An Automated Guideway Interchange

Love your car? Hate Traffic? Well, get a better road! While the freeway promotes mobility by separating vehicle types and eliminating the intersection, the societal burden of urban and suburban freeways is driven by the cost of land acquisition, interchange construction and a massive neighborhood intrusion. All generate negative community reaction. The increased capacity afforded by platooned vehicles would reduce the width of required right-of-way and the automated guideways of Automated Guideway Transportation [AGT] approaches would further promote the finesse to thread transport through existing infrastructure. Thus, fabrication of dense AGT grids within existing cities is possible. A small, low-cost interchange for AGT paths would complete such an architecture. This paper describes the morphology and performance of such an interchange. Constructed from only two levels, to fit within a ten meter square, the design allows right and left turns at 25 mph, through traffic at 40 to 50 mph, and has a capacity for up to 14,000 vehicles per hour per direction. Automation for disengaging vehicles from trains, merging them with continuing traffic, and structural compatibility with vehicle hardware to initiate turns is required.

An Introduction

Automated Guideway structures promise very compact transport for individual travelers. They do so by providing precise guidance for small vehicles and by conducting platoons of tightly packed vehicles in train-like formations. One estimate, depicted in Figure 1 concludes there is a 40 times improvement over freeway space usage. It does not, however, compare to the extreme packing of travelers endured in airliners.

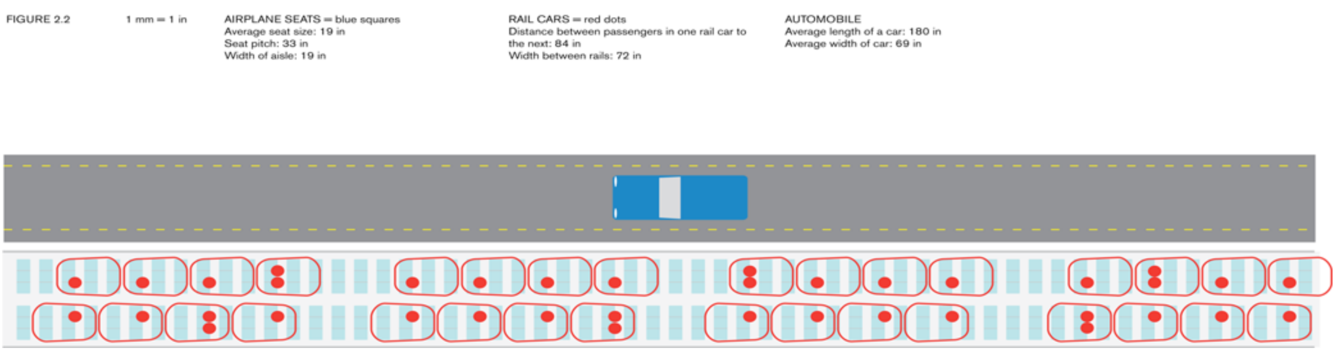

Figure 1. depicts the area required for an automobile traveling at 60 mph, automated platoons of small vehicles, and the airline passenger occupying a seat.

Thus Automated Guideways are proposed to penetrate dense urban cores where space is at a premium, blend into suburban areas, and to do so by using existing right-of-way. But to achieve ubiquitous, high-speed service Automated Guideways must be built on a grid and provide non-stop, continuous flow performance. But grids imply intersections, and the structures which allow non-stop traffic at these intersections are called interchanges. Thus a grid of high-performance Automated Guideways require interchanges.

One concept of local AGT service is construed to pick up and drop off dual-mode vehicles within a few blocks of their origin and final destination. In moderately populated areas with good surface streets, a convenient few blocks might be interpreted as less than a half mile. Thus a Roadway infrastructure using a square grid with one-mile spacings is a good start for planning local service.

