GEFT Scheduling to Maximize Value of Current Infrastructure and Upside Potential

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Abstract

Passenger end-to-end transit times can be reduced by more than 50% using existing rail infrastructure when scheduling is simultaneously advanced with implementation of multimodal ground-effect flight transit (GEFT) railcars. Initial implementations would increase ridership and better utilize existing trains with an emphasis on outskirt suburban locations with as few as three new vehicles.

The more-evolved modes of operation use dynamically-forming trains of single railcars traveling down the line as a wave with single railcars leaving and joining the wave; it is made possible by ground-effect technology that increases speed, energy efficiency, and stealth of single railcars. GEFT attain efficient aerodynamic suspension over railway tracks, reducing both drag and rolling losses toward replacing steel wheels with tires. The aerodynamic suspension reduces stress on tracks toward higher speeds on marginal tracks with tires rather than steel wheels. The tires: a) enable multimodal vehicles to efficiently turn around on roads and slabs, b) expand seamless routing to include both railways and highways, and c) reduce noise.

Key Words:

Scheduling, Multimodal, Dynamic, Rail, Highway, Commuter, High Speed

Introduction

Rail transit scheduling has been a century-old optimization problem [1-5]. Recent work emphasizing computer algorithms with rapid advancement to artificial intelligence augmentation of these algorithms [6-9]. However, the capabilities of all these scheduling efforts is limited by the capabilities of the vehicles. This paper emphasizes the impact of use of single railcars at high speed as part of dynamic train units; multimodality is briefly discussed to facilitate turning around single railcars and expanding routing to seamless transit to and from highways.

Significantly-reduced passenger end-to-end transit time on rail can be realized by simultaneously advancing vehicle capabilities and scheduling. The enabling technology is ground-effect flight over rails which reduces both drag and rolling losses. Existing rail infrastructure can be used to attain speeds faster than the fastest highspeed trains for both commuter and inter-city transit.

Ground-Effect Flight Transit (GEFT) railcars use air's dynamic pressure to create aerodynamic lift in lower cavities which is particularly effective when cavity fences operate in low clearance to rails [10-12]. The aerodynamics substantially eliminate pressure drag and rolling losses. And so, train units are not needed to reduce pressure drag, and steel wheels are not needed to reduce rolling losses. The weight of train bodies is eliminated, and wheel suspension is able to be reduced to minimal values when cruising as needed to use wheel traction to supplement aerodynamic control toward keeping vehicles on tracks and highways. The result is both: a) the ability to operate at unsurpassed high speeds on older tracks not suitable for highspeed rail and b) rubber-tired hi-rail vehicles able to access both rail and highway routes. Rail routes are preferred for extended travel due to higher efficiency and higher speeds than viable on highways.

While GEFT are potentially multimodal over railway, roadway, and highway corridors; railway applications emerge as the best initial market due to the immediate opportunity to increase the value of existing railway track and train infrastructure. Benefits include:

- reduced trail transit times and costs to surpass any alternative at distances of 5 to 1000 miles;
- a preservation of railcar luxuries including space, cafeterias, bars, and sleepers; and
- 100% (i.e., direct solar in the sun) to 70% reduction in energy consumption enabling battery-power operation without electrical upgrades for corridors.

This paper evaluates a market-entry mode of operation on periphery rail segments that operate primarily to feed service to high-ridership segments. The goal is to operate single-car GEFT in non-stop high-speed modes on the less-traveled segments while concentrating trains on the high-ridership segments. A generic scheduling model applies to both inter-city rail and metro service. The model is based on multimodal capabilities of single railcar units. The background is on GEFT technology for which digital prototypes have demonstrated the capabilities to achieve the needed single railcar performance.

Background

The basic approach to railway transit has remained unchanged for over two centuries due to the advantage of reducing rolled losses with steel wheels on steel rail where one engine is able to pull multiple cars in a streamlined train. The train's rolling losses exceed aerodynamic drag losses below transition speeds; hence, reducing rolling losses is critical to good performance. An example transition speed from rolling-loss dominance to aerodynamic-loss dominance is 50 mph [13]. Rolling losses are so dominant on trains that most trains do not take known and proven methods to reduce aerodynamic drag prevalent on underbodies.

