraction of the trip on a conventional network. (As an illustration, note that the average speed in the U. S. Environmental Protection Agency’s FTP-72 drive cycle, which is meant to simulate an urban trip in Los Angeles, has an average speed of only 19.6 mph, even though it has a top speed of 56.7 mph.)

[15]Using data files from the 1995 Nationwide Personal Transportation Survey (NPTS), we estimate that for the U. S, the average distance of walking trips is 0.5 miles, and the average of cycling trips is 1.4 miles. (There is some indication that the averages might have been higher in 2001 [Ham et al., 2005; Hu and Reuscher, 2004].) However, these distances (in particular for cycling) are based on a tiny sub-set of all travelers and trips, and are for trips made in the relative absence of infrastructure specifically designed for the safe, comfortable conveyance of cyclists. Thus we regard these average trip distances from the 1995 NPTS as lower-bound estimates of the average walking and cycling distances one would observe in a small city designed as we propose. For a discussion of the status of bicycling in North America, see Pucher et al. (1999).

around 50,000 people—which, in our view, constitutes a genuine town.[16] At this size, the town has its own zip code and main post office, its own high school, its own civic and institutional center, its own recreational and entertainment programs, its own library, its own community park, and a viable commercial/retail core. It may also have facilities of regional importance such as a college campus, theme park, county, state, or federal government buildings, and so on.

The transportation network and community thus can grow from just one short radial arm and a rudimentary town center—a few thousand people, perhaps—to as large as a small city of 100,000. A rudimentary town can grow to a larger town in two ways: by the addition or extension of neighborhood branches or by an increase in density along existing branches and in the town center.

The first way, growth by addition of new radial neighborhoods or the extension of an existing one, is subject to three general constraints:

1) No radial LLM street should be longer than is likely to be commonly acceptable to persons at the outer end of the street (i.e., should not make for a longer trip into to the center of town than they likely would have in a conventional suburb).

2) The LLM network must (eventually) grow *around* the town center, not indefinitely linearly along one side of it.

3) Land suitable for an LLM street or FHV road must be available on both sides of every structure or set of structures.

The second way, growth by densification, is constrained by the ability to increase the capacity of the existing transportation infrastructure to accommodate the increased travel generated by the increased density (as well as the ability to increase other infrastructures—water, sewage, DSL, etc.—to meet other demands of increased population).

If a small town faces pressure to grow, but does not want to become a large town, then it can polynucleate—spin off a new town with a new town center and new LLM and FHV networks. The original and the new town can share a common length of FHV beltway and be joined by grade-separated LLM crossings of the beltway. Figures 7a and

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[16] The town of Davis, California, has 62,000 people in a total of 8.6 square miles, excluding the area of the University of California and persons living in group quarters such as campus dormitories (www.city.davis.ca.us/aboutdavis/statistics.htm; http://factfinder.census.gov). Assuming that Davis is more dense than the low-density version of our prototypical town (because of the high percentage of multi-family housing units accommodating students), we suggest that the low-density version of our town has an area of roughly 10 square miles and about 50,000 people. This corresponds to a circle with a radius of about 1.8 miles, with an 0.5-mile radius (1 square mile) in the civic/commercial/educational core and 9 square miles of residential area.

Nine square miles is about 5800 acres. Assuming 50,000 people and 2.5 persons per household on average, there would be 20,000 households and about 3.5 households (including roads, sidewalks, paths, greenbelts, and parks) per total acre, on average. This is a relatively low average density ——low enough, we believe, to be appealing to virtually everyone who desires low-density suburban living.

7b show a multi-town plan, where two of the towns share a stretch of outer beltway and commercial corridor, and Figures 8a and 8b show the shared beltway commercial area. As just mentioned, the outer FHV beltway functions as a shared boundary, facilitating convenient FHV access between towns and from towns to the rest of the world.

Finally, we offer a note on retrofitting existing cities. To achieve this plan in large cities, either small cities must grow up around an LLM and FHV infrastructure, as mentioned above, or else existing large cities must be retrofitted. In general, retrofitting will be easier in cities with a radial street system and room for new infrastructure. It will be very difficult and costly in cities already completely built up around a grid pattern of wide streets, although it might be possible to retro-fit our plan to existing street grids by breaking grids in strategic locations.[17] In any case, we emphasize again that our plan is intended mainly for new developments and not for existing cities.

ASPECTS OF OUR IDEA IN THE TRANSPORTATION AND PLANNING LITERATURE AND IN THE REAL WORLD

Sustainable transportation, smart growth, and new urbanism

Obviously we are not the first to wonder what can be done within the framework of our market-oriented, mobile, time-driven, sub-urban society to create more livable, socially integrated communities. Indeed, there is now a large literature on the broad topics of "sustainable transportation," "smart growth," and "new urbanism." In the past decade much has been written about sustainable transportation, which is defined differently by different authors but generally involves the idea of leaving an economically, socially, and ecologically viable transportation system for posterity; see for example Steg and Gifford (2005), Turton (2006), MIT and CRA (2001), Dearing (2000), and Jolley (1999). Smart growth and the related "new urbanism" emphasize mixed land uses, clustered transit-oriented developments, multiple transportation and housing choices, infill development, walkable neighborhoods, and communities with a strong sense of place (*Progress*, 2000; Traffic Safety Center, 2004; Geller, 2003; www.epa.gov/smartgrowth/case.htm; Calthorpe, 2003).[18] However, we believe that

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[17]Zandee (2000) discusses retrofitting specific cities in the Netherlands. However, his basic design principals and desired ends differ from ours, and his retrofits are hypothetical, not analytical in the sense of developing engineering plans and cost estimates.

[18] See the newsletter "Smart Growth America", www.smartgrowthamerica.net and the U. S. EPA's "smart growth" web site, www.epa.gov/smartgrowth/, for more on "smart growth". See Sheehan (2001) and Burchell et al. (2002) for discussions of transportation and land-use policies intended to mitigate suburban sprawl, Burchell et al. (2000) for a comparison of the costs and benefits of a "managed growth" plan versus a "current-trends" plan for the state of New Jersey, and Burchell and Mukherji (2003) for an analysis of the resource costs of conventional "sprawl" development compared with managed or "smart" growth for the whole U. S. from 2000 to 2025. Burchell and Mukherji (2003) estimate that over the 25-year period a compact, mixed-use plan will save well over $100 billion in road, infrastructure, and other development costs compared with conventional development.

See Ryan and Throgmorton (2003) for a comparison of the transportation and land-use plans of a cosmopolitan European city (Freiburg, Germany) that focuses on high-density land use and good transit service with the plans of a typical city of the American west (Chula Vista, California) that focuses on low-density development and auto-oriented transportation. See Cervero (2002) for a discussion of the relationship between mode choice and land-use diversity, density, and urban design. For a critical while these sorts of changes to land use and transportation can improve the quality of life in many urban areas[19] and appear to have broad popular support,[20] in suburbs they are unlikely to have more than a marginal effect on the use of FHVs, and hence on FHV-related problems. As we observed at the beginning of this report, the problem is that most people apparently want to live in residential communities that are of such low density and so homogeneous that transit, walking, and cycling rarely are convenient and economical.

As a more specific example of ideas in the sustainable-transportation/smart-growth/new-urbanism literature, one synthesis of insights and opinions of many researchers, policy makers, activists, and industry experts opens with this call:

> "Urbanites should have basic access to people, goods, and services whether or not they drive cars. They should have transportation systems that enable them to move about in ways that are secure, commodious, efficient, and hassle-free; to view clear skies and breathe clean air; and to choose from among a variety of mobility modes, including walking and bicycling in a safer non-intimidating environment." (Johnson, 1993. p. v.)

However, as can be read between the lines in the preceding paragraph, proposals such as these would enhance walking, bicycling, and transit modes *at the expense* of convenient automobile use and single-family suburban living. Such proposals therefore are not likely to lead to large-scale transformations in American living and driving, although they certainly can be effective and beneficial when targeted to dense urban centers. By contrast, rather than try to get people out of their cars or suburban homes, we propose a system that *expands* travel and lifestyle choices at essentially no private cost but with very substantial social gain.

As another example, Ehrenhalt (2000) discusses the tension between the desire for and the drawbacks of a suburban lifestyle dependent on ordinary automobiles (FHVs). He notes that, on the one hand, suburbs exist because "people had desires and demands, and developers satisfied them...[and] there is nothing to be gained from demonizing the cumulative decisions of millions of ordinary Americans." At the same time, he acknowledges that there is "something disorienting to millions of people living a car-dominated life…in a subdivision where there is no place to walk, nothing to walk to and nobody on the street to converse with." He suggests that towns can be and are

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examination of "New Urbanism" assumptions about how the built environment can influence travel behaviour (e.g., Calthorpe, 2003) see the book *Travel by Design*, by M. G. Boarnet and R. Crane, reviewed in the *ITS Review* (2003). See the Traffic Safety Center (2004) for a discussion of improving safety for pedestrians and cyclists within a mixed-use "smart growth" context.

[19] Leyden (2003) finds that in walkable, mixed-use neighborhoods, people were more likely to be socially and politically engaged, and McCann and Ewing (2003) find that mixed-use, walkable neighborhoods can make people healthier.

[20] A survey published in *Progress* (2000) indicates that most people support land-use planning to make communities greener and more accessible.

being redesigned to mitigate the barrenness of automobile-dominated suburbs: communities are acquiring or revitalizing town centers and main streets, the wealthy are gentrifying city centers, and developers are inserting "traditional touches of old-fashioned suburban life...in even the most conventional suburban residential projects." He concludes that while suburban living, big-box retail stores, and the automobile are here to stay, "growing numbers of Americans do want a different sort of life, one with neighborhood commerce and short commutes and streets designed to make sociability easy rather than difficult." Our plan provides even greater neighborhood and community benefits than do any of the other ideas mentioned by Ehrenhalt (2000), and it does it without compromising automobile travel or access to "big-box" retail stores.

General transportation planning measures

More mundanely, we also note that there are long-standing proposals and programs for making public transit, bicycling, and walking more attractive and for reducing the undesirable impacts of FHVs (for example, by "traffic calming" or traffic re-routing), but as we noted above none of these have accomplished much nationally or indeed *can* accomplish as much as one might desire at large suburban scales,[21] either because they face powerful forces for automobile ownership and suburban living or else do little to address the inherent problem of the high kinetic energy of FHVs.[22] For example, traffic calming can reduce speeds and hence fatalities, but generally cannot be implemented on *all* roads—all local roads, collectors, minor arterials, and major arterials—within a regional suburban setting, and often is perceived as a nuisance wherever it is introduced. A recent comprehensive review of traffic calming schemes in New England found strong opposition to traffic calming among town officials and the general population, and concluded that it might be better to experiment with ways of limiting the speed of the vehicle itself (Garder et al., 2002)[23]—which is precisely what our LLM system accomplishes. Campbell et al. (2004) note that the disadvantages of conventional traffic calming include local opposition to some methods of calming (such as speed bumps), the displacement of traffic and hence traffic-related problems from "calmed" to

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[21] The macro statistics on motor-vehicle use are stark and unambiguous. Outside of central cities, private motor vehicles account for about 90 percent of all passenger-miles of travel everywhere in the U. S., without exception, and have for many years. For example, in 2001, 88% of all passenger miles and 86% of all passenger trips were made in privately owned motor vehicles (Hu and Reuscher, 2004). These percentages have not varied dramatically since 1990 (Hu and Reuscher, 2004).

[22] One problem is that traffic planners sometimes use crude measures of "accessibility", such as the number of links or nodes within a given distance, to determine whether people will be inclined to walk, cycle, or take public transit. Obviously, though, a great many factors other than number of nodes, distance, and even travel time or cost bear on the mode-choice decision: details of urban design, other characteristics of transport modes (such as safety and reliability), characteristics of the activities to be undertaken at destinations, lifestyle preferences, and more. A successful transportation and town plan will be sensitive to more of these factors.

For further discussion of measures of accessibility, see the special issue of the *Journal of Transportation and Statistics* (2001). For a discussion of connectivity in the context of bicycling, see Dill and Voros (2007).

[23] Garder et al. (2002) believe that "traffic calming will never succeed in North America unless people perceive that they can travel with approximately the same level of comfort as prior to the traffic calming implementation" (p. 30). We agree.

"uncalmed" streets, and the inapplicabiliy of calming to high-speed through routes (where accidents often are most serious). We conclude that conventional solutions such as trip-reduction policies and traffic calming cannot achieve the sorts of reductions in transportation-related problems that our plan promises.[24] Put another way, we are suggesting that the most effective "traffic calming" measure is to calm the vehicles themselves *by design*, so that the vehicles themselves simply *cannot* exceed unsafe speeds and masses, and are driven on a network that simultaneously enhances convenience and safety.

Prior studies of on small vehicles and associated infrastructure

We are not the first to see the problems inherent in having just one road system. Years ago, Garrison and Clarke (1977) observed the primary impediment to extending modal options in the direction of low-speed and light-weight is the "one size fits all" mentality that permeates our transportation infrastructure and thus the structure of our lives. Following up on this, Pitstick and Garrison (1991) analyzed how the transportation system could be restructured to accommodate "lean" vehicles—small, fuel-efficient, one or two-passenger vehicles. Most pertinently, Bosselmann, et al. (1993) examined how neighborhoods and roads should be changed to accommodate small, clean, inexpensive motor vehicles. They addressed many of the issues we do here and come to many similar conclusions, although they do not propose the transportation and town plan that we do.[25]

Sheller and Urry (2000) analyze the interaction between automobility and urban planning, and conclude with suggestions on how to redesign automobiles and urban public spaces to "address the negative constraints, risks, and impacts of automobility" (p. 753). They propose extensive use of

> micro cars...integrated into a mixed transportation system that allowed more room not only for bikes, pedestrians, and public transportation, but also for modes of travel that we have only begun to imagine. This would require redeployment of existing urban zoning laws to exclude or severely delimit "traditional" cars....and to place lower speed limits on them. The aim would be not only to free up space for new kinds of intermodal flows but also time for new socialities that would juggle the complex timing of schedules in more flexible ways (p. 753).

Shelly and Urry (2000) thus also recognize the advantages of making cars smaller and slower and of redesigning urban areas to better accommodate such vehicles. In a sense our plan is an elaboration of this idea in a suburban (rather than urban) setting.

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[24] We are not implying that one must choose between traffic calming and our idea, and that since traffic calming has disadvantages one should choose our idea. Indeed, traffic calming can be employed relatively easily on the FHV network in our plan, and where it is desirable on balance, it ought to be employed. Rather, we argue against the proposition that conventional traffic calming by itself or in conjunction with other conventional solutions can sufficiently mitigate transportation-related problems to obviate the need for ideas such as ours.

[25] A more remotely related issue is the separation of cars and trucks via truck-only lanes and tollways. See de Palma et al. (2008) for a recent discussion.

Planned communities

Although there is a very long history of "new town planning" and plenty of planned communities, there is to our knowledge no actual plan or transportation system with the key feature of ours: two autonomous but universally accessible personal transportation systems, segregated according to the kinetic energy of the modes. For example, Zandee (1999) proposes a "Mobilopolis" which facilitates the use of bicycles and public transit and has a few features in common with our plan—an outer-ring road for motor vehicles, with roads penetrating in towards the city center, and many transit and cycling routes in to the city center—but the design mainly is for relatively dense urban areas, and has significant restrictions on motor-vehicle use. Most importantly, it is a not a dual-network in which every place is accessible relatively easily by both LLMs and FHVs.

Planned communities with LLM networks. A few existing communities (mainly sun-belt retirement communities) have the equivalent of a complete dedicated LLM network, but none of them also have a universal FHV network. As a result, they are unsuitable for the vast majority of households. Some communities, such as Palm Desert (California), have LLM streets and lanes integrated with FHV roads, but in these places the LLM network is not completely separated from the FHV network, and hence is too unsafe and, by contrast with the FHV network, too inconvenient to be heavily used.[26]

Peachtree City, Georgia, a master-planned community southwest of Atlanta, has a 70-mile network of paved recreational paths for pedestrians, bicyclists, and golf carts (www.peachree-city.org). The paths connect neighborhoods, retail centers, churches, schools, and recreation areas, using underpasses and overpasses to cross major streets (www.peachtree-city.org). While this system, which allows motorized golf carts to share paths with pedestrians and cyclists, is a step closer to our proposal than is the sort of plan that dedicates separate paths to nonmotorized transport only, it still falls short of our proposal in several ways: it is not designed to accommodate full-featured LLMs (the paths are designed for golf carts, which are limited by city ordinance to a top speed of 20 mph [www.peachtree-city.org]); the paths are not designed to handle heavy traffic flows (for example, the paths are not wide enough for two golf carts to pass [Stein et al., 1995]); and the paths are not completely co-extensive with the FHV network.

[26] In these communities not all locations are connected by LLMs traveling in parallel lanes. For example, Palm Desert enacted a three-level hierarchy of lanes, from mixed traffic, to parallel, to grade separated. Even then not all locations could be conveniently accessed by LLM (in this case, golf carts). Grade-separated lanes were implemented in specific locations precisely because of the great danger and relative inconvenience of parallel lanes, as traffic in the FHV lanes travels much faster. Some people found driving golf carts in these parallel lanes (or worse yet, in mixed FHV-LHV, i.e., automobile-golf cart, traffic lanes) to be disquieting (Kurani, et al. 1995). Specifically, the pressure applied by drivers of FHVs in shared FHV/golf cart lanes and the squeezing of perceived space to operate the golf cart by the presence of on-street parking caused golf cart drivers to feel unsafe.

Even though there are only a few of these mixed-network communities, and they carry very little LLM traffic, already there have been a number of fatalities and serious injuries as a result of crashes between LLMs and FHVs (Federal Register, 1998). In our view, this risk quite reasonably deter people from using LLMs on any network in which there is any possibility at all of any interaction with FHVs.

Planned communities with separate networks for cars and non-motorized modes. We know of several neighborhoods and towns that have a complete conventional street system *and* extensive dedicated bicycle and pedestrian paths that are accessible to most or all homes and which (within the neighborhood or town) do not intersect with the conventional street system: Village homes in Davis, California; the town of Radburn in New Jersey; the town of Houten near Utrecht in the Netherlands; and Milton Keynes in southeast England.[27]

Village Homes is a 70-acre subdivision with 225 homes and 20 apartment units in the west part of Davis, California. Most houses "face" a community greenbelt with a bicycle and pedestrian path serving all the houses. Automobile access is via narrow, curving roads along the side of the house opposite the bicycle and greenbelt side. The roads end in cul-de-sacs (www.villagehomesdavis.org). The social space created by the car-free pedestrian and cycling greenbelt in Village Homes is pleasant, and it inspired us to develop the same idea on a city-wide scale. In a sense, our plan is an elaboration along several dimensions of the plans in Village Homes: our infrastructure and associated modal differentiation is more elaborate; our scale is considerably large, and our integration within a fully planned small city more complete.

The traffic and cycle plans in Radburn, New Jersey, and especially in Houten, the Netherlands, are considerably more developed than is the plan for Village Homes. Radburn, built in 1930, has 469 single family homes, 48 town houses, 30 two-family homes, and a 93-unit apartment complex, arranged to "face" public pedestrian and park open spaces, with car access at the "back" of the houses via roads that end in cul-de-sacs (Freeman, 2000; http://en.wikipedia.org/wiki/Radburn). The pedestrian path does not cross any major roads (http://en.wikipedia.org/wiki/Radburn) .

The dual-transportation system in Houten is even more extensive. It comes closest to what we have envisioned and even shares some key features with our idea (although we developed our idea before we learned about Houten). Houten, a town of some 50,000 near Utrecht in the Netherlands, has a dedicated bicycle network consisting of collector arms that originate in residential neighborhoods and connect to a "backbone" that runs to the city center. The car-only network consists of an outer ring road from which car roads penetrate partly into the residential areas of the city, interlacing to some extent with the dedicated bicycle roads. There is limited access by car to the city center. (See Beaujon, 2002, and http://home.planet.nl/~tieme143/houten/engels/home-en.html for more information.)

Houten thus shares several key features with our plan:

- It is defined by two extensive, largely separated circulation networks.

[27] The English "Garden Cities" of Welwyn and Letchworth incorporate greenbelts and in some cases accommodations for pedestrians, but it appears that the pedestrian and cycling circulation systems are not as extensive as in the other towns just mentioned (http://en.wikipedia.org/wiki/Welwyn_Garden_City; http://en.wikipedia.org/wiki/Letchworth,_England).

- It was built from the ground up in a new town, and serves a city of some 50,000 people.
- The bicycle (non-car) network is designed for people to travel directly to the town center.
- The car network has an outer ring road, and limited access to the city center. In many cases, travel to the center is more convenient by bicycle than by car.

The differences between our plan and the Houten plan are:

- Our system separates low-speed, low-mass modes (LLMs)—mainly full-featured automobiles—from high-speed, high-mass vehicles (FHVs), whereas Houten mainly separates bicycles from cars.
- In our system, the two networks go everywhere, but *never* intersect at grade or share travel space, whereas in Houten the bicycle and car network often intersect at grade or share the same road space, mainly in residential areas. Thus, the interlacing in our plan is considerably more extensive.
- Our system has an inner road ring road for LLMs, from which collectors radiate outwards, whereas Houten has a central "backbone" for bicycles leading to the town center.