Before we begin, we must answer a basic question: is there room for AGT interchanges? Two attributes will reduce AGT interchange sizes from the impossibly large structures used to achieve interchanges for freeway surfaces. First, the new interchanges will precisely control the path of their small vehicles, and, second, if the vehicle is firmly attached to the guideway, acceleration limits will not determined by rubber on suspect pavement but by the fragility of the passenger.

Thus, as Figure 2 illustrates in terms of area consumed, there are dramatic differences. The large circle is proportional to the area consumed by a representative high-speed freeway interchange. The actual area needed is approximately 40 acres – fully 26 city blocks! The larger of the two interior circular areas is proportional to the area [0.9 acres] needed for high speed, 60 mph AGT interchanges that can be proposed.

Finally, the smallest circular area is that needed for local interchanges proposed here for 25 mph turns and 40 mph through traffic. The area represented is 0.024 acres, that is, about 1,1 00 square feet or 10 meters square. Note the lines drawn, to scale, used to illustrate 18 meter-wide streets at their intersection, above which the neighborhood interchange can be built. An interchange fits.

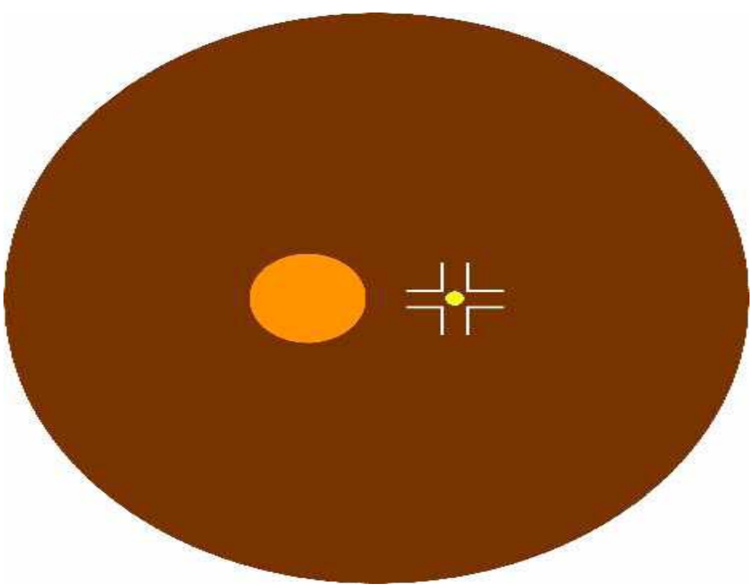

Figure 2 illustrates to scale the relative areas needed to construct a high speed freeway interchange (brown), a high speed AGT interchange

(orange), and a neighborhood low speed AGT interchange (yellow). The freeway interchange destroys neighborhoods; the low speed AGT interchange fits above the small street intersection shown.

Local Interchanges

Any city street with substantial traffic load is a candidate for an AGT line. Indeed, even a tightly restricted and minimally sized four lane urban street is a candidate for a line. This narrow street might intersect with a similarly sized street also equipped with a line. Thus their small intersection is a candidate location for an interchange. Assuming both streets have no left turn lanes and no added width for parking or right turns, these minimally sized streets will both have a width of 4 x 12 feet = 48 feet. Can a full Rail Car interchange be built well within the footprint of such a street intersection?

The interchange's architecture must meet a number of demanding specifications. The interchange must allow unimpeded use of the street below, perform well with speeding vehicles, be cost effective to implement, and be maintainable over time. So as not to interfere with street use, the structure must have ground clearance for tall vehicles, lack posts within the intersection, and allow signage and lighting for the ordinary intersection below. To be cost effective, it must be fabricated to good measure in a factory setting and require minimal assembly in the field. Aesthetically it must maintain and even enhance the ambiance of a pleasant streetscape. Light, airy, leaving the intersection corners open, it must allow pedestrians to be comfortable walking beneath.