For GEFT, the same aerodynamics that substantially eliminates pressure drag also provide aerodynamic lift that eliminates rolling losses. In practice, viscous drag will always persist and optimal operation demands that some wheel suspension remains due to the effectiveness of wheels to maintain fence-rail clearances and path guidance (i.e., steering) over rails. Figure 1 illustrates unique features of GEFT.

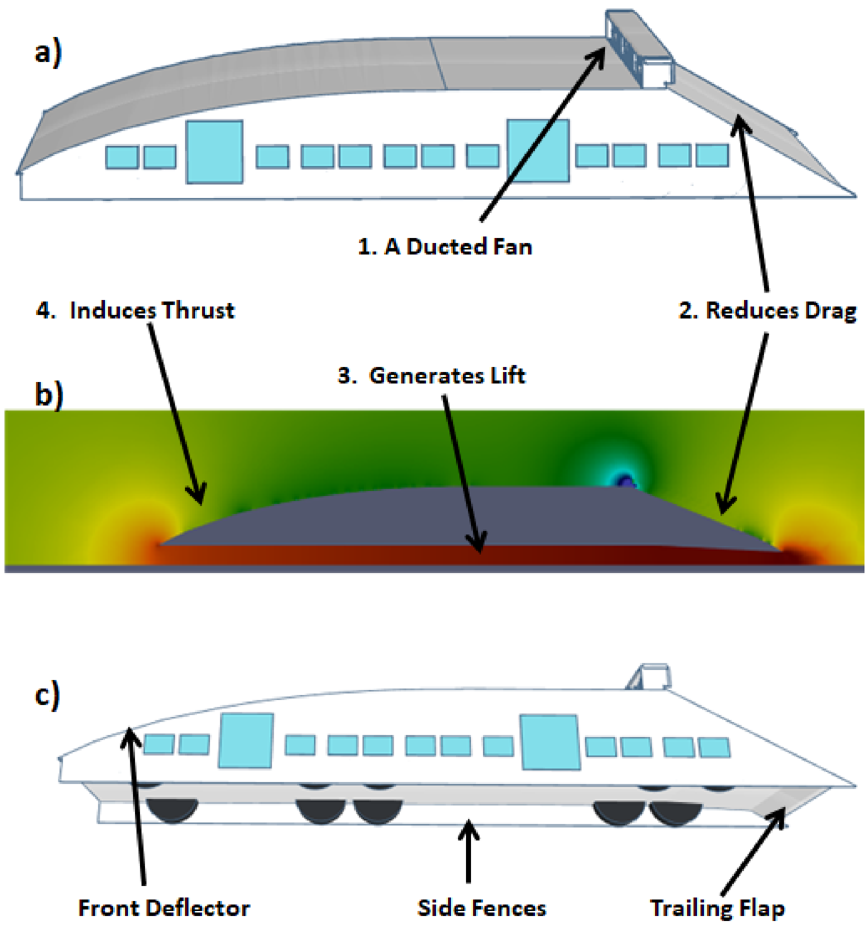

Figure 1. GEFT illustration including vehicle and CFD pressure profiles.

Streamlining of semi-trucks, buses, and single railcars all point to similar design as illustrated by Figure 1. Trucks have been extensively studied, with use of forward-section deflectors, trailing tail boats, and fences to reduce drag [13, 14]. To these features, GEFT adds an upper-surface trailing-section ducted fan which forces air over a trailing taper that extends from the fan to the underbody at an angle of about 30° [12].

In the sequence as illustrated by Figure 1, the following occurs: 1) the fan pushes air over the trailing taper. 2) this fan discharge air flow reduces induced drag behind the vehicle and creates a trailing edge stagnation point, 3) the higher pressures of the trailing-edge stagnation expand forward below the underbody from the trailing edge to the leading edge, and 4) as a consequence of the higher-pressure region reaching the leading-edge stagnation point more air is pushed over the front deflector leading to more induced thrust at the front section. A low clearance between the fence and the rail, or highway, reduces the loss of higher pressures along the sides and promotes sustained high pressure throughout the underbody which generates aerodynamic lift.

The generation of aerodynamic lift is a “free” bonus of design which promotes the aerodynamic lift; no additional drag is associated with the generation of aerodynamic lift. This feature of GEFT design has gone unnoticed for over a century since the benefits of reducing rolling loss were clouded by the issue that hovercraft are very inefficient at generating aerodynamic lift. GEFT are extremely efficient toward generating aerodynamic lift as summarized by Table 1.