Although we believe that the differences between the plans are critical at least in the U. S., we acknowledge the precedence of the Houten design and its several important similarities with our plan. It appears to be the first and only town plan of its type in the world.

Milton Keynes is a large town of about 200,000 northwest of London, England. It's transportation system has two key features: a series of "grid" roads that run along the boundaries of communities, and separate "cycleways" network that runs along or crosses under the grid roads (http://en.wikipedia.org/wiki/Milton_Keynes). The grid roads are landscaped with dense plantings and often berms to reduce the noise and intrusiveness of the traffic.

Urban design

Our town plan has some urban design features (apart from the dual transportation infrastructure) that distinguish it somewhat from many if not most conventional suburban developments in the U. S.: a clearly defined town center ringed by a decreasing residential density gradient; in the residential areas, neighborhood centers areas with elementary schools, parks, and some commerce; residential streets that end in cul-de-sacs (or dead ends); and at the largest scale a region consisting of several ties linked by transportation arteries, rather than one large continuous metropolitan area. Of course, none of these features are original or rare, and all have been discussed extensively in the planning and design literature.

Our urban design elements are similar in some respects to the "neighborhood" concepts first developed in 1929 by Clarence Stein and Henry Wright and separately by Clarence Perry (Patricios, 2002a, 2002b), and described by Patricios (2002b) as "undoubtedly one of the major landmarks in twentieth-century urban planning" (p. 21). Generally, these neighborhood concepts included cul-de-sacs rather than a grid with through streets; neighborhood centers or junctions with schools, parks, and other functions; a hierarchy of street and planning units (e.g., enclave, block, superblock, and neighborhood); and plans for linking towns by transportation arteries (Patricios, 2002a, 2002b).

According to Patricios (2002a), the developers of the original neighborhood concept wanted to use physical design to promote social interaction and a sense of community, but were only partly successful. He writes:

> "…physical factors play a role in neighborhood satisfaction, but the variables involved are not those of the neighborhood concept. General maintenance level of the neighborhood, adequate outdoor space for family activities, and a quiet rather than a noisy environment, are the important variables. Despite the idealistic predilection of architects and planners' attempts to create community through physical design, the recent surge of gated neighborhoods points to residents' preference for privacy and security, not community" (p. 79).

Freeman (2000) and Bayley et al. (2004) come to similar conclusions. Freeman (2000) suggests that developers have not built more towns like Radburn because they believe that homeowners prefer to have larger lots and less public space (rather than the other way around) and don't like not having a private backyard (recall that in Radburn, the "backs" are alleys for cars, and the "fronts" are public pedestrian spaces). However, according to Freeman (2000) developers did like the idea of cul-de-sacs and eventually incorporated them into some suburban developments

In their survey of residents of a north London community regarding the aesthetics of vehicles and streets, Bayley et al. (2004) found that people preferred street and yard layouts with clear demarcations between public and private space. This is consistent with Freeman's (2000) finding, mentioned above, that people generally prefer more private to public space, and that their private space is clearly and securely separated from the public space. These findings have clear implications for the design of streets and yards in our plan: public right-of-way devoted to circulation should be clearly separated from private yards, and should subtract from private yards a little as possible.

Lightweight, low-speed vehicles

A key element of our proposal is the motorized "full-feature" LLM: a motor- vehicle similar in every respect, save for weight and top speed, to present motor vehicles. We expect that these motorized LLMs will carry most of the traffic on the LLM network. Already, one such vehicle, the "ZENN EV", is commercially available. The ZENN EV is a low-speed (less than 25 mph), lightweight (510 kg—a bit more than our suggested maximum),[28] fully enclosed 3-door hatchbook with a structural composite monocoque body and real doors and windows. It has a CD/AM/FM stereo, air conditioning, heating including rear defroster, power windows, remote keyless entry, 2+2 seating, high-powr lead/acid battery, regenerative braking, and aluminum alloy wheels. The

[28] We believe that if the vehicle were designed specifically for operation on an LLM network rather than on conventional streets, it could be both lighter and less dangerous to pedestrians and cyclists. This is because on an LLM network the fully featured automobile will be the fastest and heaviest and hence most dangerous and least vulnerable vehicle, whereas on a conventional street it will be one of the slowest and lightest and most vulnerable of vehicles.

manufacturer believes that the vehicle will sell for $10,000 to $13,000, presumably in low volumes.

"City" EVs (CEVs) such as the Toyota e-com, Nissan Hypermini, and Th!nk City are too heavy and have speed capabilities that are too high to be used as LLMs in our plans Most vehicles built to the new low-speed vehicle (LSV) definition (Federal Register, 1998)—e.g., the Th!nk Neighbor, Bombadier NV, and GEM Neighborhood EV, are not appointed to the same level of comfort. They typically do not fully enclose their occupants (except for optional cloth and plastic enclosures). They lack climate control, advanced sound systems, and other features we assume would be available in a full-feature LLM. As these LSVs have been developed, researchers have investigated various approaches for introducing them to cities and towns (e.g., Stein et al., 1995; Lipman and Kurani, 1995; Kurani, et al. 1995). However, none of the existing literature on LSVs, NEVs, or CEVs has proposed anything akin to our dual-road system.

THE IMPACT OF THE LLM NETWORK ON TRANSPORTATION PROBLEMS

Safety

The transportation and town plan described here provides substantial social and economic benefits, while at the same time enlarging choices for travel and living. Most importantly, the LLM network dramatically improves transportation safety, without increasing the time or cost of travel. In fact, it should be possible to virtually eliminate fatal crashes on the LLM without sacrificing travel convenience. This unique, qualitative safety improvement —and indeed most other social benefits of the LLM network—are attributable to one remarkable attribute: *The average kinetic energy on the LLM will be as little as 1/20th of the average on the present road network*.[29]

Figure 9, which shows normalized kinetic energy as a function of vehicle mass (from 0 to 6,000 lbs, in 200-lb increments) and speed (from 0 to 60 mph, in 2-mph increments), illustrates the dramatic difference between the kinetic energy of LLMs and the kinetic energy of FHVs. The kinetic energy has been normalized so that level 1.0 (the area in torquoise) is close to the maximum likely average kinetic energy on an LLM network. In the scheme of Figure 9, an 800-lb. vehicle traveling at the maximum speed of 25 mph, or a heavily loaded vehicle of 1250 lbs traveling at 20 mph, have a kinetic energy of 1.0. Many LLMs, much of the time, will have even less kinetic energy, and fall well within the torquois area of Figure 9. Bicycles and mopeds have kinetic energy in the range of 0.1 to 0.2. By contrast, Sport Utility Vehicles (SUVs) traveling at 30-35 mph, and small compact cars traveling at 40-45 mph, have a kinetic energy an order of magnitude higher than the LLM maximum average —level 10 in Figure 9 (the top of the yellow area). SUVs traveling at 45 mph have a kinetic energy roughly 20 times higher than the likely LLM maximum (the top of the orange area). The kinetic energy of heavy-heavy trucks traveling faster than 20 mph is way off of the chart.

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[29] The kinetic energy, or energy of movement, is equal to $1/2\ MV^2$, where M is the mass of the object and V is the magnitude of its velocity. The kinetic energy thus is more sensitive to velocity than mass. An 800 lb. vehicle moving at 20 mph has 1/20th the kinetic energy of a 4000 lb. vehicle moving at 40 mph.

It is evident from first principles that this enormous reduction in kinetic energy will result directly in a reduction in crash energy, and ultimately in a corresponding reduction in the risk of personal injury or death (Aarts and van Schagen, 2006; Elvik et al., 2004).[30] These principles have been amply documented; many studies have shown that the risk of *any* fatality (whether to pedestrians, cyclists, drivers, or passengers) decreases with decreasing vehicle speed such that below 20 mph, the risk—even with heavy motor vehicles in the system—is close to zero (Waller, 2002; Robinson et al, 2000; Leaf and Preusser, 1999 [see also the Insurance Institute for Highway Safety, 2000]; Federal Register, 1998; Kallberg and Luoma, 1996; Elvik et al., 2004). Even relatively modest reductions in speed, such as result from so-called "traffic calming,"[31] significantly reduce accidents (Garder et al., 2002; Elvik, 2001; Clarke and Dornfeld, 1994).[32] And it is obvious that were vehicle weight as well as speed reduced, as it is in our proposal, the risk would be diminished further.[33] There is much less risk to

[30] In principle, the only situation in which higher vehicular kinetic energy reduces the risk of injury is the case of hitting a breakable or moveable roadside objects, such as street lights: the higher the vehicles' kinetic energy, the greater the likelihood of knocking aside, breaking through, or destroying the object. However, three things can be said about this. First, in our present (FHV) traffic system number of serious injuries that wouldn't have occurred had the vehicle run into the object with slightly more kinetic energy is trivial, because the number of accidents satisfying the necessary conditions is trivial. Second, it is by no means clear that in a low-speed, low-mass vehicle it is preferable to break through an object rather than be stopped by it: even a small vehicle is likely to have sufficient crush volume and a basic enough restraint system to prevent serious injury in the event it crashes into an immovable object at, say, (only) 20 mph, whereas it may well be that a broken object is more likely to penetrate the passenger compartment. Third, to the extent that it is determined that vehicles should be able to break-through roadside objects, it is relatively easy to make the man-made structures, such as signs and street lights, more breakable.

[31] Retting et al. (2003) cite one study that found that traffic calming reduced pedestrian-vehicle crashes by 25%, but noted that a systematic review of 13 controlled before-after studies found that traffic calming had no effect on pedestrian-vehicle crashes.

[32] The importance of speed is illustrated in several studies. Data on fatal pedestrian accidents in Maine show that when the *posted* speed limit is 25 mph, the probability of a pedestrian fatality given a crash is about 3%, whereas with a posted speed limit of 40 mph the probability is about 20% (Garder, 2004). More pertinently, Kallberg and Luoma (1996) cite a 1990 Scandinavian study that provides estimates of the probablity of a pedestrian fatality as a function of *impact* speed:

impact speed (mph)	15	20	25	30	35	40	50
probability fatal (%)	~ 3	~ 7	~ 15	~ 30	~ 63	~ 85	~100

Similarly, Wier et al. (2009) cite a 1987 British study that indicates that the likelihood that a pedestrian dies after being hit by a car is only 5% if the car is going 20 mph but is 85% if the car is going 40 mph. (See also Ernst and Shoup [2009].)

These findings are striking because they pertain to the most vulnerable group (pedestrians), and because the vehicles involved were conventional heavy vehicles. They support the proposition that with *light* vehicles traveling at less than 25 mph, even pedestrian fatalities will be very near zero—especially if vehicles are designed specifically to minimize injuries to pedestrians.

[33] This discussion should not be conflated with the debate about the effects on safety of improving the present fleet-average fuel economy by making more small cars. It is clear that on roads with large numbers of 5,000 lb. sport-utility vehicles moving at speeds over 70 mph, relatively small vehicles are

everyone from two 800 lb. vehicles traveling at 20 mph than from two 4,000 lb. vehicles traveling at 20 mph. The few studies that have also considered vehicle weight and speed have documented the additional advantage of having less weight as well as lower speed.[34]

Finally, this near-zero fatality rate is achievable without any special attention to safety design specifically in the context of an LLM network. But it is likely that relatively simple and inexpensive design considerations—for example, shaping vehicles so that they are more likely to deflect pedestrians and cyclists rather than hit them head on, and making vehicle shells rounder and softer[35]—could practically eliminate serious

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riskier for their occupants in some situations. But it also is likely that the main factor here is not size per se, but rather the great *difference* in size (Gabler and Hollowell, 1998; Kahane, 1997; Tolouei and Titheridge, 2009). And this often is not highlighted because it is presumed to be irrelevant to policy: if we will not fight the consumer choices that lead to the disparity in vehicle sizes, why discuss situations in which those disparities don't exist? If anything, the debate over fuel economy standards lends additional support to the theoretically obvious conclusion that an LLM network with a maximum speed of 25 mph and a maximum loaded mass of around 1600 lbs. will be vastly safer than the present road network.

[34] Wang and Kockelman (2005) use a logit model to examine the effects of vehicle weight and other factors on the severity of injuries, given that a crash has occurred. Their "results suggest that lighter vehicles reduce, rather than increase, the probability of death" (p. 202). Kahane (1997) analyzes the historical relationship between vehicle mass and fatalities and estimates that a 100-lb reduction in the weight of passenger cars would reduce fatalities in car-car, car-motorcycle, car-bicycle, and car-pedestrian collisions by about 1%. Note that this estimate pertains to a mere 100-lb. reduction in the weight of conventional vehicles, whereas in our plan LLMs would weigh thousands of pounds less than conventional vehicles. Although Kahane (1997) does find that *at current vehicle speeds* the occupants of lighter vehicles would be more at risk in collisions with fixed objects, we expect that at the very low speeds on the LLM network there would be very few fatalities in vehicle collisions with fixed objects regardless of vehicle mass.

Moreover, it is not clear that there is even an inherently higher risk to lighter FHVs in a conventional system: Wenzel and Ross (2005) analyze the effect of vehicle model and driver behavior on motor-vehicle fatalities, and find that "mass may not be fundamentally associated with risk-to-driver in all types of crashes" (p. 486).

Furthermore, for two reasons, LLMs are less likely to roll over than are FHVs. First, because they have such a low maximum speed (25 mph), they are less likely to reach their "critical sliding velocity" (CSV), which is the lateral (sliding) speed at which the vehicle can trip. (Data in Heydinger et al. [1999] indicate that the CSV increases with decreasing vehicle weight and might be about 15 mph for 1000-lb. vehicles.) Second, the "static stability factor" (SSF), which is a measure of rollover resistance and is equal to the track width divided by the twice the height of the center gravity, might be higher for LLMs than for FHVs. (Heydinger et al. [1999] report that the SSFs of passenger cars are less than the SSFs of light trucks and SUVs, which are heavier than passenger cars.)

[35] There is evidence that even FHVs can be re-designed to be rounder and softer and thereby mitigate harm to pedestrians. For example, Crandall et al. (2002) note that manufacturers could make simple, inexpensive changeschangs to bumpers and hoods that would reduce pedestrian fatalities by at least 20% (see also Breen [2002]). Similarly, Robertson (1990) reports that designing vehicles with smooth rather than sharp front corners could reduce pedestrian fatalities by 26%. The Insurance Institute for Highway Safety (1999) states that it is possible to design FHVs to cause less damage to pedestrians at impact speeds as high as 25 mph —the maximum speed on our LLM network. A British politician has called for automanufacturers to make car bodies softer in order to reduce pedestrian injuries (Sheerman, 2002). (Interestingly, in a survey of residents of London, England, Bayley et al. [2004] found that people liked cars with rounded fronts because they seemed less dangerous to pedestrians.) Subsequently, Hardy et al.

injuries and fatalities and the fear and stress that they engender. In light of the extraordinary human suffering caused by crashes in conventional transportation systems, the near-perfect safety of an LLM network will have great social value.

Perhaps most significantly, we believe that an LLM network will *seem* completely safe, and for this reason alone be very appealing. Bicyclists and pedestrians will be much more comfortable around small, light, slow-moving motor vehicles. Drivers of small, slow-moving motor vehicles will be better able to see pedestrians, cyclists, and small children, especially when they (the drivers) back out of driveways, and hence will be and feel less threatening.[36] Many older drivers will be much more comfortable with the low speeds and small vehicles (Waller, 2002). With so much less mass and movement than a conventional road, the LLM network will seem pleasant rather than foreboding. The psychology of travel will change, and the pleasure of freedom of mobility will replace stress.

The other aspect of road safety affected by our plan is the road layout itself, and in this respect there are two important features. First, the use of roundabouts at key intersections should reduce collision rates on the LLM network.[37] Second, almost all of

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(2006) provided a detailed analysis of the feasibility of vehicle design measures and regulations to protect pedestrians in Europe.

However, because of Federal Motor Vehicle Safety Standards (FMVSS), which in effect require that FHVs be rigid enough to protect the FHV occupants from the impact energy of other FHVs, there is a practical limit to the extent to which FHVs can be made pliable, soft, and round. But there is no such limit for LLMs, because LLMs face at least an order of magnitude lower impact energy and would not have to meet FMVSS standards for automobiles.. As noted above, on the LLM network impact energy will be reducedredued by at least 90 percent, which means that vehicles won't need a hard shell and rigid structure to protect their occupants. The Federal regulations recognize this: there are *no* Federal safety regulations whatsoever for vehicles with a top speed of less than 20 mph, and only a very minor, unrestrictive set of regulations for "low-speed vehicles" with a top speed between 20 and 25 mph (Federal Register, 1998). Thus, whereas FHVs must be designed mainly to minimize risk in high-energy collisions, the fastest, heaviest LLMs may be (and should be) designed mainly to minimize risk to pedestrians, cyclists, and operators of other non-motorized LLMs. (Seluga and Ojalvo [2006] do suggest that low-speed vehicles should have brakes on all four wheels to improve braking performance downhill.)

[36] For general discussions of strategies for improving pedestrian and cyclist safety in conventional towns and suburbs, see the Insurance Institute for Highway Safety (1999) and the U. C. Berkeley Traffic Safety Center (2004).

[37] Roundabouts, which probably will work particularly well with LLMs, have been shown to be much safer, more convenient, and often less expensive than conventional crossing intersections with stop signs or traffic signals (National Highway Cooperative Research Program, 2007; Brabander et al., 2005; Federal Highway Administration [FHWA], 2000; Robinson et al, 2000; Persaud et al., 2000; Insurance Institute for Highway Safety [IIHS], 2000; Leaf and Preusser, 1999). Roundabouts can improve safety and convenience simultaneously because they eliminate right-angle and head-on crossings (which are the cause of most multi-vehicle crashes) and slow down but don't stop traffic. Persaud et al. (2000) evaluated changes in motor-vehicle crashes following the conversion of 24 intersections from stop signs or signals to roundabouts in urban, suburban, and rural locations in 8 states in the U. S., and found that injury crashes were reduced by 76% and fatal and incapacitating crashes by 90%. Persaud et al. (2000) and FHWA (2000) note that other studies have documented similar reductions. Brabander et al. (2005) analyzed the effect on road safety of 95 roundabouts built in Flanders between 1994 and 1999, and found that roundabouts

the streets in our plan terminate in cul-de-sacs, and according to the Lovegrove and Sayed (2006) analysis of collision rates in different types of road layouts, cul-de-sacs are three times safer than conventional grid networks. We note that this second result should apply to the FHV network as well, because it also terminates in cul-de-sacs.

Mobility and public transit

Mobility for groups that cannot drive FHVs. Because they are low-speed, safe, inexpensive, and convenient, LLMs are attractive to four groups for whom ownership and use of FHVs is now problematic: the young, the elderly, the poor, and those otherwise without licenses to drive FHVs. The LLMs and the LLM network provide a safe means for teenagers to get to and from school, recreational opportunities, and part-time jobs which for teenagers are likely to be located in the town center or in the neighborhood along their LLM street. Because the LLM network is inherently safe, it will be reasonable to allow young teenagers to operate at least some motorized LLMs, such as mopeds, motor scooters, and vehicles with a top speed of 20 mph or less. Similarly, LLMs are safe and convenient for some of those elderly whose physical skills render them unable or unwilling to operate FHVs. Thus, the licensing requirements for motorized, low-speed low-mass automobiles ought to be less restrictive than those for FHVs. Even some of those who have lost their license to drive FHVs ought to be allowed to drive LLMs on account of the inherent safety and low social cost of LLMs. Finally, the low cost of owning and operating LLMs will make them affordable to some households too poor to purchase FHVs (a point to which we return below).

LLMs and the need for conventional public transit. Debates about conventional bus and train transit are among the most heated in transportation planning. Compared with travel by private automobile, public transit is heavily subsidized, even when one considers all costs to society (Delucchi, 2000a). Hence, public transit is a costly way to

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reduced all accidents by 34% and serious injury accidents by 38%. Most recently, the National Highway Cooperative Research Program (2007) analyzed the safety of roundabouts in the U. S. and concluded that roundabouts "have improved both overall crash rates and, particularly, injury crash rates in a wide range of settings (urban, suburban, and rural) and previous forms of traffic control (two-way stop and signal)" (p. 109). Research to date also suggests that roundabouts generally are much safer for pedestrians, but that care is required to make them safer bicyclists (FHWA, 2000; Persaud et al., 2000; Retting et al., 2003).

The IIHS (2000) emphasizes that "the safety benefits don't come at the expense of traffic flows. In fact, where roundabouts replace intersections with stop signs or traffic signals, delays in traffic can be reduced by as much as 75%" (p. 2) (see also FHWA, 2000). The IIHS (2000) and the FHWA (2000) assert that roundabouts often are less expensive than signalized and even some stop-sign controlled intersections. Elvik (2003) estimates that evaluated on safety grounds, roundabouts in Norway and Sweden have a benefit-cost ratio of about 2.0.

Given these economic, safety and convenience benefits, why aren't roundabouts more widely used in the U. S.? The IIHS (2000) suggests that U. S. traffic planners and engineers simply aren't well informed about the benefits of roundabouts. The FHWA (2000) notes that roundabouts usually require more land than do conventional intersections, and that in many places the additional land is not available. However, since our LLM network is part of a complete new town, there generally will not be any land-availability constraints on incorporating roundabouts into the network.