Sixteen feet, about five meters, of ground clearance might be the standard codified to allow full use of the intersection below. Running lower to the ground, street AGT lines will require each line to have a transition zone as it approaches an intersection. The lower street spans have allowed cars, SUVs, and pedestrians to pass under, but, for cost and aesthetic reasons, may provide no more than about eight feet of clearance. As such the line has prohibited trucks from crossing the street mid-block. Trucks are obligated to turn at the intersections. And thus turn under the interchange.

The Roundabout

The simplest possible configuration for an interchange – let's broadly define an interchange as an intersection with a 100% duty cycle where no one has to come to a stop – is the roundabout, that geometry most Americans associate with European roads. Vehicles driving on the right side of the road enter a roundabout proceeding to drive counter-clockwise on the circle from which the structure gets its name. Right turn, straight through, and left turn paths are executed after a quarter, half, or three quarter circular transit respectively. Conceptually, and many times in practice, a vehicle turning right never completely enters the circle. With that exception, all vehicles from each direction are on the circle for some length of time.

With this in mind, examine the illustration of SIKA/VisuLogik here in Figure 3. First, notice the structure is a single level interchange for two way Roadways entering from all directions. The ability to configure an interchange on one level clearly simplifies the design and construction.

Several limitations in the performance of the structure are readily apparent. While not severe, these limitations will restrict the roundabout interchange to a local type with low vehicular capacity and speed. Low capacity is of course a relative term. Low relative to the tremendous numbers inherent in a second low-headway design. Capacity limitations result from two causes. First vehicles from all directions on four separate lines must enter onto the single line from which the circle is constructed.

Figure 3 is an illustration of a roundabout design, courtesy of SIKA.

Second, they must enter and exit the circle slowly. Let's discuss vehicle speed through the interchange first. Assumed throughout this discussion is that horizontal accelerations will be limited to 1 g. Thus Cars, attached at their top, in response to the horizontal acceleration, will roll sideways to 45 degrees from their normal up-right orientation. The turn is designed for this speed and the Rail will be tilted at 45 degrees to accommodate the expected angle. The same is true for a Car mounted from the bottom. [For comparison a commercial airline in operation is limited to 35 degrees and a railroad to 39.] A passenger will feel an apparent 1.41 times his/her normal weight pushing directly into the seat. For multilevel structures vertical accelerations will be limited to 0.5 g. In a vertical acceleration up, the apparent weight will be slightly more at 1.5 times normal weight; and in vertical acceleration down, one will press into the seat with only half one's normal force. With such assumptions, vehicle speed and the Rail's turn radius have a functional relationship.

Speed is constrained by another parameter. Muscles tense and bodies brace themselves against accelerations. And when equilibrium is reached, moderate accelerations are not disagreeable. But changes in accelerations are different. Unpleasant rapid changes in acceleration have an equally unpleasant sounding name: jerk. Unsuspecting muscles and bodies are flailed in one direction or another as unanticipated forces are suddenly incurred. One can sip a cup of coffee at 1 g of acceleration, but react like a rag doll to moderate jerk.

A small street will limit the circle’s diameter to approximately 8 m. Limiting horizontal acceleration to 1 g limits speed on the roundabout to 6 m/s or about 14 mph. Since all vehicles must enter the intersection, in heavy traffic at 14 mph, if the computer exerting control can maintain an 80% fill factor, no more than 8,400 Cars per hour can transit the interchange from all directions, on average 2,100/hour from each direction. All traffic slows to 14 mph. Still, both these numbers are quite attractive for a local interchange.

Another concern with the design involves jerk. A driver making a right turn who does not enter the circle proper incurs a lateral acceleration to the right increasing to 1 g followed by a symmetric lateral decrease in acceleration to 0 g to the left. But drivers proceeding straight-through – and most drivers are going straight-through - and drivers making a left incur something more complex. Their path turns right, then left, then right, then straight. The Car swings first to the left, then the right, then the left, and then back down. These swings will not go unnoticed. Furthermore, if the circle is truly a pure circle, and the feeding line needs contact for a short segment, and the Car will be jerked into a 1 g curve as it enters the circle. If the circle is modified, those already on will be jerked. Admittedly any conceivable turn involves two accelerations, and four is not much more than two. But, the majority of travelers are going straight through and they will have to endure four transverse accelerations. In our next design they would endure almost none.