Table 1 summarizes the lift-drag ratios attained by digital prototypes of GEFT. Example dimensions are 2.5 m wide, 2 m high, and 10 m long with a fence-rail clearance of 2 cm at CR=0.01. To improve performance, two pairs of fences may be used: one pair over the tracks in line with the tires and one pair at the sides of the vehicle over the edges of railroad ties.

Table 1. Example digital prototype performances of GEFT railcars. W is width, H is height, Ch is chord, AR = W/H, TR=H/Ch, CR is clearance divided by height, and S is Source power in m^4/s^2.

AR	TR	Propulsor	CR	L/D	S
0.2	0.11	No	0.01	17.1	N/A
0.2	0.11	Yes	0.01	25.4	2.5
0.3	0.2	Yes	0.01	14.7	10

0.3	0.1	Yes	0.02	34	10

Well-designed lift generation is about $\boldsymbol{0.5\,\rho\,U^2}$; where $\boldsymbol{\rho}$ is air's density and $\boldsymbol{U}$ is vehicle velocity. Example lift generations are provided by Table 2. The lift is sufficient for support of comfortably seated passengers on a lightweight fuselage.

Table 2. Air's dynamic pressure at density of 1.25 kg/m^3 and trailer width of 8.5 ft [12].

U (m/s)	U mph	Pa kg/m/s2	Load lb/ft
30	67	563	100
40	90	1000	178
50	112	1563	277

The capabilities of GEFT are similar to maglev trains. GEFT use existing rail infrastructure. Optimal designs include: a) supplementing the thrust of the ducted fan with either wheel-based propulsor or linear induction motors and b) near-zero and laminar flow relative to the ground immediately behind the GEFT. The noise is minimal due to the streamlined aerodynamics and rubber tires. These features are consistent with very low energy consumption that enables use of batteries to provide power and enables solar panels on the vehicle to reduce battery weights as logistics permit.

Other advantages of aerodynamic lift are: a) multimodality due to tires replacing steel wheels and b) ability to travel at high speeds on low-speed tracks due to reduced weight-related stress on tracks at higher speeds.

The most efficient use of GEFT is at non-stop high-speed service to maximize the benefits of aerodynamic lift replacing wheel suspension.

Methods

A base case schedule is set up for three equally spaced end segments of a rail route which are operated by GEFT with non-stop service. The assumptions are 90 second load/unload times and 30 seconds to reach a cruising speed of 120 mph. The base case and subsequent modes of operation emphasize market entry operation of individual GEFT vehicles with minimal modification of infrastructure and operation of trains as normal except for end and branch segments [15, 16].

Results

Base Case - Five GEFT vehicles are used in the inbound base case simulation of Figure 2; three at Station 1 and one GEFT at Station 2 and Station 3. The vehicles use the same tracks, the trailing vehicle stops at an approaching station and the vehicle at the station takes the lead position of cars moving through the station. Once at the station, this base case assumes the vehicle stays at the station for a repeat of the sequence, such as every 4 minutes.

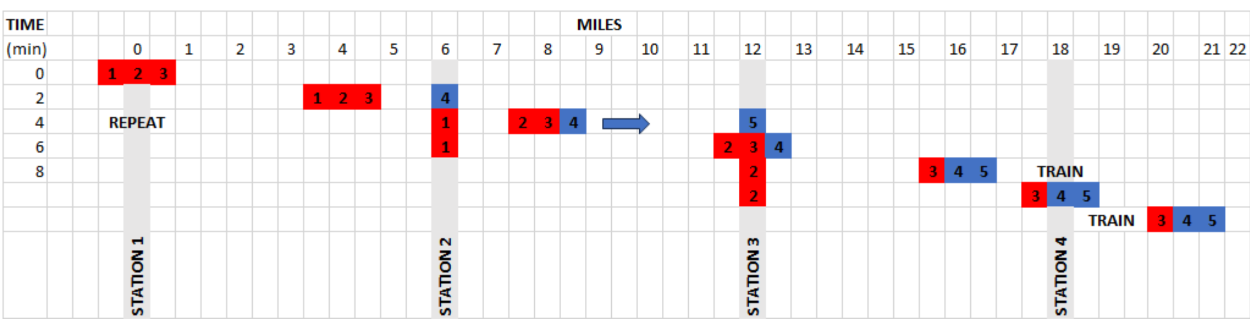

Figure 2. Scheme 1 base case schedule using GEFT vehicles three beginning route segments.