For a discussion of smaller roundabouts, such as might be used on the LLM network, see www.mini-roundabout.com/.

provide transportation to those unable to use private transportation. And the distorted prices caused by public subsidies to transit give incentive to some to use this inefficient mode of transportation. In our plan, private and publicly operated LLMs can replace conventional public transit and provide considerable savings to the public.

To begin with, conventional public transit is of marginal and declining significance in the U. S. (Federal Highway Adminstration [FHWA], 1993; Hu and Young, 1999; Polzin et al., 1998).[38] Outside of the center of a few large urban areas, public transit generally accounts for less than one percent of trips (Polzin et al., 1998). Thus, in suburbs and small towns—the target of our transportation and town plan—the present need for public transit is extremely small,[39] and on the face of it can be met by LLMs. Therefore, we will look more closely at different kinds of public transit users and consider more carefully whether our transportation and town plan, without conventional public transit,[40] can reasonably meet their needs.

We will consider five kinds of public transit users (the categories are not mutually exclusive): (i) those unable to drive an FHV (the young, the elderly, and the unlicensed); (ii) those too poor to afford FHVs; (iii) children who are bused to school; (iv) those who choose to use transit because it is more convenient or less costly than driving; and (v) commuters (primarily commuters to central cities).

As we discussed above, many of those who are unable to drive FHVs will be able to drive motorized LLMs, from mopeds to full-featured mini-cars, and many of those unable to afford an FHV will be able to afford some kind of LLM. For those few who are unable or unwilling to own or use personal LLMs, public entities can provide LLM mini-vans, LLM taxis, or LLM-sharing arrangements.

According to the 1990 NPTS, school buses served nearly as many person-trips as did all other transit—1.7 percent of all person-trips in 1990 (FHWA, 1993). (We expect that the percentage is significantly smaller in small towns and suburbs.) For this analysis, it is useful to consider three classes of users of school buses: (a) those who are close enough to walk or cycle to school, but do not because the roads are too dangerous; (b) those who live too far from school to walk or cycle and would be driven to school by their parents were the driving a little more convenient; and (c) those for whom walking, cycling, or being driven by parents is impossible or very inconvenient. Because an LLM network will be vastly safer and significantly more convenient and pleasant than an

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[38] However, *Progress* (2000) reports FHWA data that transit boardings increased about 5 percent per year from 1996 to 2000—greater than the annual increase in vehicle miles of travel.

[39] Suburbs and small towns have relatively few transit users in part because they have relatively few low-income households, which tend to use transit more than do higher income households (Murakami and Young, 1997; Polzin et al, 1998)

[40] Since the FHV road system in our plan is ubiquitous, it is possible to provide conventional bus transit within the town we propose. However, because the FHV network is more circuitous for intra-town travel than is the LLM network, and indeed than is a conventional grid system, a bus transit system in our town would be even more inefficient than are current suburban bus systems.

FHV network, most of the class (a) school bus users will walk or cycle to school on the LLM, and many of the class (b) school bus users will be driven to school on the LLM by their parents. For those who cannot walk or cycle or drive to school on the LLM, the schools themselves can provide LLM van service. Assuming that a substantial portion of the present bus trips to school can economically and conveniently be transferred to LLMs, van service provided by the schools will have to handle many fewer students than do current conventional school buses.

The fourth class of transit riders we consider here is people who chose transit because it offers advantages over private vehicles. These so-called "choice" users are about 30 percent of all transit users (Polzin et al., 1998). (They may be an even greater percentage of transit riders in suburbs and small towns.) For these transit users, LLMs generally will be at least as convenient as conventional transit, and certainly less costly to society, and therefore attractive to both users and society. In any case, such users may use any public LLM mini-van, taxi service, or car-sharing arrangements.

Finally, in present land-use/transportation systems, commuters to central cities are a sizable plurality of transit riders—according to data from the 1995 NPTS, 44 percent of transit trips are reported to be made during the peak commute periods of 6 a.m. to 9 a.m. and 4 p.m. to 7 p.m. But residents of towns planned as we propose here will have access to jobs within town via LLMs, which in many cases should prove more economical and especially more convenient than present public transit. People working outside the town either can use private FHVs to leave town via the outer high-speed beltway or else take the LLM network to an inter-city transit station in the center of town. This intercity transit center connects via the FHV through-roads and outer beltway with intercity transit centers in other town centers (see Figures 1c, 1d, 7a, and 7b).

The LLM network and town plan thus facilitate conventional public transit *between* towns. Each town center can have an inter-town bus or rail station. The station is easily accessible within the town via the LLM network,[41] and is connected to stations in other towns along the FHV corridors that penetrate from the outer beltway to the town core. By providing convenient "feeder" access to a central transit node, the LLM network makes it more likely that inter-city transit system will be able to operate cost effectively.

Public service vehicles (police, fire, and utilities)

The LLM network will not require much in the way of highway patrol services, because vehicles by design cannot exceed the 25 mph maximum speed and because there will be no traffic lights and few stop signs to violate. Whatever minimal police services are required on the LLM can be provided in a new class of LLM police equipment (Bosselmann, et al. [1993] make a similar point), just as police horses are used in urban parks and police bicycles are used in pedestrian areas. And because the enforcement cost on the LLM network will be less than the enforcement cost on the FHV network, per vehicle-mile of travel, the use of the LLM network will result in lower total

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[41] In this regard, our proposal is ideally suited for "station cars"—LLMs owned by a transit agency or some other mobility provider and rented to transit users for travel to and from the transit station (Shaheen et al., 2004).

enforcement costs for the town, assuming that enforcement costs in general are nearly proportional to vehicle miles of travel.

In our plan, all fire, trash, water, sewer, and communications infrastructure would be installed along the FHV network, and the associated services would be provided by conventional albeit perhaps slightly smaller-than-average vehicles using the FHV network. To enable these service vehicles to turn around at the end of the FHV roads (recall that in our plan, all FHV roads as well as all LLM roads end in cul-de-sacs or deadends), each road would end in a “T”, where the top of the T is a short road with no parking allowed.

Signs and lights on the LLM network will be small scale and serviceable by specially equipped LLMs.

Finally, it is important to keep in mind that every point in the city is accessible via the FHV network to conventionally equipped police and emergency services

Road capacity and congestion
Congestion depends on the relationship between travel demand and infrastructure capacity. Congestion is most serious at peak commute hours on major roads that serve a wide travel area and tends to worsen as the areas served by the major roads expand. Traffic planners for new communities thus try to anticipate the eventual extent of development and where and how people will travel. Because our plan prescribes limits on the extent of major LLM roads and directs flows towards the center of town, it may facilitate planning street capacity for maximum and average daily traffic flows.

As illustrated in Figure 2, the LLM network directly connects the residential areas with neighborhood nodes and the center of town. There are no cross-links within or between major branches. For the purpose of planning street capacity, it probably is reasonable to assume that households will travel down the branch to the neighborhood node or town center and then back. The traffic volume along a main LLM branch then will be determined by the extent of the minor branches feeding into the main branch (see Figure 2), and by the housing density along minor branches. The extent of the minor branches is limited ultimately by the requirement that the travel time from the end of the outer LLM branches to the center of town not be significantly greater than it would be in a conventional street system (otherwise, people might prefer a conventional street system). As we discuss elsewhere, we hypothesize that a town radius of about two miles is the upper limit on desirable town size.

Given this, we believe that in planning an LLM street system one can find relatively easily balance the costs (money and loss of land) and benefits (faster and safer travel) in choosing street width and speed limits. For example, because the outer ends of the residential LLM branches are dead-ends that serve only a few houses, the traffic volume will always be very low, and thus the streets can be quite narrow—about 12 feet of pavement, with a few feet of adjacent right-of-way for pedestrians. On these narrow streets non-motorized LLMs will share the road with motorized LLMs, and the largest LLMs (4 or 4-1/2 feet wide) traveling in opposite directions will have to slow down considerably to pass. However, the total traffic volume will be too low to warrant wider, more obtrusive, and more costly streets. But because these streets will be narrow and because motorized and non-motorized LLMs will share undifferentiated right-of-way, there should be in these areas only be a *posted* speed limit of less than the 25 mph technological maximum — say, 15 miles per hour.

Further toward the town center, where more houses feed into the traffic stream, LLMs will pass each other more frequently. Therefore, the street will need to be wide enough to allow to LLMs to pass comfortably and some provision may be need for left-turning (i.e., cross traffic) movements. For this, pavement about 15 feet wide (plus unimproved right-of-way for pedestrians) should be sufficient. Near the town center, the streets will have to accommodate a relatively high volume of traffic, more frequent left-turns,[42].[43] and a mix of motorized LLMs and non-motorized LLMs. This will require pavement about 20 feet wide (27 feet where left turn lanes are required), with separate lanes for motorized and non-motorized LLMs, left turn lanes, and unimproved paths for pedestrians. (The pavement would include 3 feet of pavement for non-motorized LLMs and 7 feet for motorized LLMs, in each direction. An additional 7 feet will be required wherever there are left turn lanes.) The central LLM ring road and the radial LLM roads feeding into it will have two relatively wide lanes for motorized LLMs, a completely separate paved path for non-motorized LLMs with an unimproved pedestrian path alongside and roundabouts at major intersections. Here, the pavement will be about 25 feet wide. This will allow the high traffic volumes near the town center to flow smoothly, yet will consume no more space than do local roads in suburban areas.[44]

The FHV roads will range from more than 30 feet wide at their junction with the outer beltway to about 20 feet wide at their innermost ends near the town center. (Recall that the FHV roads radiate inward from the outer beltway and terminate near the center of town, the reverse of the LLM roads. See Figures 1a-1d.) Towards the outskirts of town near the junction with the outer FHV beltway, where the traffic volumes will be relatively high, the FHV roads will be widest. Each FHV/outer-beltway junction is the FHV entrance to a neighborhood and will be designed to accommodate with no more than tolerable delays the maximum daily flows generated by people traveling in and out of the neighborhood. Although the volume at these FHV/beltway junctions will tend to peak during commute times if many people work outside of the town in which they live, experience with the present road network tells us that we can accommodate

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[42] Left-turn lanes will be required where traffic volumes are high enough that without turn lanes turning vehicles would significantly delay through traffic, but not high enough to warrant the use of roundabouts, which as we note elsewhere are especially well suited to LLMs (albeit more expensive than turn lanes). We have not determined where on the LLM network such “in-between” volumes that warrant left-turn lanes might occur.

[43] Left-turn lanes will be required where traffic volumes are high enough that without turn lanes turning vehicles would significantly delay through traffic, but not high enough to warrant the use of roundabouts, which as we note elsewhere are especially well suited to LLMs (albeit more expensive than turn lanes). We have not determined where on the LLM network such “in-between” volumes that warrant left-turn lanes might occur.

[44] Delucchi (2005) uses data from the Federal Highway Administration to estimate that local roads (including shoulders and dividers) in urban areas are 28 feet wide on average.

such peak flows onto the FHV branches by having dedicated turn lanes off of the beltway onto a wide two-lane FHV branch-road . If the traffic density declines toward the center of town, the FHV roads can narrow accordingly, with the result that at the very inner ends closest to the town center, the FHV roads may be relatively narrow alleys. Speed limits on all radial segments of FHV roads would be 30 mph—to limit noise and enhance safety on these relatively narrow roads. The speed limit on the outer beltway FHV road and the FHV roads that penetrate to the town center can be higher.

In our plan, there is nothing unusual about the outer FHV beltway. It is a typical high-speed, multi-lane, high-volume roadway, and hence can be designed and built according to current practice.

The size of the LLM and FHV networks is illustrated in Figure 2, which shows a detailed scale map of the LLM/FHV network around the town center.

Parking

We believe that it is undesirable and unnecessary to pave space for on-street parking on either the FHV or the LLM network. Pavement space for on-street parking would nearly double the width of the LLM, an unacceptable aesthetic intrusion[45] and waste of land, with no appreciable benefit. In the single-family residential areas, households are free to have as much off-street parking as they think is necessary and multi-family housing units and all of the town center should be designed with sufficient off-street parking.

There are several ways to accommodate the rare occasions when a single-family household attracts more vehicles than can be parked on its own property:

i) allow for an unimproved, off-street, public parking easement along some stretches of the paved part of the LLM network;
ii) have small off-street parking areas (for, say, 4 to 8 LLMs) at each block (this is common in private communities governed by homeowners' associations);
iii) have large off-street public parking areas along each main neighborhood branch, within reasonable walking distance or a quick shuttle of most households (see for example the parking areas in the neighborhood center, in Figures 2 and 3);
iv) let individuals petition their neighbors to use one lane of the street for on-street parking for rare events in which there are a lot of cars.

We believe that any combination of the foregoing should adequately satisfy demands for extra parking without requiring contiguous paved road space dedicated specifically to parking cars.

[45] In their survey of residents of a north London community regarding the aesthetics of vehicles and streets, Bayley et al. (2004) found that people preferred to see cars parked in driveways or garages because of the visual and physical intrusiveness of cars parked on the street.

Environmental impacts: energy use, oil, and greenhouse gas emissions
From shortly after the Arab oil embargo of 1974 to the fall in the price of oil in the mid-1980s, U. S. energy policy was concerned with conserving energy and reducing oil use. Since about 1988, energy policy has been concerned increasingly with reducing emissions of so-called greenhouse gases, which are thought to be changing global climate (Intergovernmental Panel on Climate Change, 1996a, 1996b, 2001, 2007a, 2007b). Analysts now routinely evaluate transportation plans for their energy use, oil use, and greenhouse-gas emissions.

LLMs use much less energy and have much lower emissions than do conventional FHVs. The huge reduction in average kinetic energy (see Figure 9 and associated discussion) throughout a town based on an LLM network translates directly (although not proportionately) into a large reduction in the total lifecycle energy required for the manufacture, operation, and maintenance of vehicles and infrastructure. Because emissions of CO_2 and other greenhouse gases are closely related to energy use, a large reduction in lifecycle energy use results in large reductions in greenhouse-gas emissions.

To analyze lifecycle energy use and emissions of greenhouse gases, we use a recently expanded version of the lifecycle emission model (LEM) developed by Delucchi (2003, 1997). This model estimates emissions of urban air pollutants and greenhouse gases from the lifecycle of fuels from feedstock production to end-use and from the lifecycle of materials from raw resource extraction to manufacture and assembly. It does this for a wide range of transportation modes, vehicle technologies, and energy sources, including buses, trains, and electric vehicles.

For this analysis, we compared conventional travel modes with LLMs in the U. S. for the year 2010. Table 1 shows the lifecycle CO_2-equivalent emissions estimated by the LEM. The CO_2-equivalent is a way of expressing the impact of emissions on global climate; it is equal to actual emissions of CO_2, plus emissions of other gases expressed in terms of the amount of CO_2 that would have the equivalent effect on climate. The other gases are CH_4, CO, hydrocarbons, NO_x, SO_x, particulate matter, and refrigerants.

The results reported in Table 1 show that LLMs will provide large reductions in lifecycle emissions of greenhouse gases, even when compared with relatively efficient subcompact gasoline FHVs (e.g, 28 mpg in city driving). Full-feature electric LLMs, which we anticipate will be most of the traffic on the LLM network, offer emissions reductions of around 80% percent compared with FHVs. They offer lower emissions than public transit, except as compared with rail transit that has *double* the current average load factor. And of course the smaller LLMs, such as scooters and bicycles, offer greater reductions in emissions than even high-occupancy public transit.

Because of the close relationship between energy use and greenhouse-gas emissions, percentage reductions in energy use are similar to the percentage reductions in emissions shown in Table 1. Percentage reductions in oil use are similar for the petroleum-using options and greater for the electric options. LLMs reduce total energy use for transportation, and thus reduce petroleum consumption.

Considering the difficulty and cost of doubling current average load factors for transit in the U. S., we conclude that no other near-term transportation strategy aimed at FHVs or transit—not fuel economy improvements for FHVs, not fuel substitution for FHVs, not demand management, not increased use of public transit—promises reductions in energy use, oil use, and greenhouse-gas emissions as large as those that can be provided by LLMs operating on a dedicated LLM network.

Environmental impacts: water pollution and solid waste
Water pollution. Oil, fuel, coolant, and other chemicals leak or are discarded from motor vehicles and service stations and eventually pollute rivers, lakes, wetlands, and oceans. Several studies have shown that motor vehicles are a major source of pollution in urban runoff (Latimer et al., 1990; Lord and Smith, 1990; Bannerman et al., 1993) and storm runoff (EPA, 1993). Impervious surfaces, such as roads, collect the pollutants and transmit them to water bodies during runoff from rain and snowmelt. This polluted runoff, in turn, can significantly degrade rivers, lakes, streams, and wetlands, and even threaten human health. Gaffield et al. (2003) note that storm runoff "is one of the major threats to water quality in the United States and is linked to chronic and acute illness from exposure through drinking water, seafood, and contact recreation" (p. 1527).

LLMs and the LLM infrastructure will greatly reduce problems associated with run-off and water pollution. Consider the LLMs first. If LLMs are either non-motorized or electric-powered, then compared with FHVs and LLMs powered by internal combustion engines, leaks and discharges of lubricating oil and engine coolant will be greatly reduced, and leaks of fuel (and constituent chemicals, such as MTBE) from vehicles and underground tanks will be eliminated. Furthermore, to the extent that the use of motor fuel affects the probability of large spills of crude oil in sensitive habitats, the use of non-motorized or electric LLMs will reduce the frequency and costs of oil spills. Finally, the much lower vehicle mass and speed of LLMs compared with FHVs will reduce the creation of dust from tires and brakes and hence reduce the concentrations of these pollutants in run-off.

Turning now to the LLM infrastructure, the fact that streets for LLMs need not be designed to support wide, heavy, high-speed vehicles opens up the possibility of using permeable street surfaces rather than conventional solid pavements with curbs, gutters, and storm drains to control street run-off. Permeable pavements allow water to seep through the surface of the road, so that something akin to natural filtration can occur. This filtration removes water pollutants and replenishes local groundwater, thereby enhancing soil quality and promoting plant growth. Permeable pavements also may absorb and store less heat and be less reflective and less prone to cause glare. Finally, by reducing the amount of water that collects on the surface of the road, permeable pavements reduce the possibility of hydroplaning and thus makes roads safer. (For a discussion of permeable pavements, go to www.toolbase.org, then choose "sitework".)

Solid waste. The production, use, and disposal of motor-vehicles and fuels produces a variety of solid wastes, including dredge from resource extraction, waste sludge from oil refineries, excess material from vehicle manufacture, and of course scrapped vehicles and parts.

Scrappage is the most important source of solid waste in the current (FHV) motor-vehicle production-and-use system. In Europe, about 75% of the mass of a scrapped vehicle is recovered or recycled (Bellmann and Khare, 2000). Most of the rest of the vehicle —glass, plastics, textiles, rubber, batteries, and various hazardous substances — along with debris from highway construction, is disposed of in landfills or hazardous waste facilities. However, a small fraction of the end-of-life material is dumped or abandoned illegally. (See Maxfield [2008] for a discussion of abandoned vehicles.) This improperly disposed waste is always an eyesore and can be dangerous and damaging to human health and ecosystems.

If people dispose of LLMs more or less as they now dispose of FHVs (and if the use of LLMs does not appreciably change total travel, a point we take up below), then the amount of waste created by LLMs relative to the amount created by FHVs will be roughly proportional to the mass of LLMs relative to the mass of FHVs. Murrell, et al. (1993) report that 1991 model-year passenger cars had an average curb weight of 2853 lbs. and that 1991 model-year light-duty trucks had an average curb weight of 3649 lbs. Given that the heaviest LLMs will have an unladen weight of 1000 to 1200 lbs., and assuming as above that the generation of waste is proportional to mass, LLMs will generate no more than one-third as much solid waste as FHVs.

The batteries in electric LLMs may contain toxic materials such as lead. Lave, et al. (1995) argue that the use of lead/acid batteries in EVs may significantly increase the amount of lead in the environment, especially if the vehicles are inefficient and environmental controls and recycling in the lifecycle of lead are relatively ineffective. Because lead is such a harmful compound, this would be a serious concern. However, as discussed below, the battery pack in an LLM will be much smaller than the pack in an electric FHV. (Lave, et al. [1995] analyze only FHVs.) Moreover, state-of-the art facilities in the lead lifecycle are extremely clean (*Science*, 1995). We believe that any increase in lead flows that might result from the use of battery-electric LLMs will be handled acceptably by modern environmental and recycling programs.

Despite the virtual disappearance of lead-acid batteries from discussions of traction batteries for modern FHV EVs, LLMs operated in LLM street networks are suitable vehicles for lead-acid batteries. The vehicles will be light, speeds will be low, accelerations will of necessity be modest (or at least short in duration), and daily travel distances will be short. Thus, the high specific energy and power of other more expensive battery chemistries would not be highly valued in LLMs.

Environmental impacts: noise

In many urban areas, noise is a serious problem. Noise disturbs sleep, disrupts activities, hinders work, impedes learning, and causes stress (Linster, 1990). Indeed, surveys often find that noise is the most common disturbance in the home (Organization for Economic Cooperation and Development, 1988). Motor vehicles generally are the primary source of that noise.[46]

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[46] Delucchi and Hsu (1998) present an analysis of the social cost of motor-vehicle noise in the U. S.