The Double Helix and Barrel Roll Interchange

Interchange Topology

If a two-way AGT line is vertically stacked with two lines of traffic proceeding in opposite directions, vehicles are free to exit left or right from either Rail. Such a two-way arrangement is depicted in Figure 4 in an AGT alignment down the median strip of a small boulevard.

Figure 4 illustrates a vertical AGT set deployed in the median of a common suburban street. The curved post allows for a minimum width of right-of-way. A median width of 8 feet might be ample. Thus the scene depicted with 12-foot driving lanes and 6-foot sidewalks would have 68 feet between buildings. Pedestrians and automobiles safely cross beneath as the right-of-way is non-exclusive, but large trucks must cross the right-of-way only at intersections.

This ability to exit and enter lines will be exploited here as a huge advantage for a proposed two-level interchange design. With the freedom to exit left or right from either line, vehicles thus execute simple 90-degree turns at an interchange. Vehicles on the top going, say, north are free to leave to the left and join Cars going west on the top. Or leave to the right and proceed east. [Likewise, Cars going east on the bottom would be free to take a right and join Cars going south on the bottom.]

Unfortunately a very nasty problem is now apparent. The poor Car going west on the top, should it choose to turn right and go south, will meet traffic head-on going north!

A second problem is also incurred with the straight through support rails. That is, for the two sets of vertically stacked rails to miss each other, four levels are required; rather than the more compact 2 x 2 configuration associated with horizontal stacking. Thus visually at least the apparent size of the structure would be doubled.

Both problems are solved with one trick. If each of the two rail sets twist 90 degrees in relative orientation, that is they go from a vertical stack to a horizontal one as they approach the center of the interchange, the two sets will cross as a two-level structure of four rails. If the rails continue to twist another 90 degrees in the same direction, they will return to a vertical stack, only with the top and bottom Cars in reversed positions. Exactly what our poor Car going west turning south needed! A quick check will convince the reader that all combinations are satisfied.

Through the entire 180 degree process the rail continues to orient the Cars in an upright position. The Cars rotate around a central axis as if on a double helix with a slow pitch. The Cars are on a double helix, the rails in a barrel roll! See Figure 5 depicting the progressive cross-sections incurred over 40 meters by a vehicle as it travels away from us and meets on-coming traffic as well as the crossing traffic on a second line. Note the Car’s helical path.

Figure 5. Progressive cross-sections depict a vehicle traveling on a barrel roll at an interchange and meeting both on-coming traffic and cross traffic.

For 25 mph turns, the 13 m radius right and left turn rails can start and finish on the center-line of the approaching vertically stacked lines. The entire structure is therefore very compact. Half way through the turn a rail is 5.5 m from the center point and the interchange largely fits into an 8 m by 8 m square directly above the center of the street intersection below. The Cars rejoin the main rail some 13 to 20 meters down the line merging into their awaiting slot as their horizontal acceleration decreases as gradually as desired. A schematic is shown in Figure 6.