The following nonstop features are provided by the GEFT:

- Station 1 to Station 2
- Station 1 to Station 3 (express)
- Station 1 to Station 4 (express)
- Station 2 to Station 4 (express)

The first appearance of a train unit is at Station 4. The following advantages are realized with this operation:

- Three express services (service skipping at least on stop) using one track.
- Fully-occupied GEFT replace mostly-empty trains with the ability to use high vehicle capacity based on size of train and frequency of ridership.
- Higher speeds with GEFT on the single car segments than train segments.

This base case service does not provide service from Station 2 to Station 3, which can be accommodated by Car 1 proceeding to Station 2 after stopping at Station 1. The only modification needed for this base case is the ability to transfer from GEFT to the TRAIN at Station 4.

A key performance feature emerges in this GEFT simulation at Station 4 if the train stops on the opposite sides of the platform from GEFT 3, 4, and 5. In this operation, the train would automatically switch to the tracks occupied by the GEFT upon leaving Station 4 toward Station 5. Time would be allowed for passengers to transfer to/from the train units to the GEFT vehicles. The train would follow the GEFT vehicles when leaving Station 4 for Station 5.

Scheme 2 - The operation scheme of Figures 3 and 4 illustrate scheduling of GEFT which provide only express service after Station 4. The GEFT could operate in parallel to traditional trains stopping at each station. Each station would need the ability GEFT to pass parked traditional trains at stations.

At each station: a) the two trailing GEFT stop, b) three GEFT pass through, and c) two GEFT depart taking the lead position. The sequence places the two GEFT that are stopping at a station at the lead of the GEFT sequence.

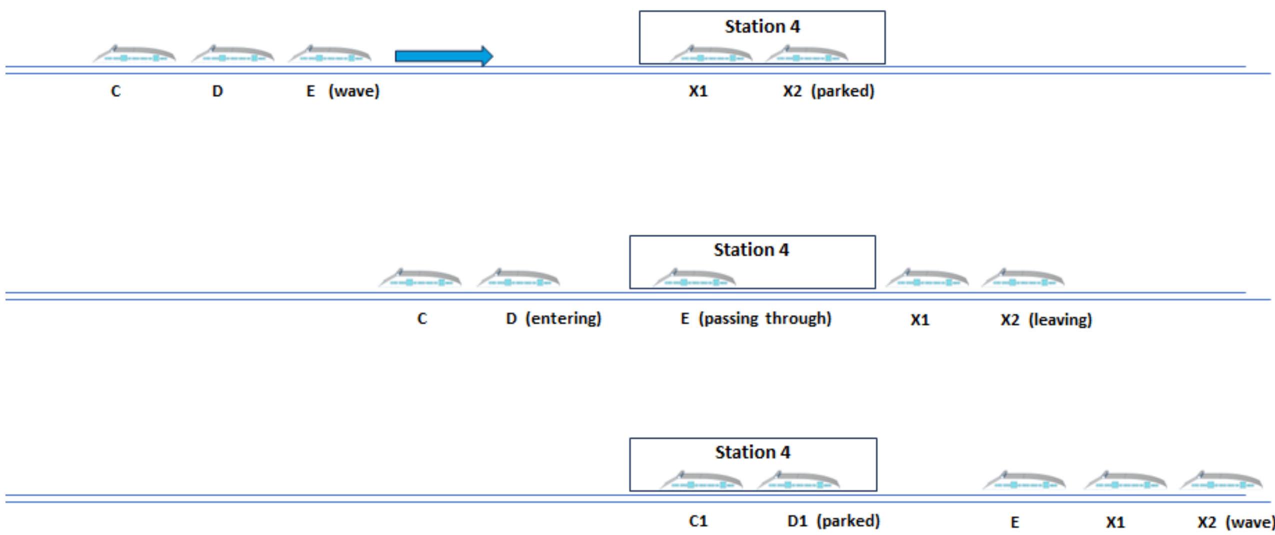

Figure 3. Illustration of a wave of three vehicles proceeding on a railway track as a more-detailed representation of Station 4 of Scheme 2 (Figure 4). Vehicles A-E participate in the illustrated wave; Vehicles X1 and X2 are from the previous wave.