Overall, people in the town plan we propose will be exposed to less vehicle noise than are people in conventional suburbs. Noise from the LLM network will be much less than noise from a typical suburban FHV road system. Conventional motor vehicles have two sources of noise: combustion in the engine, and the contact between tires and the road. Total noise emissions are very sensitive to speed because tire-road noise increases sharply with vehicle speed, such that at high speeds the tires make more noise than does the engine. Using the noise-emission equations in the FHWA's *Transportation Noise Model* (see Delucchi and Hsu, 1998), we estimate that internal-combustion LLMs traveling at an average speed of 20 mph will make about one-fifth the noise of internal-combustion FHVs traveling at 35-38 mph (a typical speed on local roads).[47] The substitution of an electric motor for an engine will reduce noise even further. And of course non-motorized LLMs make essentially no noise.

To the extent that our FHV network speed limits are lower than they are on a conventional suburban road, FHVs in our plan will emit less noise than do FHVs in conventional suburbs. (Note that in our plan the only high-speed FHV routes are the beltway at the outer edge of town and those two or three FHV routes that penetrate to the town center; see Figures 1a-1d.) Furthermore, it should be relatively easy and desirable to layout the street system and design houses and businesses to be oriented (and hence more exposed) to the LLM rather than the FHV network. This will reduce actual exposure to whatever noise is generated by FHVs.

Environmental impacts: air pollution

Although LLMs emit less air pollution than do FHVs, this social benefit may be comparatively minor given improvements in emissions from conventional vehicles. A decade ago, the air emission differences between LLMs (especially electric and non-motorized LLMs) and FHVs were relatively large and perhaps a compelling reason to develop LLM technology. Today, however, properly functioning gasoline FHVs are so clean that any further reductions in air emissions that LLMs provide may no longer be their primary benefit in suburban areas.

However, there are two "private" benefits that may be more significant than the residual social benefit. First, electric and non-motorized LLMs are inherently emission-free and hence, unlike modern gasoline vehicles, do not have to be inspected and maintained to ensure that emissions remain low. For this reason, electric and non-motorized LLMs will be more convenient to own and operate. (Gasoline-powered LLMs will have to be inspected and maintained just as FHVs are.) Second, even modern clean FHVs produce unpleasant vapors at start up and in confined spaces; electric and non-motorized LLMs will produce no noxious fumes.

Presently, emissions from heavy diesel vehicles are much more problematic than emissions from gasoline passenger vehicles. The LLM and FHV networks may facilitate some reductions of emissions from diesel trucks, compared with their emissions in a

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[47] In the *Transportation Noise Model*, noise emissions also are a function of the fraction of time vehicles are cruising rather than accelerating. (Accelerations are noisier.) We assume in our analysis that LLM traffic will flow more smoothly than does local FHV traffic in conventional street networks because there will be fewer intersections in the LLM network.

conventional street system. In our plan, large trucks can be driven directly from highways to town centers, conceivably without stopping before they arrive at the core of the town center where they make deliveries. (However, neighborhood stores may have to be supplied by some trucks traveling the radial FHV streets.) The overall plan thus may allow minor reductions in emissions from diesel trucks. In any case, the considerable efforts now underway to clean up emissions from heavy trucks must continue.[48]

Environmental impacts: aesthetics and community fragmentation

Aesthetics. The present motor-vehicle infrastructure is ugly (Button, 1993). Roads, gas stations, car-sale lots, car-repair shops, parts stores, parking lots, and garages form (or inhabit) dreary, chaotic strip developments decried by architects and city planners (e.g., Wright and Curtis, 2005; Kunstler, 1993). Surveys report the general public feels that the world would be prettier without roads (Huddart, 1978), and that residential streets would be more attractive without large cars (Bayley et al., 2004).[49] As Wright and Curtis (2005) put it:

> Human survivors find themselves confronted by buidlings and highways that are out of proportion with human scale and needs, machines for processing vehicular traffic...the components of the machine (petrol stations, car parks, one-way systems, pedestrian barriers, signs, traffic signals, street lights, and road markings) are not only obtrusive, but, some would say, symptomatic of a structural misfit. As a means of mass transport, the motor car is not compatible with the fabric of traditional cities laid out on a human scale (p. 12).

Partly as a result of the protests of the 1960s, the highway planning process in the U. S. was amended to better accommodate community concerns. However, by and large, urban planners and architects have not been able to control strip development and improve the esthetics of roadside America. We expect that motor-vehicles and the infrastructure that supports them will continue to exact an esthetic "cost" for the foreseeable future.

Because of the low speed and small size of LLMs, the LLM network will not have wide roads, traffic lights, medians, railings, or shoulders. As explained above, it need not have on-street parking. And if motorized LLMs use electric motors (which we think they could and should), the LLM network will not have gasoline stations. All of these features will make the LLM network much less visually intrusive and socially divisive than is the present street system. Indeed, properly designed, an LLM network can be an esthetically pleasing, integral part of a townscape. Even the FHV network in our plan will be less unsightly than a conventional suburban FHV road system, because in our

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[48] In 2000, the EPA adopted emission standards for new diesel trucks and buses that would cut sulfur by 97%, nitrogen oxide emissions by 95%, and particulate emissions by 90%, by 2007. See Walsh (2001) for a review of emissions regulations for diesel vehicles worldwide.

[49] The unsightliness of scrapped autos and junkyards has been formally condemned by the courts: according to Woodbury (1987), a court in Colorado ruled that a stockpile of old cars, scrap metal, petrochemical drums, and other obnoxious debris near a mountain cabin was an unsightly eyesore and had to be removed solely because it was unaesthetic.

plan houses and businesses are (or should be) oriented away from the FHV road, which function rather like service alleys and are not a prominent part of the visual landscape.

Community fragmentation. The roads and freeways intended to connect people to places can divide communities, impede non-vehicular circulation, and create barriers to social interaction (Wright and Curtis, 2005; Sheller and Urry, 2000; Marshall, 2000). Marhsall (2000) believes that "transportation determines the form of our places" (pp. x-xi), and that the automobile and highway system destroy our long-standing sense of urban "space". Wright and Curtis (2005) cite a study that attributes major declines in "neighborliness and community engagement" in American cities partly to the motor-vehicle and highway system. Sheller and Urry (2000) remark that (p. 744):

> Automobility has fragmented social practices that occurred in shared public spaces within each city...In particular, automobility divides workplaces from homes...it splits homes and business districts [and] separates homes and various kinds of leisure activities…Automobility turns access zones on urban fringes into wastelands..

The conventional FHV infrastructure itself can physically split (or even bury) neighborhoods. Indeed, the "freeway revolts" that began in the late 1960s and shut down freeway projects in several cities (for example, the dead-end Embarcadero Freeway in San Francisco, torn down after the 1989 Loma Prieta earthquake) were spawned in part by these sorts of negative social impacts. And vehicle traffic itself can disrupt the social functioning of neighborhoods and communities. Soguel (1995) cites a study by Appleyard that shows that "residents of San Francisco with light volumes of traffic have three times as many local friends and twice as many acquaintances as those on heavily traveled streets." Similarly, Bayley et al. (2004) surveyed residents of a residential community in north London, England, regarding the aesthetics of vehicles and streets, and found that people liked streets that had a low volume of motor-vehicle traffic and nice landscaping, and dislike streets with rows of parked cars because they created physical and visual barriers.

The LLM network will function to define, unify, and connect neighborhoods rather than to separate and isolate them. No high-speed, high-volume roads transect the neighborhoods. Virtually all roads—FHV as well as LLM— in our system terminate in cul-de-sacs —which, when part of a coherent town plan and pedestrian-friendly infrastructure, can help create an "ideal suburban residential environment" (Southworth and Ben-Joseph, 2004a, p. 32). All LLM roads lead to "town." These features will make the transportation system in our plan far less obtrusive and divisive, and far more integrating and unifying, than it is in a conventional suburb.

ECONOMICS

In this section we turn to the question of cost. What will the dual LLM and FHV infrastructure cost society in comparison with a functionally similar all-in-one network? What will LLMs cost households, compared with what would be purchased and used were LLMs not available? We examine the cost of the infrastructure first.

The cost of the infrastructure

How does the overall cost of the LLM+FHV network compare with the cost of a comparable conventional suburban road network? In this section, we will show that the overall cost probably will be about the same, in spite of there being two networks in our plan. Formally, we estimate the infrastructure cost of our plan relative to the cost of a conventional plan as a function of the cost per mile and the number of miles of roadway in our plan versus a conventional plan:

$$RC = RCM_{LLM} \cdot RL_{LLM} + RCM_{FHV} \cdot RL_{FHV} \qquad \text{eq. 1}$$

$$RCM_{LLM} = RCF_{LLM} \cdot RW_{LLM}$$
$$RCM_{FFV} = RCF_{FFV} \cdot RW_{FFV}$$

where:

RC = the cost of the total FHV+LLM road infrastructure in our plan relative to the cost of the road infrastructure in a conventional suburb
RCM_{LLM} = the cost per mile of the LLM network in our plan relative to the cost-per-mile of a conventional suburban road network
RL_{LLM} = the number of miles of the LLM network in our plan relative to the number of miles of a conventional suburban road network
RCM_{FHV} = the cost per mile of the FHV network in our plan relative to the cost-per-mile of a conventional suburban road network
RL_{FHV} = the number of miles of the FHV network in our plan relative to the number of miles of a conventional suburban road network
RCF_{LLM} = the cost per foot of width per mile of an LLM road relative to the cost of a conventional suburban road[50]
RW_{LLM} = the width of an LLM road relative to the width of a conventional suburban road
RCF_{FFV} = the cost per foot of width per mile of an FHV road relative to the cost of a conventional suburban road
RW_{FFV} = the width of an FHV road relative to the width of a conventional suburban road

[50] For reference, here are estimates of the cost per foot per mile. Delucchi (2005) uses FHWA cost data to estimate that in urban areas, interstate highways cost about $4 million/mile to build, high-volume arterials cost about $2 million/mile, and collectors and local roads about $1 million/mile, excluding sidewalks, sewers, and street lighting. Burchell et al. (2000) assume a "uniform costing level of $1 million per centerline mile is used for local roads in all communities" (p. 177). Burchell and Mukherji (2003) assume about $500,000 per lane-mile for local roads, which is consistent with $1 million per center-line mile assuming two lanes per road. In rural areas, the costs per mile are less. The average for a typical suburban residential network of neighborhood streets, local roads, and collectors and perhaps few arterials probably is on the order of $600,000/mile. Assuming that the road is 30 feet wide (including curbs, gutters, dividers, and shoulders, but not sidewalks) (Delucchi, 2001), the cost is $20,000/ft/mi. Similarly, data in Wilkinson, et al. (1994) indicate that expanding conventional local roads to accommodate bicycles costs about $15,000/ft./mi. for pavement and land, probably in suburban areas.

We now consider the basic cost parameters, beginning with RCF_{LLM}, the costs/ft./mi. of an LLM network. There are several reasons why the LLM network will be relatively inexpensive per foot of width per mile. First, LLM streets will be designed for a maximum gross vehicle weight of around 1600 lbs. (a maximum curb weight of 1000 to 1200 lbs. plus a maximum cargo of on the order of 400 to 600 lbs.)—almost 100 times less than the maximum weight that present residential streets must carry. This huge reduction in the maximum load translates into reductions in the capital cost of the road. For example, Bosselman, et al. (1993) suggest that it costs much less to excavate, grade, and fill for a neighborhood path that carries LLMs than for a typical FHV road. Second, the LLM streets will not need traffic lights,[51] sound walls, barriers or railings, medians, or any other roadside material save for street lights and signs. This also will reduce capital costs.[52] Third, LLM streets are narrow and thin enough that water runoff probably can be handled by making the surface permeable rather than by having gutters and storm drains (see the brief discussion under "Environmental impacts: water pollution and solid waste").[53] Considering these three factors, we estimate that the cost/ft.-width/mi. of an LLM street is 50 percent of that of a conventional suburban road. Hence, we assume that $RCF_{LLM} = 0.50$.

LLM roads will be much narrower than conventional suburban roads. Delucchi (2005) used FHWA data to estimate that local roads and collectors in urban and rural areas are 20-35 feet wide, including dividers, gutters, and shoulders, but not sidewalks. The average probably is around 30 feet. In new suburbs, though, the average undoubtedly is higher than the overall average. We assume a width of 32 feet in new suburbs. Now, as discussed above, the width of the LLM street will range from a little more than 10 feet at the end of the neighborhood roads to 25 feet at the central ring road. We can use the following assumptions to estimate the average width of the LLM network:

- 10 percent of the LLM mileage is the narrowest, lowest-volume, end-of-the line residential paths (12 ft. wide);
- 25 percent of the LLM mileage is in other narrow, low-volume, residential streets (15 ft. wide);

[51] At minor intersections in our plan, no signs are required; at major intersections, roundabouts, which are relatively inexpensive, are safe and efficient for LLMs. As documented elsewhere in these footnotes, at any given volume of traffic (up to the capacity of the roundabout), roundabouts are more convenient and much safer than are conventional intersections with stop signs or signals. Roundabouts are especially safe and efficient when the vehicles are relatively slow and small, and hence are ideal for the LLM network.

[52] Speaking about the design of Houten, a town in the Netherlands with a dual-network system similar to ours (see the discussion of Houten elsewhere in this report), Rob Derks, the original planner of Houten, states that the car streets in Houten are cheaper because they are narrower and don't have traffic lights or any other street furniture.

[53] The least costly permeable surface, permeable asphalt, is made of the same materials and in much the same way as is non-permeable asphalt, and hence costs about the same (www.toolbase.org, tab "sitework").

- 40 percent of the LLM mileage is in relatively wide, high-volume streets with two lanes for motorized traffic, and separate lanes for nonmotorized traffic (20 feet wide);

- 25 percent of the LLM mileage is the widest, highest volume streets with separate lanes for bicycles and pedestrians (25 feet wide);

With these assumptions, the average width is 19.2 feet, and RW_{LLM} in eq. 1 is 19.2/32 = 0.60. Thus, the relative cost per mile of an LLM road is 0.60 x 0.50 = 30 percent of the cost/mi. of a conventional suburban road (i.e., RCM_{LLM} in eq. 1 = 0.30).

The FHV road network in our plan also will cost less per mile than does a conventional FHV grid system. The availability of the LLM network should significantly reduce traffic volume on the FHV network and enable the FHV network to be designed to have lower capacity and hence less pavement than it would have were it to carry all of the trips in the town. We hypothesize that the LLM network will carry up to half or more of all trips made by households (see the section "How much might LLMs be driven?) Moreover, in our plan the FHV network does not need space for on-street parking, sidewalks, or bicycle lanes, because these are provided on the LLM network. Also, compared with a grid, our plan has fewer intersections and hence less of the cost associated with building and controlling intersections. In short, the FHV network will be less costly than a conventional road system because it will have lower vehicle volumes and no LLMs at all.[54] We estimate that the relative cost per foot (RCF_{FFV}) is 90 percent, and the relative width (RW_{FFV}) 80 percent (i.e., 26 ft.), with the result that the FHV network in our plan will be 72 percent of the cost per mile of a conventional suburban road network (i.e., RCM_{FFV} in eq. 1 = 0.72).

It remains for us to estimate the mileage of our road network relative to the mileage in a conventional suburban network. Because the FHV roads are everywhere parallel to the LLM streets within the boundaries of our town (Figures 1a-1d), it is reasonable to assume for our rough cost estimation here that the FHV network mileage and the LLM network mileage are the same. This means that in eq. 1 $RL_{LLM} = RL_{FFV}$. With this relation, and the estimates presented above for RCM_{FFV} and RCM_{LLM}, it is easy to see that our road network will cost the same as a conventional one (i.e., that RC = 1.0) if the mileage in the FHV *or* the LLM network is only 2 percent less than that in a conventional network. And if the mileage of the FHV or the LLM network is even less than this, then the total infrastructure cost in our plan is less than in conventional system.

For two reasons, we think it likely that the total mileage in the LLM or FHV network will be less than that in a conventional road system. First, there are relatively few

[54] Note the advantage of specialization: in a conventional system the parts of the roadway that handle mainly LLMs are overdesigned for LLMs because they must be able to handle FHVs as well. Society saves money when LLMs are transferred to a dedicated network, because the dedicated roads are designed specifically for LLMs and hence costs less per mile than do roads that also must accomodate FHVs.

intersections in our plan. Figures 10a and 10b show how an intersection displaces lot frontage space, and increases the length of road required to accommodate a given number of lots of fixed average frontal area. In Figure 10a, which depicts a road with no cross streets, the road is six housing fronts long. In Figure 10b, which depicts an intersection, the roads are nine housing fronts long (2 house fronts along each of the 4 arms of the cross, plus the one in the middle). In both figures, the lots are square.) Our radial plan (see Figures 1a-1d) has relatively few intersections compared with a conventional grid system, and hence at a given housing density will tend to have less mileage in the LLM or the FHV network.

The second reason is that in the single-family residential areas, there may be two or even three houses between each LLM and FHV. This illustrated in Figures 4 and 5. With this layout, no house borders the LLM *and* the FHV road —which means that no house has a road on both sides of it —but each house does share a driveway with one or two other houses. The alternative is for each house to have direct access to the LLM network on one side of it and to the FHV network on the other, via its own private drive, but we suspect that most people will prefer to not have a road on both sides. The shared-driveway alternative illustrated in Figures 4 and 5 does entail longer driveways than in the road-on-both-sides alternative, but assuming that driveways are narrower than roadways, the net effect should be a reduction in paved area relative to the alternative in which each there is only one house between each LLM and FHV road.

Considering all these factors with respect to eq. 1, we conclude that the total cost of the FHV+LLM street system in our plan will be slightly less than the total cost of a comparable conventional suburban road network.

Paying for the LLM infrastructure. The construction and maintenance of public roads is paid for mainly by road-user taxes on highway fuels. However, some local roads are built by private developers and treated as a "bundled commodity" in which the cost is recovered in the price of goods, services, and houses rather than from dedicated road-user taxes. Bundling makes sense when the cost being bundled is relatively small compared with the cost of the rest of the bundle and there is a significant transaction cost to establishing and maintaining a separate pricing system. We think that the capital and operating[55] cost of the LLM network is low enough, and the cost of establishing a separate pricing system high enough (especially considering the problem of collecting road-user taxes from people who use electric or non-motorized LLMs), that it makes sense to treat the cost of the LLM as a bundled commodity, paid for in the price of other community goods and services.

The cost of the modes

The LLM network allows any mode that weighs less than 1000 to 1200 lbs. and has a top speed of 25 mph or less. This accommodates everything from pedestrians to luxury vehicles indistinguishable from FHVs save for the limited top speed and weight: pedestrians, bicycles, pedicabs, electric-assist bicycles, mopeds, motor-scooters, covered motor scooters, three-wheel taxis, golf carts, simple neighborhood electric vehicles, and

[55] As discussed in the section on public service vehicles (police, fire, and utility vehicles), we believe that the LLM network will not increase the cost of providing these public services.

luxury mini-cars. Now, we know that walking is essentially free, and non-motorized transport almost free. Mopeds, motor-scooters, and simple electric vehicles designed like golf carts also are inexpensive to own and operate: they cost no more than a few thousand dollars (compared with at least $20,000 for most new FHVs) and have low running costs. Because these modes are so inexpensive, any household that can use them probably will.

The question of cost, and hence the question of what people might actually purchase and use, becomes interesting when we consider full-featured LLM motor vehicles. Although the LLM network will make cycling and walking much more attractive than they are in any conventional suburb,[56] we expect that most people will want to make most of their trips in LLMs that have all of the features of conventional FHVs. (Above, we refer to these as "fully featured" vehicles.) Put another way, we anticipate that most people using the LLM network will want to sacrifice *nothing* compared with the alternative of using an FHV on a conventional suburban network. Indeed, our effort here is motivated almost entirely by this anticipation, and as a result, in our plan users of full-feature LLMs will in fact sacrifice almost nothing, so long as the LLM network is designed so that trips on LLMs take no longer than would the comparable trip in an FHV on a conventional network.

So how much will full-feature LLMs cost? If the private lifetime cost of electric LLMs is close to the private lifetime cost of gasoline LLMs, will electric LLMs offer large enough social benefits compared with gasoline LLMs to warrant regulations that explicitly or effectively require electric drive in motorized LLMs? To answer these questions, we employed the Advanced Vehicle Cost and Energy Use Model (AVCEM) developed by Delucchi and colleagues at U. C. Davis (Delucchi, 2000b; Delucchi and Lipman, 2001). This model designs a motor vehicle to meet range and performance requirements specified by the modeler, and then calculates the initial retail cost and total lifecycle cost of the designed vehicle. The model has three major parts:

- The *model of vehicle cost and weight* consists of a model of manufacturing cost and weight and a model of all of the other costs—division costs, corporate costs, and dealer costs—that compose the total retail cost. It estimates manufacturing costs for over 40 vehicle subsystems.

- The *model of vehicle energy use* is a detailed second-by-second simulation of the amount of energy required to overcome all of the forces (including internal engine friction) acting on a vehicle over a specified drive cycle.