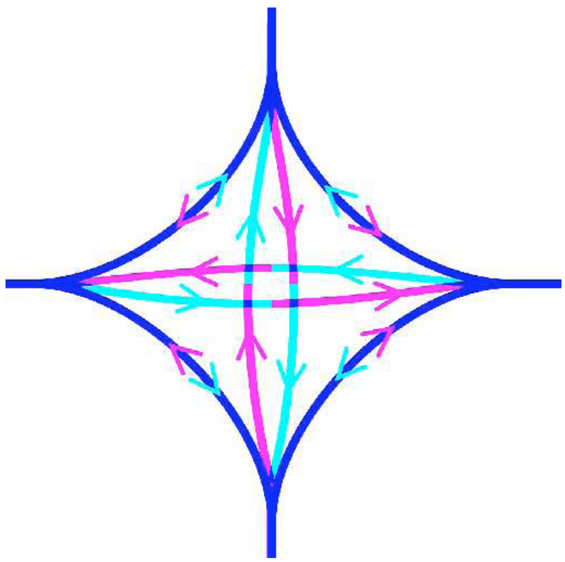

Figure 6 schematically illustrates traffic flow directions using a vertically stacked 2 rail two-way line which barrel rolls through the interchange.

A computer rendering of the skeleton of such a barrel roll interchange at the intersection of two lines is depicted in Figure 7. The illustrator has taken two guideways built as in Figure 4 and which are aligned along the medians of two streets. As shown both streets have approximate widths of 60 feet, and the structure easily fits within street boundaries. Ground clearance shown is about 16 feet. The illustration is to scale.

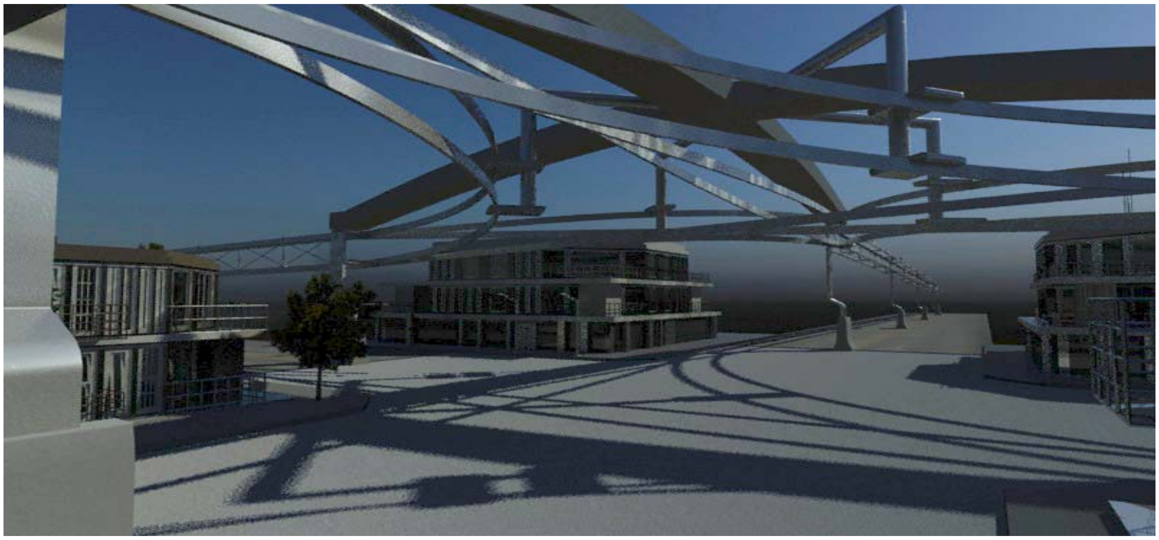

Figure 7 details the rail support structure of the interchange.

To promote a better sense of how such an interchange would be accommodated within an urban or suburban streetscape, one should examine the more architecturally embedded scene depicted in the computer graphic imaged in Figure 8. Not shown are the vehicles swinging out and any hardware to attach the Cars.

Figure 8 illustrates a full, high-capacity, 25 mph interchange above a common street intersection.

Interchange Performance

Vehicle capacity for each rail in each of the four directions is unconstrained by the interchange's speed if the street approaches are at 25 mph. Only the merge functions reduce capacity. If we assume a non-synchronous system, a series of Aerospace Corporation studies [1] concluded merging functionality can be maintained up to a fully 80% solid-train loading. At 25 mph 7-foot-long vehicles can operate bumper-to-bumper with a headway of 0.19 s or 19,000 vehicles per hour. At 80% that's 15,000 vehicles an hour each way — about twice what a big, high speed, stacked, four level freeway interchange can do.