			Station																						
GEFT #			1		2		3		4		5		6		7		8		9		10		11		12
	A	A0		-	-	-	A1	-	-	-	A2	-	-	-	-	-	A3	-	-	-	A4	-	-	-	-
	B		B0	-	-	-	B1	-	-	-	-	-	B2	-	-	-	B3	-	-	-	-	-	B4	-	-
	C		C0	-	-	-	-	-	C1	-	-	-	C2	-	-	-	-	-	C3	-	-	-	C4	-	-
	D				D0	-	-	-	D1	-	-	-	-	-	D2	-	-	-	D3	-	-	-	-	-	D4
	E				E0	-	-	-	-	-	E1	-	-	-	E2	-	-	-	-	-	E3	-	-	-	E4

Figure 4. Scheme 2 with wave of three vehicle proceeding on a railway track. Letters represent vehicles and the number after the letter represents the number of the stop of the vehicle which is different than the Station number. By example, B3 is the third stop of vehicle B which is at Station 8.

Variations of Scheme 2 include:

- GEFT skipping 0 and 1 stations (two car wave).
- GEFT skipping 1 and 3 stations (three car wave).
- GEFT skipping 2 and 4 stations (four car wave).
- GEFT only stopping at the busiest stations with conventional train service otherwise.
- Various capacities of the GEFT including two or more GEFT cars connected and operating as a single unit.

The service of the Figure 4 schedule is self-sustaining with vehicles from the previous wave in place to participate in a new wave. Figure 5 illustrates an express service with nonstop routing form multiple stations to Station 8, which represents a major transfer hub station. For the Figure 5 service, vehicles would have to arrive at the station independent of the inbound express service timing.

Station														
1		2		3		4		5		6		7		8
O	-	-	-	-	-	-	-	-	-	-	-	-	-	X
		O	-	-	-	-	-	-	-	-	-	-	-	X
				O	-	-	-	-	-	-	-	-	-	X
						O	-	-	-	-	-	-	-	X
								O	-	-	-	-	-	X
										O	-	-	-	X
												O	-	X

Figure 5. Scheme 3 wave of express railcars to multiple track connecting hub station.

Discussion

For a market entry position, the Figure 2 service can be operated with three GEFT vehicles where GEFT are only used for express service which best takes advantage of the higher speeds of GEFT vehicles. No GEFT would proceed with the train forward, and service of GEFT #1 and #5 could be by slower conventional railcar units.

Using the mileage assumption of Figure 2, 60 mph for trains and two minutes terminal times, the train operates in 8-minute cycles for station to station. GEFT could operate at 8-minute cycles when skipping stations at a speed and acceleration twice that of trains. This results in half the travel time on routes without trains on the shared rail.

Passenger-oriented aspects of the Scheme 1 include up to a 50% reduction in transit times while providing the option to take traditional train service from Station 4 forward. Vehicleoriented and efficiency aspects of the service include replacing low-occupancy trains with high-occupancy GEFT. When considering both higher occupancy and faster transit times, the passenger turnover on a GEFT vehicle would be more than twice that of a train car, translating to faster returns on investment in the new vehicles.

Multimodality – Rail-highway multimodality is valuable from three perspectives for the scheduling options of Figures 2, 4, and 5:

- **a)** the ability to transfer between tracks and highways allows extended service using the same vehicle including both service local to existing station and service extending service outward from the core network,
- **b)** the ability to operate GEFT off tracks at stations to change directions or to load and unload on slabs independent of track paths, therefore clearing tracks for more easily facilitating express vehicles and concurrent train stops, and
- **c)** direct integration while bus services and hubs. GEFT would be able to continue beyond the train transfer station 4 towards a bus transfer station or hub for greater, fast accessibility to existing public transportation methods.

Metro versus Intercity – GEFT can be used to enhance both metro and inter-city service by replacing train units on low ridership route segments [17]. Reduced transit times would increase ridership and allow trains to be used at higher capacities [18, 19]. While it is common for express trains to skip stations, GEFT would travel at higher speeds with vehicles able to leave and join a wave which translates to both higher track capacity and more passenger-oriented service.

Scheme Cycle Times – For Scheme 1 two cycle times emerge:

1. The cycle time is two minutes if two minutes is the time built in for acceleration, loading/unloading, and deceleration; this is the time for a vehicle to resume flow at the cruising speed.
2. The cycle time may also be synced for when a TRAIN is available at Station 4 for transfer.