- The detailed accounting of *periodic ownership and operating costs* includes insurance, fuel, maintenance and repair, registration, parking,

[56] FHVs and the associated FHV road infrastructure certainly deter many people from walking and cycling (Komanoff and Roelofs, 1993; Zegeer, et al. 1994). According to Zegeer et al. (1994), "one of the most frequently cited reasons for not bicycling or walking is fear for safety in traffic…narrow travel lanes, high motor vehicle speeds, congestion, lack of sidewalks, pollution, etc." (p. 24).

tolls, and so on. (For FHVs, these costs are about the same magnitude as the amortized initial cost vehicle.)

We specified AVCEM to simulate low-mass, low-speed, full-feature motor vehicles driven over a low-speed urban drive cycle. The assumed and simulated characteristics of a gasoline LLM, a battery-powered electric LLM with a 20-mile range (BPEV-20), a battery LLM with a 30-mi. range (BPEV-30), and a conventional gasoline FHV (a Ford Escort) are shown in Table 2. The vehicles have air conditioning, heating, entertainment systems, power steering, and power brakes. The low-speed urban drive cycle lasts 23 minutes and is 4.1 miles long, and has an average speed of 11 mph and a maximum speed of 24 mph. (The conventional gasoline FHV is assumed to be driven over the standard Federal Urban Drive Schedule.)

The results of the retail cost and lifecycle cost analysis are shown in Table 3. AVCEM estimates that in high-volume production, a full-feature gasoline LLM will sell for under $9,000, and its BPEV counterpart for only $500 to $800 more depending mainly on the size of the battery (which in turn is determined by the desired driving range). Our estimated retail prices are consistent with limited data on the retail price of ultra-mini gasoline cars and neighborhood electric vehicles.[57]

AVCEM estimates that a full-feature LLM will sell for substantially less than a subcompact FHV (Table 3) and less than half of the price of an midsize FHV (Delucchi, 2000b). And as we discuss below, gasoline LLMs will have substantially lower insurance, maintenance, and fuel costs than FHVS. These findings suggest that many people who can't afford FHVs will be able to afford LLMs.

The battery-electric LLM has a slightly higher initial cost than does the gasoline LLM, but has the same total lifetime cost as the gasoline LLM when gasoline costs about $2 per gallon including taxes. The small extra initial cost is due almost entirely to the initial cost of the battery, because the balance of the electric LLM costs roughly the same as the gasoline LLM. The extra initial cost is relatively small because very little battery is required to supply a very short range in a very efficient vehicle: if the LLM achieves 12 mi/kWh from the battery terminals (based on 7 mi/kWh from the outlet, as shown in Table 2), then the battery discharge capacity necessary for a 20 or 30 mile range[58] is on

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[57] For example, according to a brochure provided by the manufacturer, the ZENN EV, a low-speed, full-featured, neighborhood electric vehicle, is expected to sell for between $10,000 and $13,000, at quite limited production volumes.

For two reasons we use our model rather than the limited market data to estimate costs. First, nobody manufactures in any significant quantity the sort of full-feature LLMs that we envision here, and we wish to estimate costs at high volumes of production. Second, we wish to compare gasoline with electric LLMs (and both with gasoline FHVs) in order to gain insight into the reasonableness of requiring LLMs to be zero emissions, and to do this we must model comparable vehicles.

[58] On the LLM network, a typical trip into town is less than 2 miles, and the longest cross-town trip is less than 6 miles. Thus, a vehicle with a 25-mile range can make at least 6 and typically about 10 round trips into town, or one long cross-town round trip and several into-town round trips in a day. Considering that the entire town also is accessible by FHV, which can be used to accommodate the undoubtedly tiny

the order of 2 kWh. At a retail cost per kWh of about $350 (Delucchi, 2000b; Lipman, 1999), the initial retail-level cost of the battery is about $700. Minor cost savings in a low-power electric drivetain (motor, controller, and transmission) versus a low-power gasoline drivetrain offset this extra battery cost slightly.[59]

Any LLM, whether gasoline or electric, will have lower running costs than an FHV. LLMs will have lower insurance costs because of the reduced all-around crash risks, lower registration costs because of their lesser value or lower weight,[60] and lower fuel-tax or road-tax costs because of their much lower weight (which reduces energy use and road damage). AVCEM estimates that compared with gasoline LLMs battery electric LLMs will have lower energy costs ($0.025/mile for electricity+recharging station+space-heating fuel versus about $0.035/mi. for gasoline at $2.00/gal and 57 mpg) and slightly lower maintenance, repair, and inspection costs (about $0.04/mi. vs. $0.05/mi.). Electric LLMs also may last longer than gasoline LLMs, on account of their more robust drivelines; if they do, they will have a lower annualized ownership cost (about $0.02/mi. lower). However, AVCEM estimates that the lifecycle cost of the battery in an electric LLM will be at least $0.040/mi.

Overall, the battery electric LLM will have about the same lifecycle cost as a gasoline LLM when gasoline sells for about $2/gallon, including taxes (Table 3).

The social benefits of electric LLMs. In an earlier section, we asked: "If the private lifetime cost of electric LLMs is close to the private lifetime cost of gasoline LLMs, will electric LLMs offer enough social benefits compared with gasoline LLMs to warrant regulations that explicitly or effectively require electric drive in motorized LLMs?" One way to answer this question is to estimate the dollar value of the social benefits, which economists call "externalities." Using the analysis of externalities presented in Delucchi (2000c), Delucchi and Lipman (2001) estimate the social value of the reductions in oil use, noise, water pollution, air pollution, and climate change provided by conventional electric FHVs compared with conventional gasoline FHVs. They find that these reductions are worth $0.004 to $0.037 per mile, with a best estimate of $0.011/mi. In the case of electric LLMs versus gasoline LLMs, the best estimate of the value of these reductions would be a little lower—about $0.009/mi.—because a gasoline LLM has significantly lower oil-use and climate-change costs (but probably not lower air pollution costs) than does a gasoline FHV, on account of the relatively high fuel economy of a gasoline LLM. Thus, the quantifiable social benefits of electric LLMs appear to be positive but relatively small compared to the total private lifetime cost. We note, though, that we have not quantified all of the social benefits of electric LLMs, such as no unsightly refueling infrastructure. In any event, it is our judgment that it is worth

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fraction of in-town travel demand that will exceed the range capacity of the electric LLM, a 25-mile range ought to be sufficient for an electric LLM.

[59] We assume that the electric drivetrain in an LLM will not be as costly, per unit of power, as the electric drive in an FHV, because the LLM electric drive will not need high-power electronics.

[60] Some states base registration fees on vehicle weight; some base them on vehicle value (Federal Highway Administration, 1995).

establishing regulations in order to obtain the wide range of social benefits that electric LLMs offer over gasoline LLMs: reduced petroleum use, lower emissions of greenhouse gases, less noise, less water pollution, less air pollution, and no unsightly refueling infrastructure. We therefore recommend that LLMs be required to be zero-emission modes.

WILL PEOPLE LIVE IN THE TOWNS AND USE LLMs?

Thus far we have presented the features, impacts, and economics of the new town/transportation plan. We have presented a plan and system that requires no new technology (a wide range of suitable LLMs are available today) and in principle offers enough "private" benefits to be attractive on that basis alone without any regulation designed to sacrifice private gain for the public good. Indeed, we have shown that it is possible to plan *new* communities and transportation systems that accommodate completely the strong trends toward auto-mobility and single-family homes, yet at the same time are much cleaner, safer, more pleasant, and more socially integrating than any of the commonly proposed transportation and planning measures.

If we are right, then new towns developed along the lines we propose should be a success—people will want to live in them and use LLM. In this final section, we examine this issue of location and vehicle choice.

Advantages and disadvantages of the plan

Our broad look at the literature and at real-world experience indicates that nothing exactly like our plan has been built or discussed. We therefore turn now to a more hypothetical analysis of household transportation and location decisions in order to determine whether our plan will be attractive to buyers and drivers.

If the system we propose involved no trade-off whatsoever but still offered the private and social advantages discussed above, then in principle people would prefer it. However, the plan does involve tradeoffs. The advantages and disadvantages can be summarized as follows:

Advantages of our plan	Drawbacks of our plan
1. Travel on the LLM network is safer, more convenient, and more pleasant. 2. Travel costs less: all running costs and most ownership costs of LLMs are very low. 3. It combines the benefits of suburban living (security, private space, quiet) with some of the benefits of urban living (convenient access to schools, services, parks, and shops).	1. In some designs, travel on the FHV network will be less convenient. 2. Vehicle holding may cost more: if LLMs are additional vehicles in households, i.e., additional to FHVs, garaging and registration costs increase. 3. Our plan requires *either* that each single-family household share a driveway with one or even two other households *or* have an LLM road along the "front" and an FHV road along the "back." It is not possible to have only one road along the house *and* not share a driveway. Some people may not like this.

First, in some versions of the plan some travel on the FHV network is less convenient than is travel on the LLM network.[61] The convenience of the FHV network depends mainly on how many of the radial FHV roads go all the way to the town center, and whether the FHV roads in the town center go all the way through and connect to each other. Examine Figures 1a-1d, and Figure 6a, in which 3 FHV radial roads go the town center, but three do not, and the three that do go to the center go all the way through and connect with each other. In this plan, a person can get anywhere in town in an FHV, but some FHV trips are less convenient than they would be in a conventional town, and less convenient than by the LLM network in our plan. This is because to travel to or from a radial branch that does *not* go to the town center, to or from any other FHV radial branch, a person must travel out to the outer FHV beltway, then along the outer beltway section, then back down the destination radial FHV branch. If none of the FHV branches that do go to the town center penetrate all the way through and connect with other FHV branches (as in Figure 6b), then all travel between FHV radial branches requires going out to the FHV outer beltway. However, given that the LLM network is on the whole superior to a conventional network, this inconvenience can matter in principle only to households who are unable or unwilling to use LLMs. For

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[61] In all versions of the plan, there is one case in which travel on the FHV network actually is more convenient. As one can see by inspecting Figures 1a-1d, travel from one half of a branch/neighborhood to the *adjacent* half of the next branch/neighborhood typically will be more convenient by FHV than by LLM. As shown in Figure 2, a branch/neighborhood is bounded by the FHV radial roads and the FHV outer ring road and bisected by an LLM radial road, with the neighborhood center in the middle. Because the LLM streets do not cross the radial FHV roads, but the FHV streets do, any need to travel between areas on either side of an FHV radial road is more easily satisfied by traveling across the FHV radial road on an FHV street than by traveling around the FHV radial road via the LLM inner ring road. However, all other travel – within one's own neighborhood, to the town center, or to any other neighborhood other than the half immediately adjacent – is at least as well accommodated by the LLM network.

example, households that daily transport very heavy or bulky cargo within the town might balk at sacrificing any convenience in the use of FHVs. However, there must be but few such households, and these few can locate on or near one of the FHV corridors that penetrate into the town core.[62]

Moreover, one can design the FHV network so that all of the radial FHV roads go to the town center and connect with one-another (we have not shown a version of this plan). In this case, travel on the FHV network generally is not less convenient than is travel on the LLM network. However, this version of the plan has two drawbacks: it is the most costly, because of the extra undercrossings, and it might discourage travel on the LLM network. The "best" overall design depends on how one weighs the tradeoffs between the objectives of minimizing cost, maximizing convenience on the FHV network, and maximizing the convenience of the LLM network *relative* to that of the FHV network.

The second tradeoff in our plan has to do with cost and can be collapsed into a single important question: *how would owning and operating an LLM affect a household's total annual transportation cost?* In order to analyze this, we distinguish costs that are a function of vehicle usage from "holding costs."

As discussed in the section on economics, the costs of vehicle usage (fuel, maintenance and repair, tires, and so on) clearly are much lower in our plan than in a conventional plan. However, if in our plan households increase their total vehicle holding, then some vehicle holding costs may increase. There are several possible changes in vehicle holding to analyze:

1) *Households substitute LLMs for FHVs that they would have used like LLMs anyway*. In this case, households benefit doubly and incur no extra cost: they pay much less to own, "hold," and operate the LLM than the FHV that they otherwise would have bought, and gain all the non-monetary advantages of travel on the LLM network. *In this case, our plan realizes a latent preferred choice that otherwise is unrealizable.*

2) *Households substitute LLMs for FHVs that would have been used only occasionally as LLMs, and hence must re-arrange their vehicle usage in order to accommodate the dedicated LLMs.* In this case, households gain the monetary and non-monetary benefits of LLM ownership and use, as in 1), but with some changes in travel planning. *Ex hypothesis*, the benefits outweigh the cost in this case. Investigations of household decision-making (real and hypothetical) around electric-drive vehicle in general (Turrentine, et al. 1992; Turrentine and Kurani, 1998; Kurani, et al. 1994, 1996) and neighborhood electric vehicles in particular (Kurani, 1994; Kurani, et al. 1995) all support the contention that these changes in travel planning impose only a small additional burden on households.

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[62] Note that we speak here only of households that transport very large cargo within the town regularly. Most businesses will locate in the town center or in a neighborhood center, which have direct FHV access to other town centers and to the rest of the world via the FHV roads that penetrate into the town service core. All households can conveniently transport medium-size cargo within the town on the LLM network and very large cargo outside of the town conveniently via the FHV roads that lead directly to the outer beltway. For precisely this reason, businesses that sell large bulky items to households—for example, large home improvement stores—probably will locate on the outer beltway, along with other "big-box retailers" rather than in the town center.

Typical behavioral adaptations are simple extensions of pre-existing household decision-making processes.

3) Households *add* LLMs to a vehicle fleet that otherwise is the same as it would be in a conventionally designed town or city. In this case, households now use their FHVs less than they would have, and hence save the rather substantial cost difference between using LLMs and using FHVs. However, they incur the extra costs of simply "holding" an additional vehicle, independent of how much it is used. These usage-independent "holding" costs include:

(i) the registration cost of the LLM;
(ii) the garaging cost of the LLM;
(iii) the *difference* between the insurance cost of the LLM, and the amount that the insurance cost for the FHVs is reduced on account of the FHVs being used less; and
(iv) the *difference* between the annualized initial cost of the LLM and the reduction in the annualized initial cost of the FHVs, owing to the FHVs being used less.

Holding cost (i) is likely to be insignificant (see Federal Highway Administration, 1995). Holding cost (ii) may range from small to modest, depending on how much space is devoted to LLMs. Holding cost (iii) may be zero if the reduction in usage of an FHV gets it reclassified from a regular-use to an occasional-use vehicle. And holding cost (iv) actually will be *negative*—that is, a net cost savings—if vehicle depreciation is related more to mileage than to age per se, because the amortized cost per mile of an LLM is much less than the amortized cost per mile of an FHV.

Overall, the change in holding cost is likely to be a small increase. However, when this is added in with the unambiguous cost saving from LLM usage, it is clear that for most if not virtually all households the ownership and use of LLMs will decrease total annual transportation expenditures[63]. This plan, therefore, should be attractive to all but the few households that are unable to garage a second vehicle conveniently or economically.[64]

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[63] The decrease in total annual transportation expenditures might enable people to qualify for a higher mortgage payment and buy a bigger and better home. See *Progress* (2001) for a discussion of what have been called "location-efficient mortgages".

[64] One critique of the overall plan is that it appears to require ownership of both an FHV and an LLM. For maximal accessibility, this is true. But without intending to be elitist, we note that walking, which is free, is an LLM, and that bicycles, mopeds, and mini-scooters, which compared with FHVs are almost free, also are LLMs. In general, the financial barriers to LLM ownership are low. Further, the suburban poor do not solve the problem of the expense of automobile ownership by not owning automobiles. If we infer suburban and urban locations by employment and residential density, then the suburban poor are spending a disproportionate share of their incomes in order to buy FHVs. Gardenshire and Sermons (1999) conclude from the 1995 NPTS data that vehicle ownership increases at similar rates for both poor and non-poor households as employment density (jobs per square mile) declines, but that vehicle ownership among poor households increases faster as residential density declines. Murakami and Young (1997) point out that the poor are less likely to live in suburbs, small towns, and rural areas. Rather than being elitist (by requiring ownership of multiple vehicles), our plan puts suburban lifestyle within the reach of poor households by reducing the cost of mobility while improving accessibility..

This discussion suggests that there are not any obvious reasons that most people would prefer a conventional town and transportation plan to ours.

How much might LLMs be driven?
In the preceding sections we have discussed a wide range of potentially significant personal and social benefits of the LLM network: nearly perfect safety, reduced congestion, a unified street space and coherent community feel, very low environmental impacts, near-zero petroleum use, and so on. Obviously, the overall magnitude of these benefits, and hence the desirability of the entire system, depends directly on the extent to which LLMs are used. If LLMs are used no more than are bicycles and walking today—which is on the order of 5% of trips in low-density suburban settings—then they will not noticeably affect transportation problems anywhere. On the other hand, if LLMs are used an order of magnitude more than this, then they will qualitatively improve life everywhere they exist, and perhaps make the LLM network idea a unique success story in suburban transportation planning. So what is possible?

Because there is nothing yet in the real world quite like what we have proposed, it is not possible to provide a straightforward empirical answer to the question of how much might LLMs be driven. We can assume that, in general, our town plan will attract people predisposed to like the transportation system, but also that the features of the transportation system will attract people not originally predisposed towards it (following Schwanen and Mokhtarian, 2005). To make quantitative inferences, we consider two kinds of studies: those that examine the use of small "neighborhood electric vehicles" (NEVs) in a conventional street system, and those that look at trip-making in conventional vehicles by trip purpose and vehicle type, in the latter case with an eye towards which types of trips are potentially suitable for LLMs.

Inferences from studies of NEVs. Kurani et al. (1995) studied household adaptationadaption to small NEVs in eight households in the town of Davis, California and seven households within the city limits of Sacramento, California, over a one-week trial period. Overall, at both locations, NEVs were used for 41 percent of all household trips. Among the eight households in the town of Davis, the share of total person trips made by walking, cycling, and neighborhood EV—all of the LLMs—was 74 percent; among the seven households living within the city of Sacramento, this share was 42 percent. The difference between Davis and Sacramento may be explained by the extensive network of bike paths and lanes in Davis.

These LLMs trip shares—74% in Davis and 42% in Sacramento—are evidently quite high. When one considers that neither Davis nor Sacramento has anything like an LLM

In previous work with Neighborhood Electric Vehicles (NEVs) Kurani et al. (1995) observed that lower income households regard new, low-cost NEVs (which can be LLMs) as viable replacements for old conventional FHVs that these households have relegated to local travel due to their age and unreliability.

Analysts also often worry about capital constraints in poor households, but that will be less of a factor here. Good, used, high-end LLMs should sell for under $4,000, at which price they can be bought on time for relatively small monthly payments (under $100/month) that will be further reduced by the monthly cost savings realized from substituting LLM for FHV travel.

network, and hence that in both places the NEVs had to be driven on conventional street systems mixed with conventional FHVs, one might be tempted to conclude that the shares would be higher still had a dedicated LLM network been available. While this is a reasonable inference, there are three countervailing qualifications. First, the NEVs in these trials were not quite LLMs: they had a top-speed of approximately 35 mph and weighed more than 1,000 lbs. This probably made these particular NEVs more acceptable on the FHV network than true LLMs would be. Second, as discussed in the section "Note on changes in total travel and mode share," the addition of a NEV into households in the Davis/Sacramento trials did not simply displace travel in conventional FHVs, it also displaced travel by bicycling and walking, which generally is not desirable. For example, in the eight households in the trials in Davis, bicycling and walking had a 30% mode share before the introduction of the NEVs, and about a 20% share during (Kurani et al., 1995). Third, the LLM share of *VMT*—which arguably is the more relevant measure, since transportation-related problems are a direct function of VMT—is likely to have been less than the LLM share of trips (which is what Kurani et al. [1995] reported), because trips by LLMs probably were shorter than trips by conventional FHVs.

On the base these studies, one might infer that LLMs can displace in the range of 30-50% of VMT by light-duty vehicles (LDVs)

Inferences from studies of trip-making by trip purpose and vehicle type. Surveys of travel behavior often classify trips by purpose: commute to work, family or personal business, going to school or church, and so on. It is reasonable to expect that some kinds of trip purposes can be accommodated by LLMs more readily than can others. For example, we expect that most trips taking children to school, but relatively few trips by commercial light-duty trucks, could be accomplished in LLMs. If one extends this sort of inferential reasoning to all trips made by LDVs, where the trips are classified according to trip purposes that facilitate the making of inferences with regards to whether or LLMs or suitable for the type of trip, one can get an idea of the potential of LLMs to displace travel by FHVs.

In Table 4 we present this sort of analysis. Note that the analysis of Table 4 is done with respect to vehicle-miles of travel (VMT), rather than with respect to trips (as was the basis for our examination of the use of NEVs, immediately above) or passenger-miles of travel, because almost all transportation-related problems are directly related to VMT. Note, too, that Table 4 starts with a complete listing of *all* motor-vehicle trip and vehicle-type categories, including heavy-duty vehicles, buses, government vehicles, and commercial vehicles, and not just household vehicles. This ensures that all possibilities for LLM substitution are captured, but also that the baseline LDV VMT against which LLM usage is estimated is as broad as possible (so that we do not misleadingly represent the potential for VMT displacement by comparing against an arbitrarily small baseline).