When the interchange is operating near full capacity, solid trains of Cars would be asked to slow to 25 mph as Cars exit to the right or left. But for the vast majority of time the interchange would see small trains unimpeded by individual Cars slowing and executing a turn. Setting a speed limit of 40 mph for street segments of AGT with all turns at 25 mph establishes a highly attractive network.

Can Cars traverse the barrel roll segment of the interchange at 40 mph? How fast can a Car roll though the interchange? The rail's barrel roll begins 20 m before the center point of the interchange, at the same point the turn rails begin, and ends 20 m after the center point. This beginning point has been extended down the street so that the turns, and the barrel roll, can begin gently, thereby minimizing the jerk values of the ride and maximizing passenger comfort. We needn't worry whether Cars tilt right or left since all are in their exclusive time/position slots.

Horizontal accelerations in the barrel roll are complex but small in value. Relative to a straight line, horizontally, the Car will first move out, slow, stop, move in, and then stop. Vertically, the Car will simply leave its level path by accelerating downward and then slow to another level path. Thus, vertical accelerations will be simpler, rising to some value, dropping to zero and reversing to some value, before dropping in magnitude to zero. We have committed throughout to allowing no vertical accelerations greater than 0.5 g. As a consequence the horizontal accelerations will never approach our imposed limit, 1.0 g. Only horizontal jerk will be of concern.

Vertical acceleration, if the pitch of the barrel roll were held constant, would be a cosine function of argument 0 to pi, starting and ending at maximum absolute values. This is unacceptable. However, if we pick a maximum jerk value, allow the acceleration to rise at that rate to 0.5 g, and then fall sinusoidally to 0.0 g, we will arrive at a travel half-time with acceptable passenger comfort. That is, the minimum time to transit half way, or 20 m. Minimum time to travel a set distance implies a maximum speed. Picking 2 g/s for maximum vertical jerk, the pitch decreases and the acceleration increases to 0.5 g during a quarter second. In this quarter second the rail has moved over 18 cm and down only 5 cm given the barrel's 1 m radius. The horizontal jerk has been high, 3 g/s. But the Car is now accelerating downward at full value, 0.5 g. It will take only 0.56 s for the Car to drop the remaining 95 cm as its acceleration sinusoidally drops to zero . Total time is 0.25 second + 0.56 seconds to traverse the 20 m path. Our answer is 55 mph.

Interchange components are few. One primary component is the set of eight conceptually-identical turn pieces although, if exit and entrance hardware is different, it would consist of two sets of four pieces. There are two barrel-roll bent sets. These might be complicated but they are only two. There are eight 1-to-3 rail switch guides, and eight 3-to-1 guides. Numerous connecting and bracing pieces will also be needed.

Various Accelerations

At this point it is appropriate to compare the accelerations imposed upon AGT riders as they traverse the various interchanges that have been discussed. It is also appropriate to compare these interchange accelerations with that of a well-known event designed to stress the adventuresome: the roller coaster ride. Figure 7 plots acceleration vs time occurring during transit of three different structures. The first plot is data taken by Richard L. Taylor for the Shock Wave roller coaster at the Six Flags over Texas and plots the absolute value of the vector sum of accelerations for the 10 second trip. Accelerations of up to 5 g, as well as jerks of 8 g/s are incurred. These accelerations, combined with a 3-dimensional path obviously promote an impending sense of doom.

The second set of data is calculated for transit on the Double Helix Interchange just discussed. Horizontal accelerations have been designed to be 1 g for a 25 mph turn on the tapered curve with minimum radius of 13 meters. Tapering the ends of the turns has limited the initial and final jerks to 2 g/s. Right and left have the same absolute values as the turns are mirror images. Also plotted are the vertical and horizontal accelerations incurred for traffic that does not turn and goes straight through the interchange.