The speed of the GEFT railcars do not significantly impact cycle time, but the speed does impact passenger transit time for the express services.

Scheme 3 is a variation of Scheme 1 where the last car does not stay at each station; this increases end-to-end routing as part of the scheme. Scheme 1 is designed for four sequential stations. The number of stations can be increased as TRAIN scheduling decreases between rush hours without need for the full capacity of train cars.

Scheme 2 operates with two vehicles parked at each station with a wave of three vehicles. The "train" is a dynamic train of vehicles leaving the end of the train and joining at the front of the dynamic "train". This can all happen on a single pair of rails forming one continuous track.

The presentation of Scheme 2 in the Discussion identified that the Figure 3 scheme could operate in parallel to traditional train service with transfer of passengers to and from a parked train at the station as the GEFT wave passes through the station.

Figure 6 illustrates a wave operating scheme where the number of vehicles in the wave changes. This is possible since the number of cars at stations is the same before and after the wave. Figure 6 illustrates waves of two and four vehicles with service between all stations when accounting for the ability to transfer to another vehicle at the station; and so, no traditional train service is necessary.

	Station																						
CAR	1		2		3		4		5		6		7		8		9		10		11		12
A			A1	-	-	-	-	-	A2	-	-	-	A3	-	-	-	-	-	A4	-	-	-	A5
B		-	B1	-	-	-	-	-	-	-	B2	-	B3	-	-	-	-	-	-	-	B4	-	B5
C		-	-	-	C1	-	-	-	-	-	C2	-	-	-	C3	-	-	-	-	-	C4	-	-
D		-	-	-	D1	-	-	-	-	-	-	-	D2	-	D3	-	-	-	-	-	-	-	D4
E		-	-	-	-	-	E1	-	-	-	-	-	E2	-	-	-	E3	-	-	-	-	-	E4
F	F0	-	-	-	-	-	F1	-	-	-	-	-	-	-	F2	-	F3	-	-	-	-	-	-
G	G0	-	-	-	-	-	-	-	G1	-	-	-	-	-	G2	-	-	-	G3	-	-	-	-
H	H3	-	-	-	-	-	H4	-	-	-	H5	-	-	-	-	-	H2	-	-	-	H3	-	-
I	I3	-	-	-	-	-	-	-	I4	-	I5	-	-	-	-	-	-	-	I2	-	I3	-	-
J			J3	-	-	-	-	-	J4	-	-	-	J5	-	-	-	-	-	J2	-	-	-	J3
K	K2	-	K3	-	-	-	-	-	-	-	K4	-	K5	-	-	-	-	-	-	-	K2	-	K3
L	L2	-	-	-	L3	-	-	-	-	-	L4	-	-	-	L1	-	-	-	-	-	L2	-	-
M			M2	-	M3	-	-	-	-	-	-	-	M4	-	M1	-	-	-	-	-	-	-	M2
N			N2	-	-	-	N3	-	-	-	-	-	N4	-	-	-	N1	-	-	-	-	-	N2

Figure 6. Wave operating scheme with changing number of vehicles in the wave.

The number of vehicles in a wave can vary as well as the number of vehicles entering and leaving the wave at stations. Therefore, every station down the line from a given station could have nonstop service from that station; all occurring with one track in each direction. When allowing two minutes for deceleration, acceleration, loading, and unloading; the cycle time could be as low as two minutes between waves.

The number of maximum passengers served at a station per hour would be the number of passengers per GEFT unit multiplied time 60. For 100 passenger GEFT units, the station capacity would be 6,000 per hour for loading and unloading—far more than could be reasonably handled for loading and unloading train passenger cars. The average train on the tracks is the average wave size plus two cars. If the average wave size was five cars, the track capacity would be 35,000 passengers per hour.

GEFT are capable of scaling vehicle sizes. A doubling of the GEFT unit size would double these capacities; and no additional road, curb, or parking spaces would be necessary to accommodate personal automobiles. Nonstop service at 120 mph could become a service standard in cities with greater speeds likely outside cities. Faster wave velocities are possible.