The analysis of Table 4 has two parts: the establishment of the appropriate breakdown of VMT by trip purpose and vehicle type, and the estimation of the fraction of VMT that might be suitable for LLMs within each trip-purpose/vehicle-type category. To the extent that the available data allowed us some leeway in defining trip-purpose/vehicle-tpe categories, we used criteria that distinguished the attractiveness of LLMs relative to

FHVs: whether or not the trips are likely to be made within a "town" (in-town trips generally are suitable for LLMs), the length of the trip (the longer the trip, the less it is suitable for LLMs), and whether heavy goods are hauled (if so, LLMs generally are not suitable).

With the estimates and assumptions of Table 4, the overall potential fraction of VMT by LDVs that can be displaced by LLMs is calculated by multiplying the VMT fraction by the LLM suitability fraction for each trip/vehicle type, and summing over all trip/vehicle types. The result of this exercise is that approximately 25-50% of all VMT by LDVs might be suitable for LLMs.

Thus, our analysis of trip-making behaviour leads to the same tentative inference as did our examination of studies of the use of NEV: one reasonably might infer that LLMs can displace in the range of 30-50% of VMT by all LDVs.

Other issues bearing on the use of LLMs

Our analysis of the cost and convenience of motorized LLMs focuses on the utilitarian aspects of car ownership and use. The car, however, is more than a utilitarian object. As Wright and Curtis (2005) note, referring to a 1986 book called *The Psychology of the Car*, "the car offers pleasures and rewards of various kinds, including the opportunity to control a powerful machine (which some owners find seductive), the exhilaration of fast movement, and the expression of personality through the automobile as status symbol and fashion accessory" (p. 14). Motorized LLMs can accommodate as much personal expression as FHVs do, so in this respect they should be just as appealing. LLMs obviously cannot satisfy desires for power and speed, but as these desires are dangerous, socially unproductive, and easily satisfied in other ways (at lower social cost), this is not a drawback of LLMs from the standpoint of society.

Wright and Curtis (2005) also point out that in a conventional street and FHV system the needs of drivers conflict with the needs of pedestrians: drivers like wide, straight roads with visual uniformity, whereas pedestrians like a meandering paths with variegated, small-scall visual details. Because the roads in the LLM network are smaller and possibly curvier than conventional roads, they may be more appealing to pedestrians. More generally, for everyone who uses or lives along an LLM network, the experience of travel will be quite different than from the experience of those who use or live along a conventional FHV road system. People traveling in motorized LLMs will be traveling relatively slowly, and will be near to scooters, cyclists, and pedestrians. Because of this, and because the vehicles will be smaller and closer to the ground, the whole visual, aural, and car-handling experience of driving will be different. Likewise, although cyclists and pedestrians will be more densely mixed with motorized traffic, the vehicles will be less physically threatening, less visually obtrusive, and quieter. For everyone concerned, transportation on the LLM network will be less obnoxious and much less unpleasant.

Note on changes in total travel and mode shares

In the analysis of environmental impacts presented above, we assumed that every mile driven in a large, motorized, full-featured LLM replaces a mile of travel in an FHV. There are two ways that this assumption may be false and the environmental benefits of LLMs thus slightly less than we have estimated. First, some trips in LLMs might be "new" trips in the sense that when LLMs are used total travel by *all* modes increases compared with the status quo. This will be the case if compared with conventional alternatives travel by LLMs provides greater net benefits, due to some combination of greater benefits and lesser costs. In this case, the environmental impacts of LLMs will increase in proportion to the amount of new travel. However the environmental impacts per mile of travel of LLMs are so small that it is virtually impossible that the social costs of the extra trips would exceed the social benefits.

Second, it is possible that the availability of large, motorized, full-featured LLMs will reduce the use of non-motorized LLMs, such as walking and cycling (which have almost no environmental impacts) compared with the status quo. However, this concern is not peculiar to our land use/transportation system design. Small EVs in conventional land use and transportation networks may have the same effect, as may car-sharing systems.[65] However, we note that the substitution of a motorized LLM for walking or cycling can only happen if walking or cycling are viable modes in the first place. That is, walking and cycling mode shares in communities designed as we propose will be higher than in existing communities.

Summary of research needs

We see two major research needs, one of which we have talked about at some length. First, we need to learn how people feel about the LLM system, from three perspectives:

1) The perspective of a driver of a full-featured motorized LLM, who will see the world much differently than does the driver of an FHV on a conventional road network, on account of being lower to the ground, closer to cyclists and pedestrians, and driving much more slowly.
2) The perspective of bicyclists and pedestrians, who will be sharing the road with small, slow moving, impact-friendly motorized vehicles.
3) The perspective of residents, who will be living alongside a transportation network qualitatively different from conventional networks.

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[65] Kurani et al (1995) reported on household travel mode shifts during household trials with a small, two-seat electric vehicle. In the course of their trial weeks, eight households in Davis, California substituted the EV for 47 percent of the trips they would normally have made by bicycle, and 36 percent of trips they would have made by walking. (These figures do not include "test-drive" trips.) In all, during their EV-trial week, the average bicycle mode share of these eight households fell from 26 percent to 15 percent; their walking mode share fell from 5.7 percent to 3.6 percent.

In a car sharing experiment involving ten households in Graz, Austria, Steininger et al (1996) report that participants showed no overall shift in mode share toward or away from cars (privately owned or shared), but did show a shift toward cycling and a shift away from walking. These effects were expressed differently according to trip distance. Perhaps unexpectedly, among households that owned vehicles prior to the test, long distance travel shifted toward transit. And since mode shift across all distances shifted slightly toward cars, the shift toward cars must have been more distinct for short distance trips. Summarizing the effect on car-owning households, vehicular VMT declined, but a greater proportion of local trips were made by car. Among households that did not own a vehicle, middle distance trips shifted toward cars, and vehicular VMT increased (though strangely, Steininger et al's data seems to indicate that car mode share declined for non-car owning households during the car-sharing experiment).

Second, to figure out how wide the roads should be and, in the case of the LLM network, where to add bicycle lanes and pedestrian paths, we need to model traffic flows on both networks. To accomplish this, we will need more information on how people are likely to use different kinds of LLMs.

Out in the world
Around the world, increases in population and migration from rural to urban areas is swelling the number of people in cities, towns, and suburbs. In many of these growing urban areas, from South America to Asia to the American West, the urban newcomers are developing the exurban fringe. Cities and towns are expanding into farmland, forests, wetlands, and deserts. According to Pollack (2000, p. 19), between 1992 and 1997, 16 million acres of farm and forest were developed in the U. S.—twice the annual growth rate from 1982 to 1992.

This expansion can be accommodated well by the sort of town and transportation plan we propose.[66] As explained above, ours is a plan for new towns, not a plan for retrofitting cities. In principle, it can be applied wherever urban areas are expanding. However, in rapidly expanding cities in developing countries, it may be difficult to commit the necessary capital up-front to establish the basic dual-network transportation infrastructure. The plan is more naturally suited to large new subdivisions on the urban fringe of cities in the American West, such as in California's Central Valley. Nonetheless, it is worth considering ways to implement the basic features given the capital and planning constraints in rapidly developing cities.

CONCLUSION

Most transportation-related problems are attributable ultimately to the high kinetic energy of fast, heavy motor vehicles. The challenge is to find a way to dramatically lower the kinetic energy of personal travel, without compromising any of the benefits of motor vehicle use and suburban living. We believe that the only way to do this is to create two autonomous and universally accessible travel networks: one for fast-heavy vehicles, the other for low-speed, light transportation modes.

The town plan and transportation system we propose is safe, convenient, clean, and pleasant. It should be attractive to households *without* economic or regulatory incentives or injunctions. The requisite technologies, and analyses of their economic and social impacts, are available now.

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[66] For example, China recently adopted a policy to encourage the manufacture and use of small, low-emission automobiles (Walsh, 2006).

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TABLE 1. LIFECYCLE CO_2-EQUIVALENT EMISSIONS FROM TRANSPORTATION MODES, U. S., YEAR 2010

Mode[b]	Mode technology	g/pass-mile (gasoline FHV) % ch. vs. gasoline FHV[a]	
		Fuel cycle[c]	**Fuel+ material**[c]
FHV	gasoline vehicle, 28 city mpg	442 g/mi	532 g/mi
FHV	diesel (low-S) vehicle version of gasoline	+ 13%	+ 10%
FHV	hydrogen (NG) fuel cell version of gasoline	−61%	−52%
transit	diesel-fuel (low-S) bus: 10, 20 passengers[d]	+ 2%, −49%	−2%, −51%
transit	heavy-rail train: 20%, 40% capacity[d]	−60%, −80%	−60%, −80%
transit	light-rail train: 20%, 40% capacity[d]	−62%, −81%	−65%, −83%
LLM	gasoline car, 57 mpg city driving	−55%	−56%
LLM	electric car, 7 mi./kWh, U. S. power[e]	−80%	−76%
LLM	4-stroke gasoline scooter	−82%	−82%
LLM	electric scooter, U. S. power[e]	−87%	−84%
LLM	Bicycling	−99%	−96%
LLM	Walking	−100%	−100%

a For the FHVs and LLMs, we assume one passenger per vehicle

b FHV = fast, heavy (conventional) vehicle; transit = public transit; LLM = light, low-speed mode.

c The fuel cycle includes the lifecycle of fuels, from feedstock production to end use, and emissions related to vehicle maintenance, repair, and servicing. The fuel+material lifecycle includes the lifecycle of fuels plus the lifecycle of all materials, vehicle assembly, and infrastructure construction.

d The average occupancy of buses in the U. S. is around 10, and the average capacity factor for trains is around 20 percent (see statistics reported by the Federal Transit Administration). We show emissions per passenger mile at both the current average occupancy and double the current average.

e The average power mix in the U. S. in the year 2010 is estimated to be 50 percent coal, 1 percent fuel oil, 25 percent natural gas, 14 percent nuclear, 8 percent hydro, and 2 percent biomass.

TABLE 2. CHARACTERISTICS OF FULL-FEATURE CARS IN THE LIFECYCLE COST ANALYSIS

Item	Gas FHV	Gas LLM	BPEV-20	BPEV-30
Weight of the complete vehicle (lbs.)	2,214	959	922	990
Maximum power to wheels (hp, (kW)[a]	90 (67)	30 (21)	13 (10)	14 (11)
Coefficient of drag[b]	0.30	0.28	0.22	0.22
Acceleration 0 to 25 mph, 7% grade (sec)	4.64	6.08	6.08	6.09
Fuel efficiency (mpg or mi./kWh-outlet)[c]	27.9	56.7	7.01	6.86
Vehicle life (miles)[b]	150,000	70,000	84,000	84,000

Gas FHV = a conventional Ford Escort; Gas LLM = a low-speed, low-mass gasoline vehicle; BPEV-20 = battery-powered electric vehicle with a 20-mile range; BPEV-30 = battery-powered electric vehicles with a 30-mile range. The BPEVs have pb/acid batteries that store about 35 Wh/kg, weigh about 150 lbs., and cost $300-$360/kWh.

[a] The maximum power available to the wheels assumes no air conditioning or heating or optional accessories. The BPEVs have much less maximum power than, but the same performance as, the gas LLM because an electric motor, unlike a heat engine, can deliver maximum torque at very low rpm.

[b] We assume that battery-electric LLMs have a lower coefficient of drag and a longer life than does a comparable gasoline LLM.

[c] The fuel efficiency calculation does assume year-round average use of air conditioning and heating.

TABLE 3. RETAIL AND LIFECYCLE COSTS OF FULL-FEATURE LLMS

Item	Gas FHV	Gas LLM	BPEV-20	BPEV-30
Full retail cost of vehicle, including taxes ($)	14,891	8,707	9,268	9,443
Battery contribution to retail cost ($)	n.a.	n.a.	692	892
Levelized maintenance cost ($/yr.)	483	190	134	134
Energy cost ($/gal or $/kWh)[a]	1.62	1.62	0.06	0.06
Total lifecycle cost (cents/mile)[b]	33.3	31.1	31.5	31.0
Breakeven gasoline price ($/gal)[c]	n.a.	n.a.	2.22	1.94

a Excludes fuel taxes, which add about $0.38/gallon. For EVs we have assumed low nighttime recharging rates.

b Equal to the initial cost, plus the present value of all future cost streams: insurance, maintenance and repair, fuel, registration, parking, tolls—everything.

c The price of gasoline, including taxes, at which the total lifecycle cost per mile of the BPEVs equals the total lifecycle cost per mile of the gasoline LLM.

TABLE 4. POTENTIAL FRACTION OF VMT BY ALL LDVS THAT COULD BE SATISFIED BY LLMS

Trip/vehicle category	**Fraction of total LDV VMT**		**Fraction suitable for LLMs**		**Comment on "suitable" fraction**
	Low [a]	*High* [b]	*Low*	*High*	
PVs, for personal use, daily travel (LDAs, LDTs)					
-- work	0.100	0.070	0.15	0.25	Assume most people would work outside of their town of residence
-- work-related	0.019	0.010	0.15	0.25	Assume same as for "work," due to canceling effects (e.g., some people who commute in personal FHVs might use LLMS for work-related travel, and vice-versa).
-- family/personal business	0.300	0.400	0.40	0.60	Assume roughly half would occur within town and wouldn't involve heavy hauling
-- school/church	0.066	0.130	0.60	0.80	Most should occur in within town and not involve heavy hauling
-- social/recreational	0.182	0.220	0.30	0.60	Won't involve heavy hauling, but much may occur outside of town
-- other	0.005	0.000	0.40	0.60	Assume same as family/personal business
PVs, for personal use, long trips (LDAs, LDTs)	0.095	0.010	0.00	0.00	Trips are too long for LLMs
PVs, for business use					
-- LDAs, without paid drivers	0.123	0.080	0.10	0.20	Most business trips are too long for LLMs
-- LDTs, without paid drivers	0.083	0.060	0.10	0.20	See immediately above
-- LDTs, with paid drivers	0.008	0.010	0.05	0.10	Assume most commerical vehicles travel too far and carry too much to be LLMs
-- HDTs, with paid drivers	0.000	0.000	0.00	0.00	LLMs cannot replace HDVs
Buses					
-- intercity and transit buses	0.000	0.000	0.00	0.00	LLMs cannot replace intercity buses (but see discusion in text regarding transit)
-- school buses	0.000	0.000	0.00	0.00	See immediately above
Goverment vehicles					
-- federal civilian (LDAs, LDTs, HDTs)	0.002	0.000	0.05	0.05	Assume virtually all federal vehicles are in large urban areas
-- federal military (LDAs, LDTs, HDTs)	0.000	0.000	0.00	0.00	See immediately above
-- state & local civilian (LDAs, LDTs, HDTs)	0.013	0.010	0.10	0.15	A few local vehicles could be LLMs
-- state & local police	0.003	0.000	0.05	0.10	Assume a few LLM police

Notes: PV = private vehicle, LDA = light-duty auto, LDT = light-duty truck, HDT = heavy-duty truck.

[a] The "low" case distribution of LDV VMT by trip and vehicle type is the estimated average for all LDVs in the U. S. LDV VMT shares for all categories *except* those *within* the category "PVs, for personal use, daily travel (LDAs, LDTs)" are based on Delucchi's (2004) comprehensive analysis of total motor-vehicle travel in the U. S. in 1990. LDV VMT shares *within* the category "PVs, for personal use, daily travel (LDAs, LDTs)" are estimated on the basis of data from the 2001 National Household Travel Survey (NHTS) (Bureau of Transportation Statistics, 2003). Also, a comparison of Delucchi's (2004) estimates for the category "PVs, for personal use, long trips (LDAs, LDTs)" in 1990 with NHTS estimates for this category for 2001 indicate the same travel share. Thus, our estimated travel shares for most of the largest VMT categories are consistent with 2001 survey data, which are the most recent available as of Spring 2009. (The NHTS does not include private vehicles for business or commercial use, buses, or government vehicles.)

[b] The "high" case distribution of LDV VMT is our judgment of what the shares might be in suburban areas specifically, as opposed to in the whole nation (which is the basis of the "low" case). Generally, one would expect to see a lower fraction of commute, business, long-distance, and government-vehicle trips and a higher fraction of daily personal non-commute trips in suburban areas than in the nation a a whole, because a substantial fraction of commutge, business, and long-distance trips occur outside of or on the periphery of suburbs.