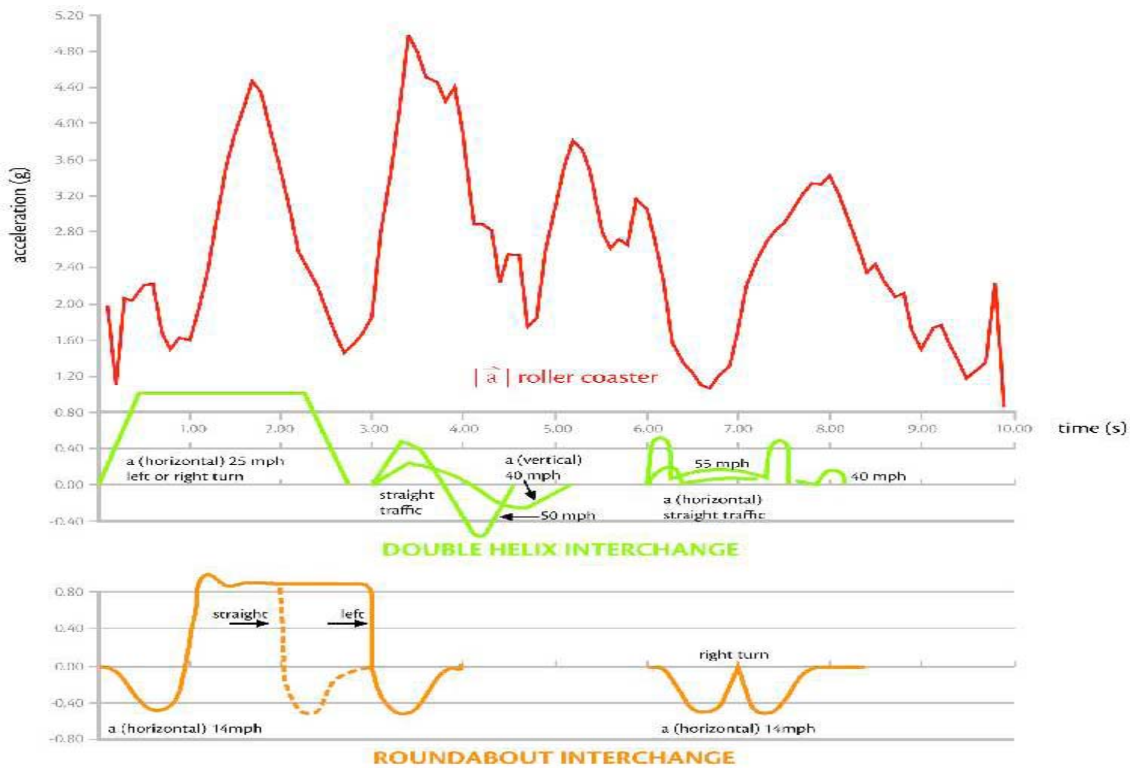

Figure 7 plots accelerations for a roller coaster ride, transit on a Double helix interchange, and transit on a round-about interchange.

Plotting at two different speeds allows the illustration of several points. One, traveling through at a speed of 55 mph is possible at acceptable accelerations. Two, traveling through at 40 mph, required in relatively heavy traffic to facilitate easier merging with slower traffic turning at 25 mph, achieves very benign disturbances for a traveler. Also the careful observer will notice that the tapered ends of the helix, designed in the text for minimum vertical jerk, are not optimum when considering horizontal acceleration – witness the rabbit ears at beginning and end – and a redesign is warranted.

Conclusions

The ability to incorporate full interchanges above ordinary major urban streets is a major goal of AGT technology as the component allows full penetration of the urban landscape without unduly disrupting the city. This paper describes a new topology for an AGT interchange with attractive physical characteristics and superior performance.

[1] "Fundamentals of Personal Rapid Transit" Jack Irving 1978 Lexington Books