FIGURE 1A. PLAN OF THE WHOLE TOWN, WITH ONLY THE ROADS SHOWN

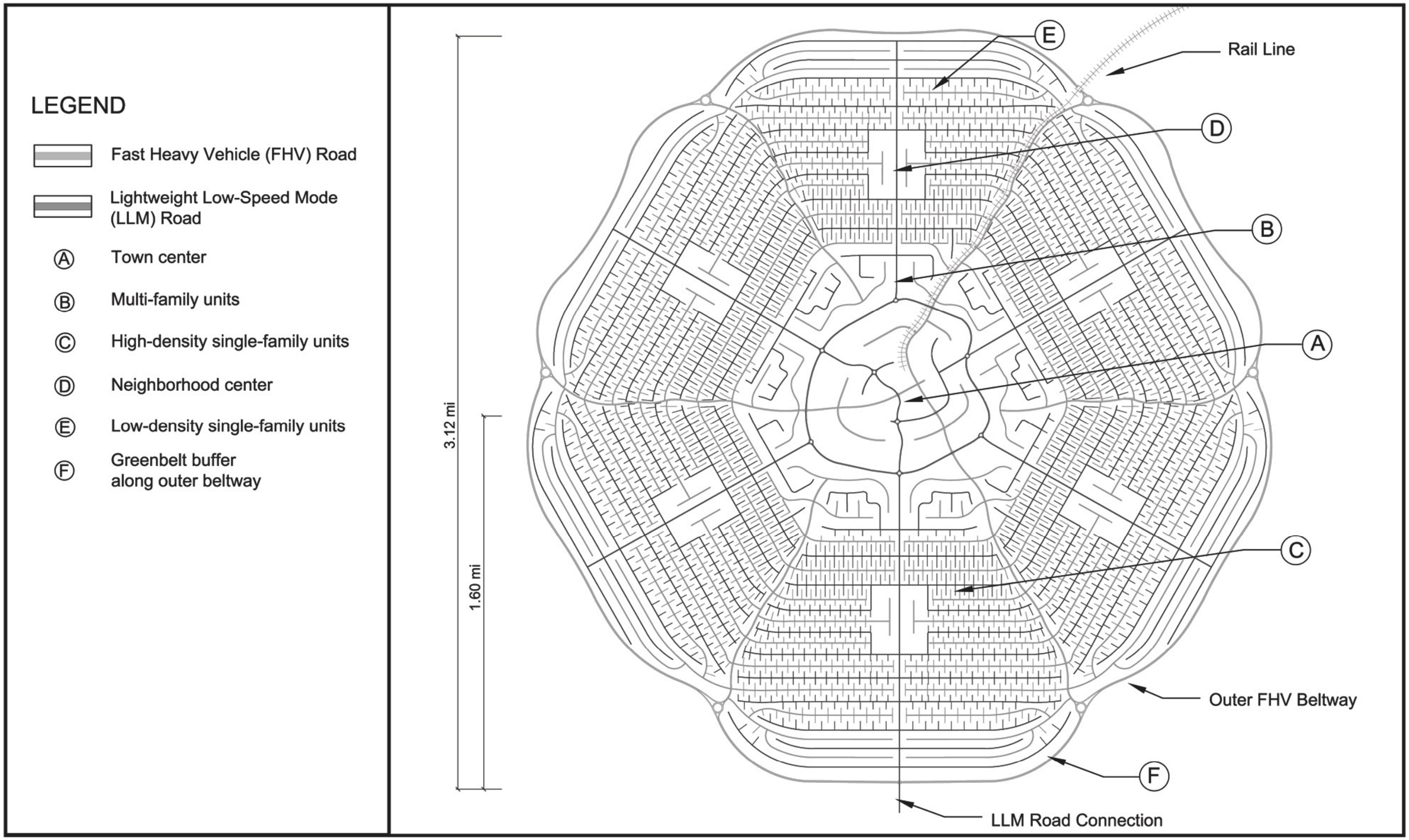

FIGURE 1B. PLAN OF THE WHOLE TOWN, WITH ROADS AND LAND USES

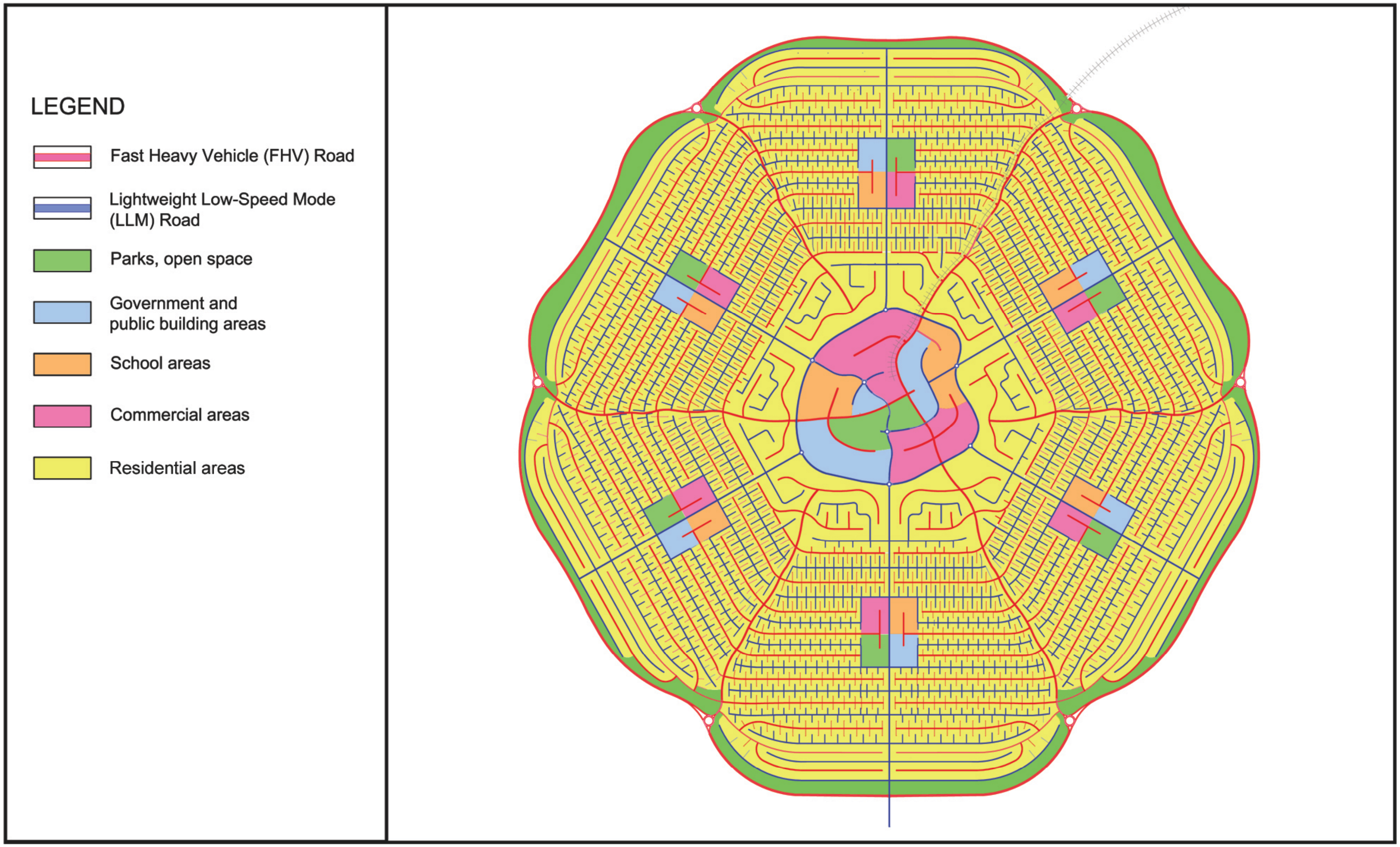

FIGURE 1C. PLAN OF THE WHOLE TOWN, WITH ROADS AND BUILDINGS

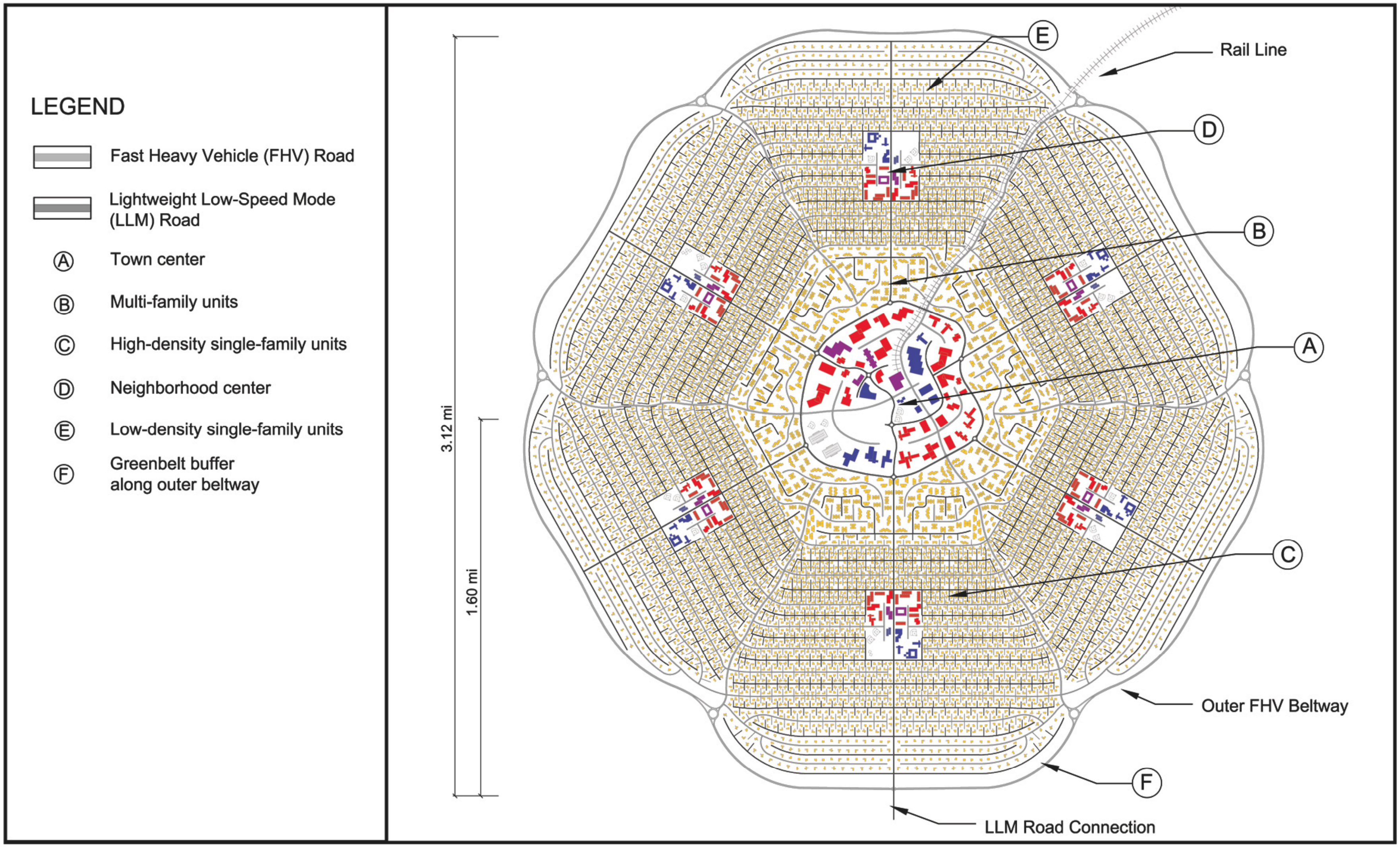

FIGURE 1D. PLAN OF THE WHOLE TOWN, WITH ROADS, BUILDINGS, AND LANDSCAPING

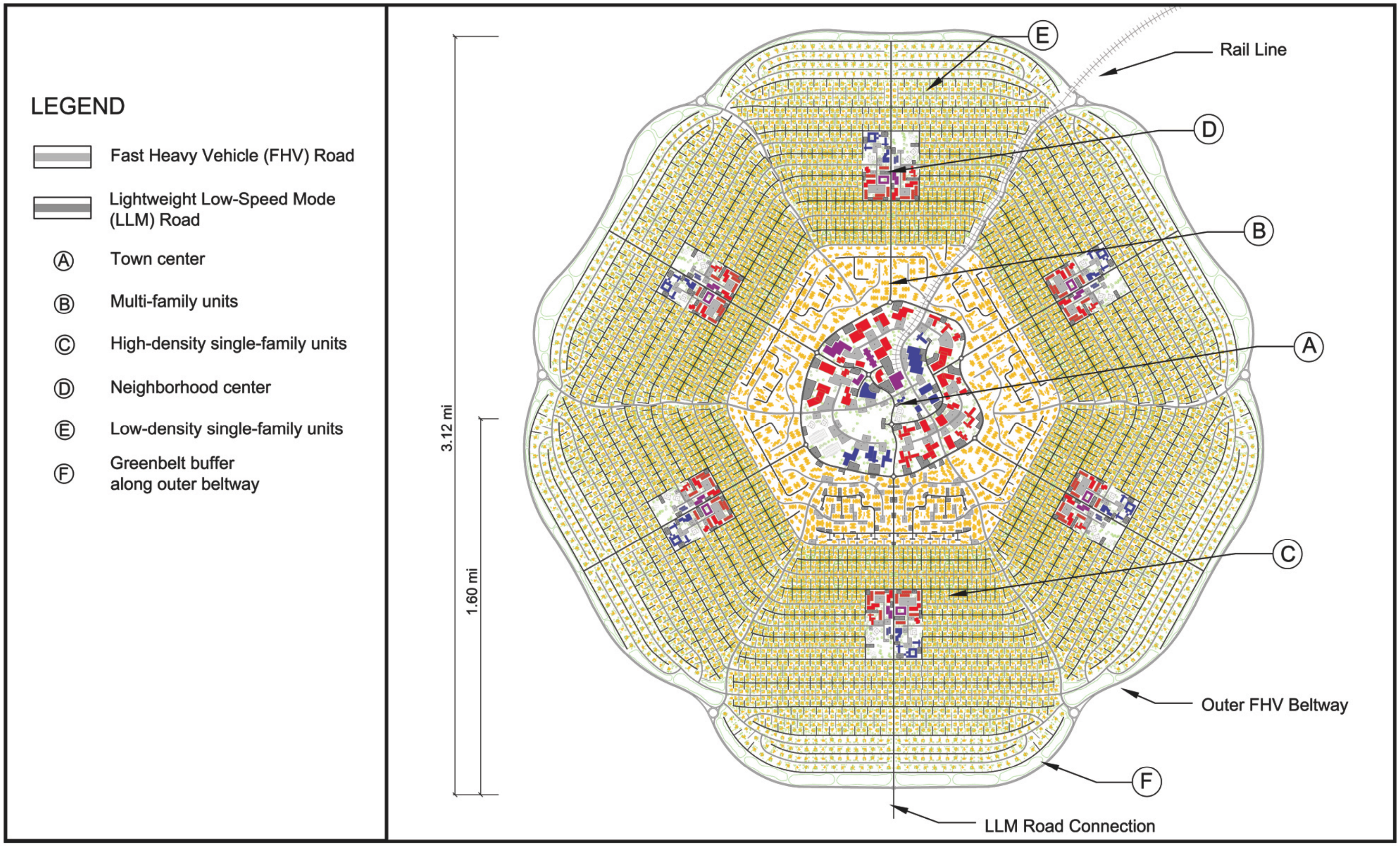

FIGURE 2. PLAN OF A NEIGHBORHOOD BRANCH, WITH ROADS, BUILDINGS, AND LANDSCAPING

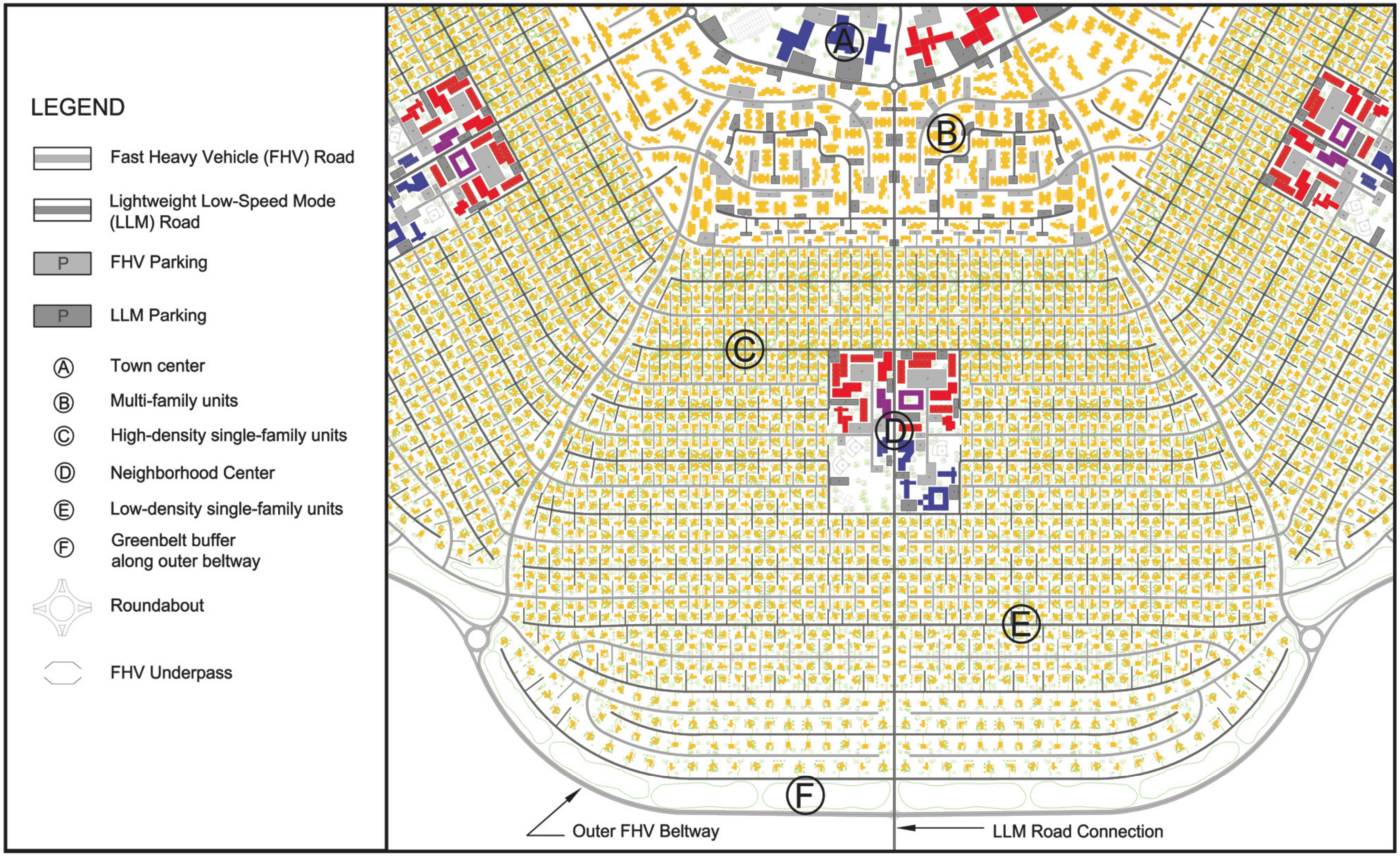

FIGURE 3. NEIGHBORHOOD CENTER IN A RESIDENTIAL AREA OF A NEIGHBORHOOD BRANCH

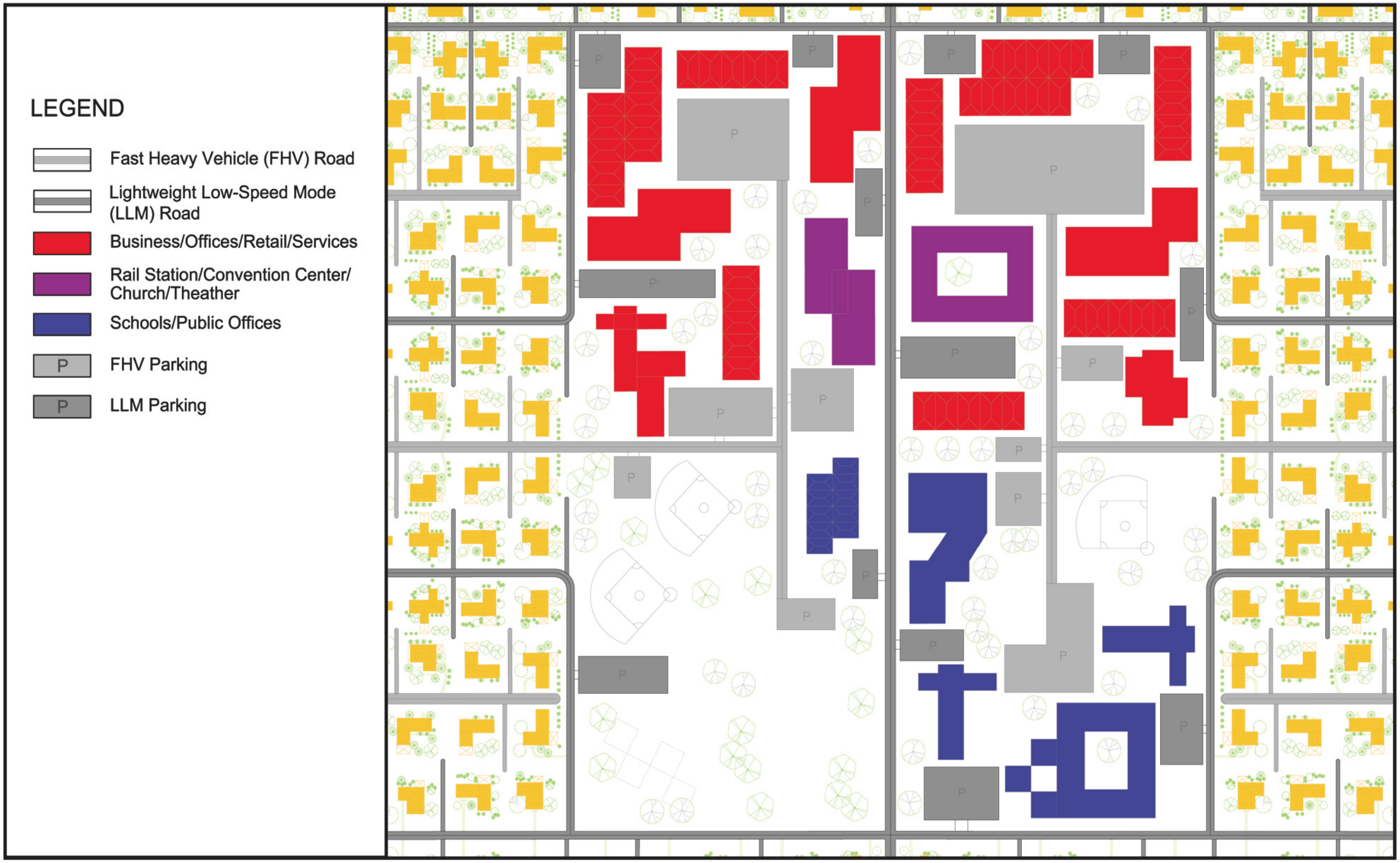

FIGURE 4. RESIDENTIAL BLOCK IN A HIGH-DENSITY RESIDENTIAL AREA

FIGURE 5. DETAIL OF A RESIDENTIAL STREET

FIGURE 6A. TOWN CENTER, WITH ROADS THROUGH THE CENTER

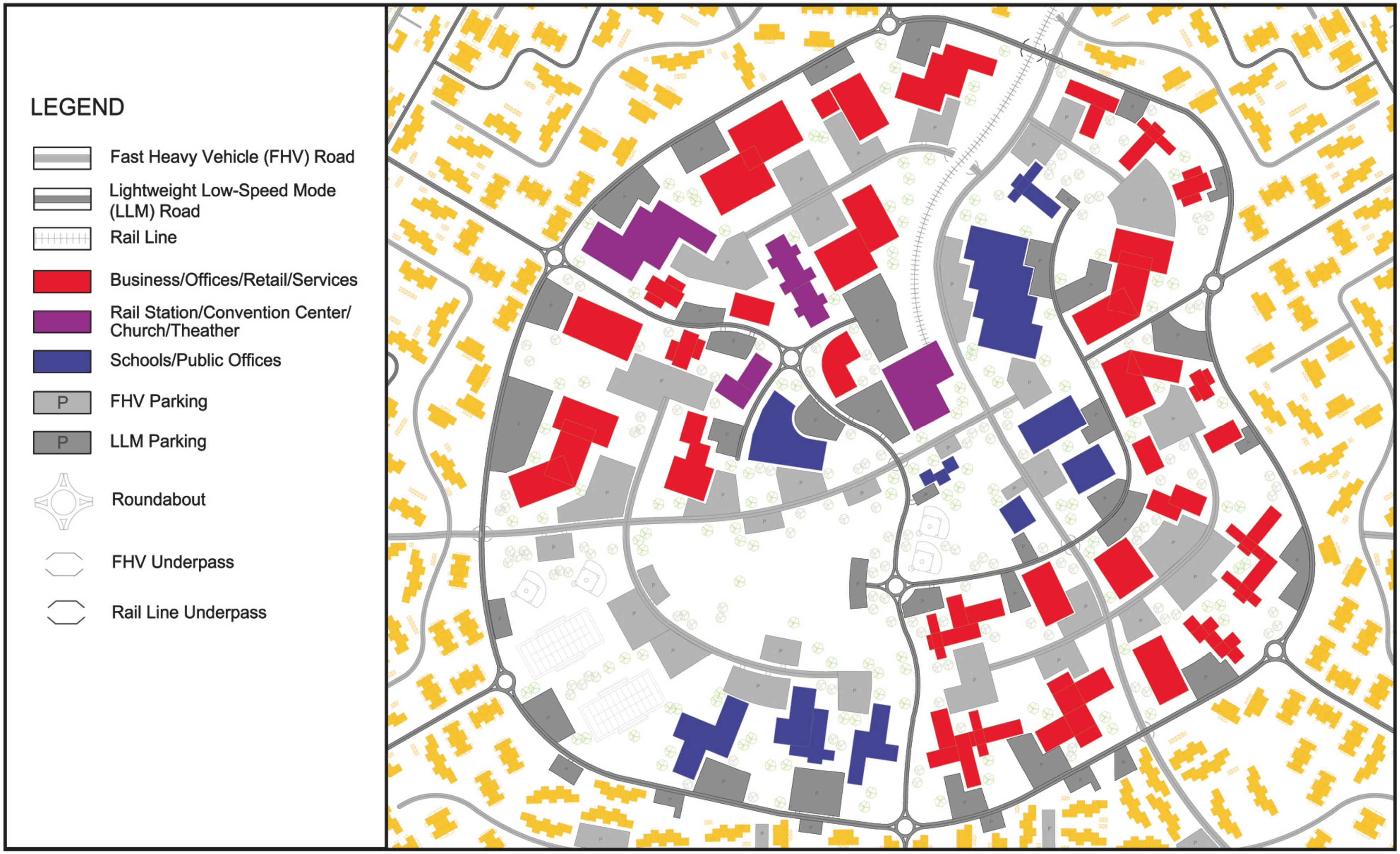

FIGURE 6B. TOWN CENTER, WITHOUT ROADS THROUGH THE CENTER

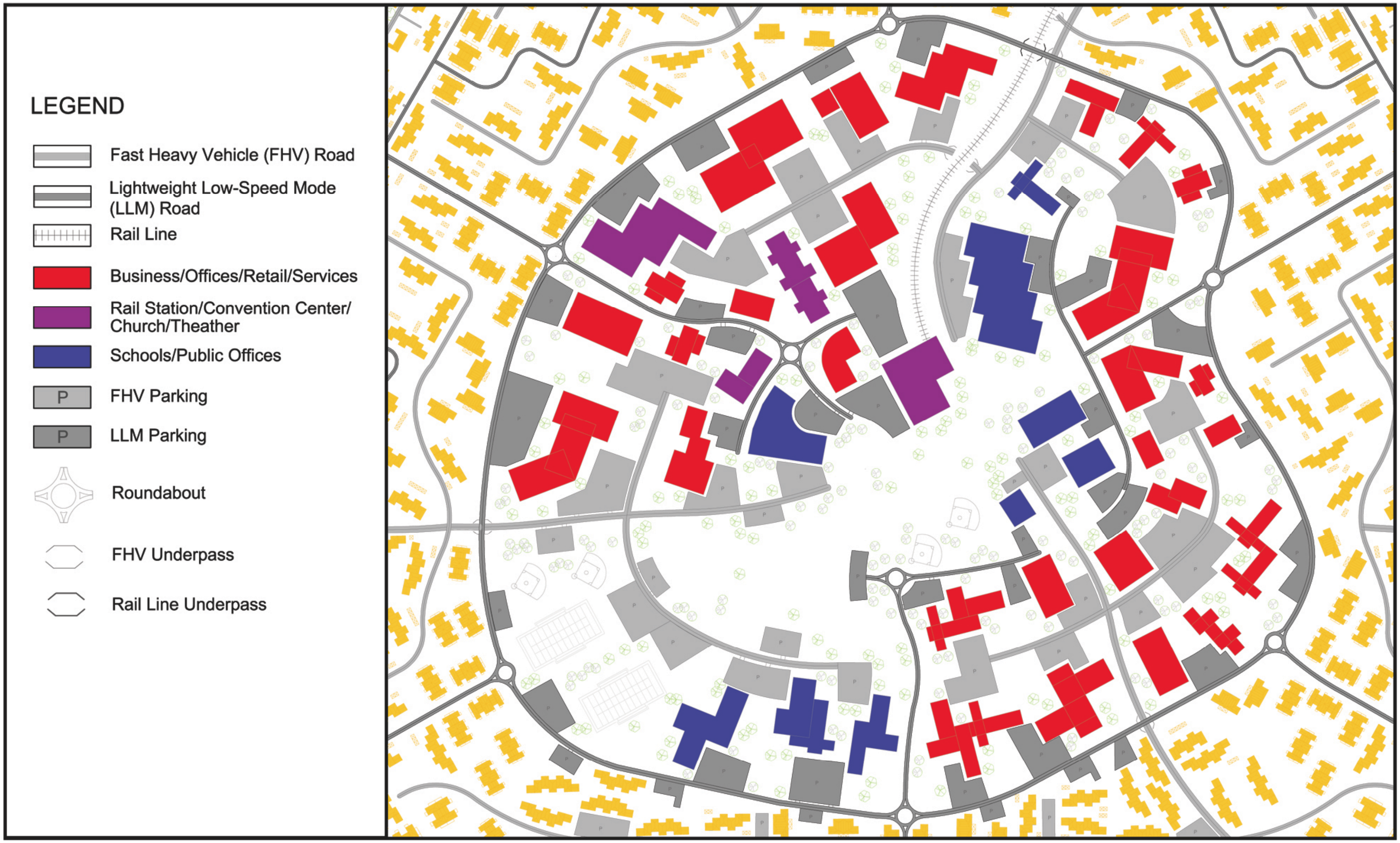

FIGURE 7A. MULTI-TOWN PLAN, WITH ROADS, BUILDINGS AND LANDSCAPING

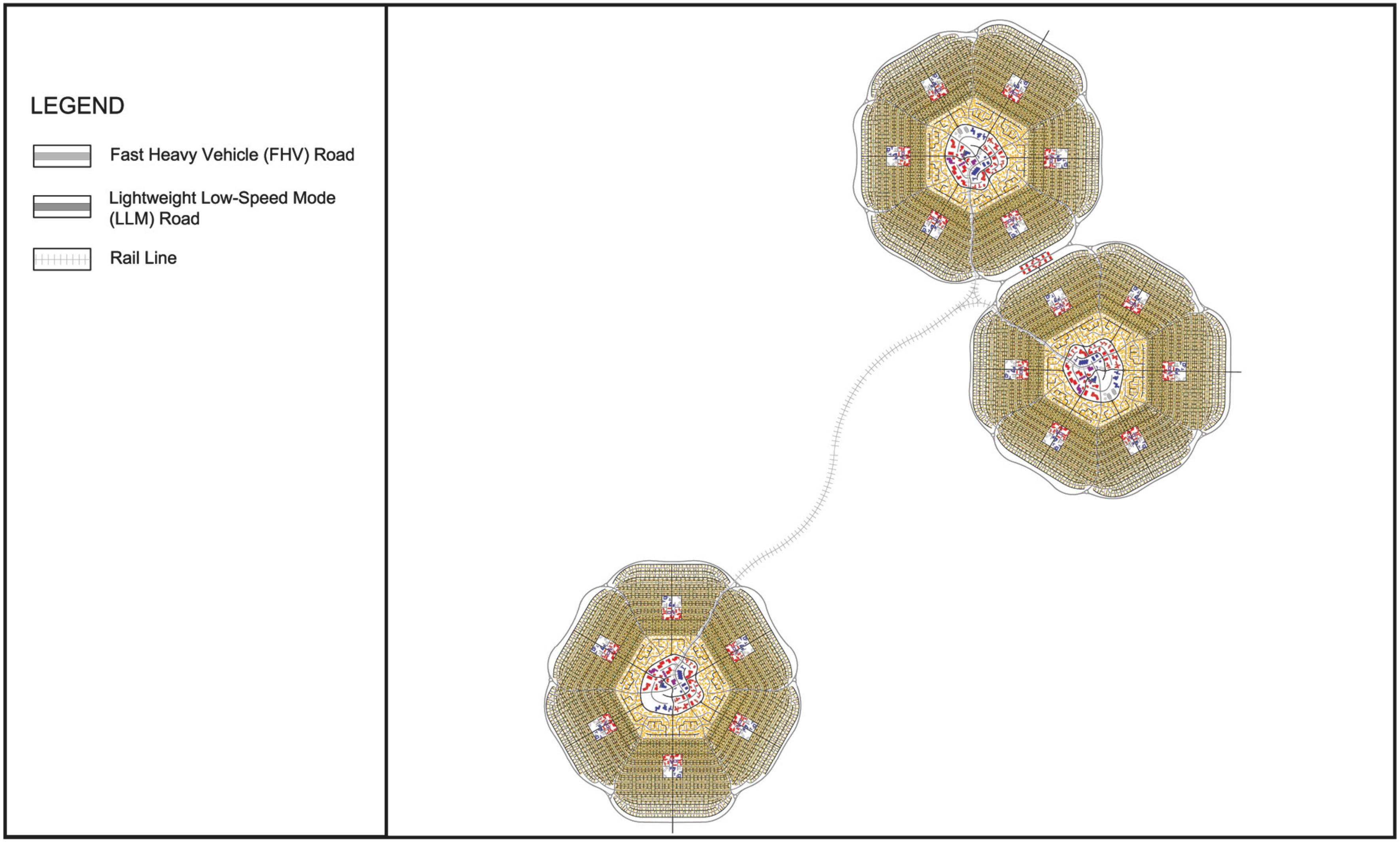

FIGURE 7B. MULTI-TOWN PLAN, WITH ROADS AND LAND USES

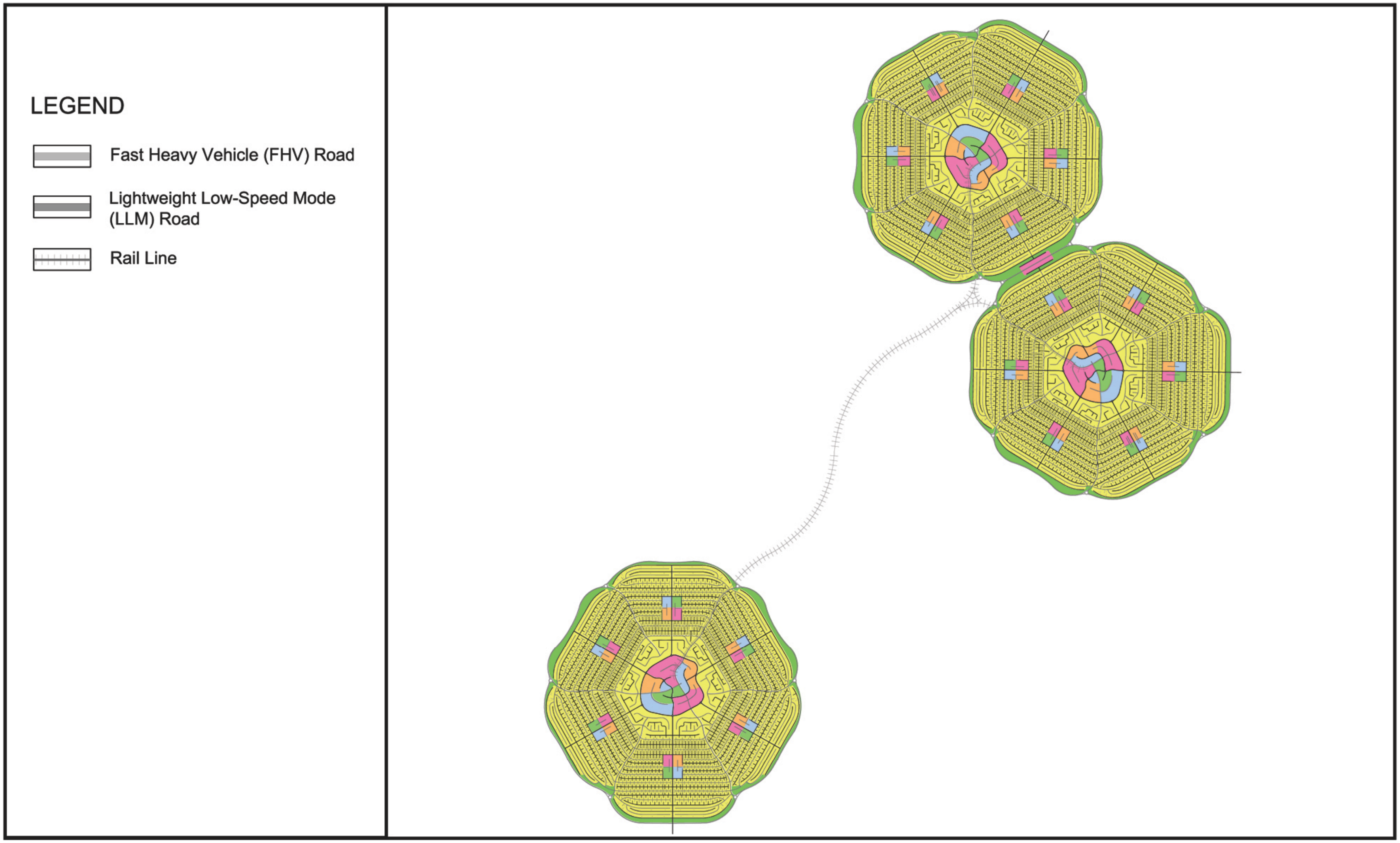

FIGURE 8A. SHARED OUTER-BELTWAY COMMERCIAL CORRIDOR AND NEIGHBORHOOD BRANCH

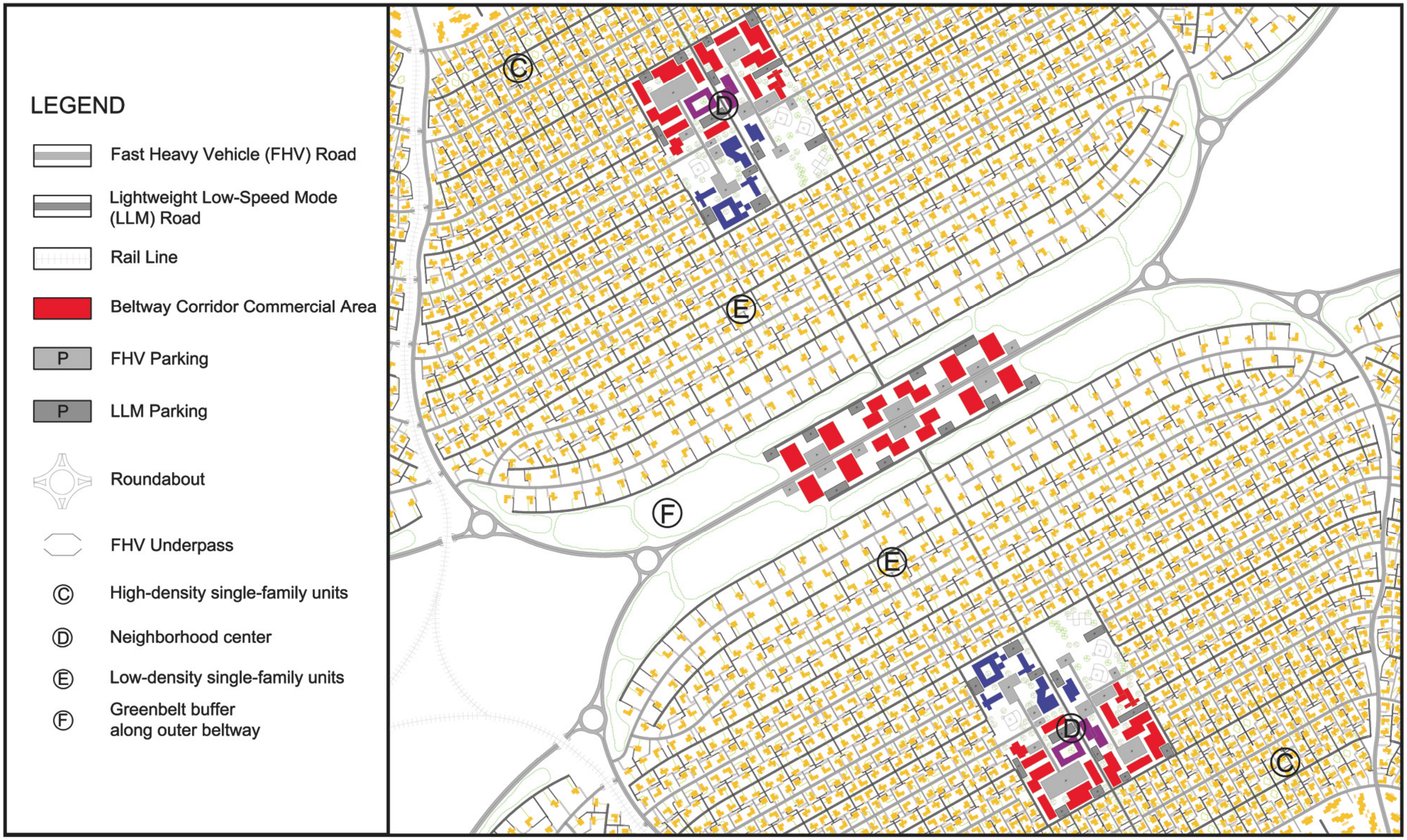

FIGURE 8B. SHARED OUTER-BELTWAY COMMERCIAL CORRIDOR

FIGURE 9. NORMALIZED KINETIC ENERGY OF VEHICLES AS A FUNCTION OF SPEED AND MASS

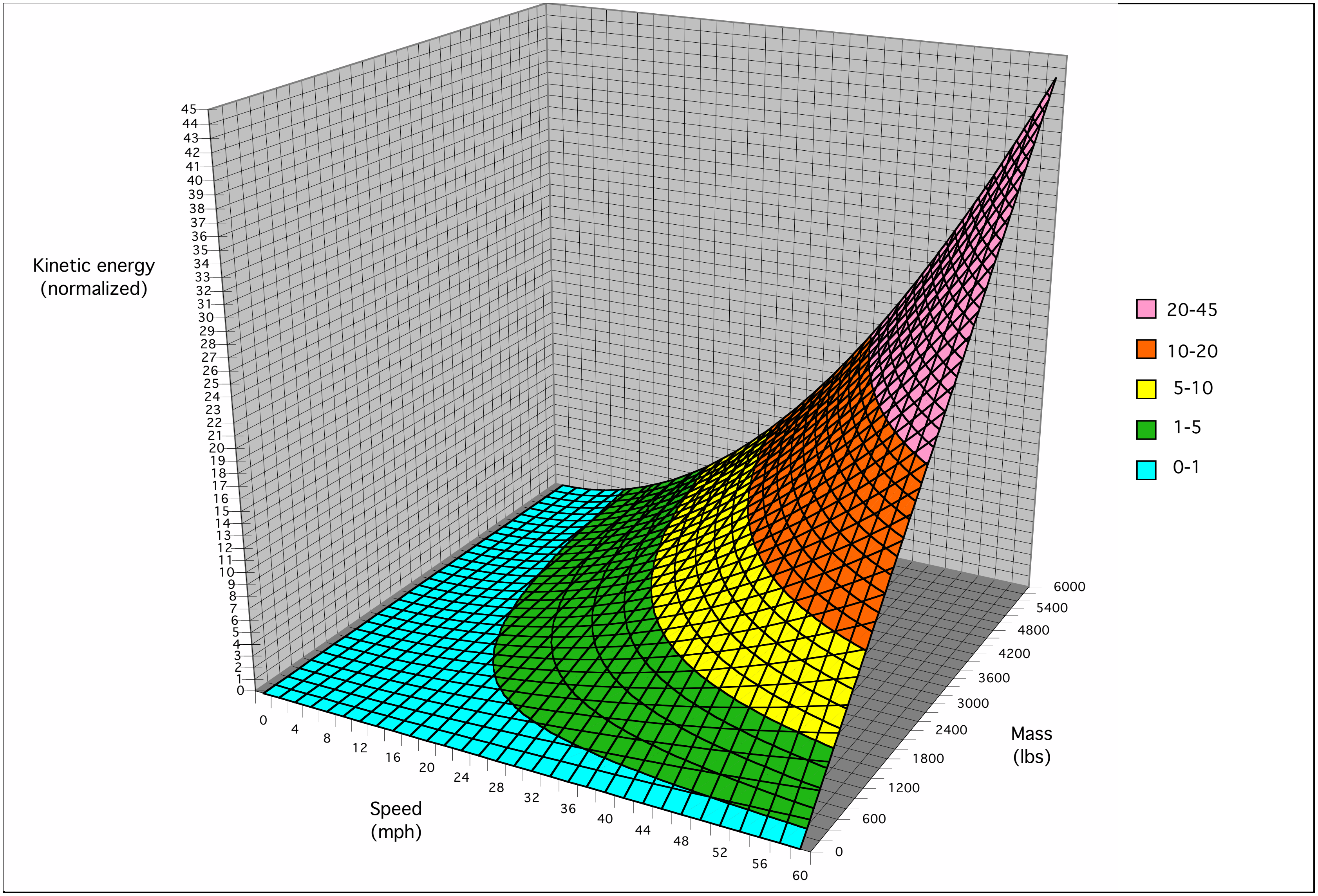

FIGURE 10A. TWELVE HOUSES ALONG A ROAD WITH NO CROSS STREETS

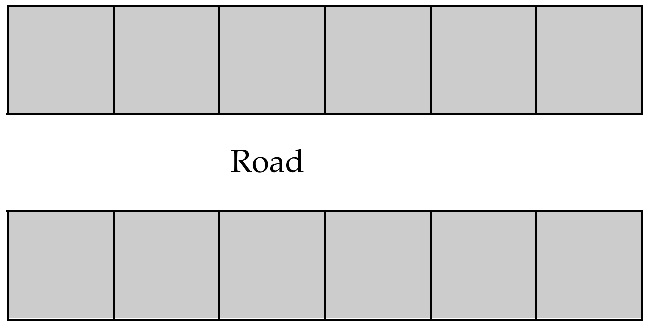

FIGURE 10B. TWELVE HOUSES WITH A CROSS STREET