By example, a traditional train operating at 60 mph maximum speed would have the equivalent velocity of 40 mph when 4 miles of transit includes two minutes of transfer time. The GEFT of the Figure 6 wave operation could operate at 200 mph non-stop with a two-minute transfer after 20 miles at a time of 12 minutes versus 30 minutes for the conventional train at a 60% reduction in transit time.

An objective of this work is to identify a low-entry cost for GEFT that increases the value of current train and rail infrastructure [20]. At some point in the evolution, the trains may be phased out of service as GEFT efficiency is proven and improved.

System Evolution – Scheme 1 allows a low-cost entry of GEFT service with traditional train service. The Figure 6 scheme replaces traditional trains with GEFT with the advantage of nonstop service between stations throughout the line using a single track in each direction. Connecting tracks or multimodal capabilities would allow two different waves on different paths to exchange vehicles, expanding non-stop passenger-oriented end-to-end service.

- Other capabilities that could be added to vehicle operation and scheduling include:
- Route expansion to roadway
- Dynamic switching to/from a railway track in exit or entry to the wave at locations other than lead and trailing vehicles. This is analogous to how interstate highways operate.
- Additions of parallel railway lines.
- Use of GEFT of different sizes down to personal GEFT service.

More-concisely stated, multimodal GEFT with dynamic formation of trains can provide the flexibility of automobiles on highways, only with the following advantages:

- Higher speeds as allowed in controlled railway environments.
- Access to large networks of railway corridors and subway systems.
- Improved safety due to stricter control of scheduling with the prospect for rapid continuous improvement.
- Increased efficiency due to operating a low fence-rail clearances.
- Reduced environmental impact due to quieter operation and increased energy efficiency.

The Competition – Traditional alternatives to the high-speed multimodal GEFT railcars are: a) one, two, or three car train units operating in low-ridership outskirts with transfer to trains at stations on the fringes of higher-ridership segments and b) conventional express trains [21]. These traditional alternatives:

- do not reduce transit times to the extent possible. Trains at the velocity of traditional rail adversely impacts ridership and increases time for passenger turnover in vehicles thus reducing the return on railcar investment available with GEFT and
- congest the tracks with more vehicles to achieve the same capacity which increases chances for delays and decreases the agility of the system to adapt for disruptions.

The multimodality of GEFT vehicles and reduced size further increases abilities to adapt for disruptions.

The greater upside potential for the scheduling schemes of Figures 2, 4, and 5 is realized when the “new” vehicles are able to travel at more than 2X the speed of trains, which reduces the transit times by up to 50%. High speeds on low-speed tracks are achieved by replacing steel-wheel suspension with aerodynamic suspension which directly translates to reduced stress on the tracks. Some tire suspension is desirable to control both lift generation and guidance at cruising speeds while at low speeds aerodynamic suspension diminishes and is replaced with tire suspension.

From a passenger-oriented perspective, an additional transfer may be necessary relative to trains serving the outskirts; however, the inconvenience of a transfer is replaced with reduced total transit times and aligning schedules of GEFT to coincide with trains at key hub stations [22, 23].

Both higher speeds and multimodality are able to reduce the number of vehicles on the tracks. This leads to the ability to switch between operating schemes. Switching between operating schemes increases the number of non-stop end-to-end transit options. An ability to travel at 3X the speed limitations of trains on the tracks further increases end-to-end transit options.

Inner-city transit using cars in tunnels is being considered in Las Vegas and capacities up to 90,000 passengers per hour are identified for the tunnels; however, that capacity does not include infrastructure for loading and unloading passengers and parking which would be substantive for personal passenger cars [24, 25]. The adaption of multimodal GEFT into a similar model would achieve these objectives with less of an administrative overhead and infrastructure development required.

No air taxi system has been proposed that could approach: a) the capacity, b) the high average speed, c) inner-city access, or d) energy efficiency of dynamic wave scheduling using GEFT. Both car tunnels and air taxis would require substantial new infrastructure. These GEFT schemes would use existing stations and rails with some intermodal slabs added to turn vehicles around at select stations.

Conclusions

GEFT vehicles have performance advantages of high speeds, low noise, high energy efficiency as single railcars, and vehicle multimodality. This allows market entry service with as few as three vehicles to replace low-occupancy trains with faster higher-occupancy GEFT on the outer three segments and stations of many railway services. To accommodate, Station 4 would need an additional track at the station to allow transfer from and from GEFT cars. If the additional track for the train automatically changes lanes upon exiting with change of direction, only on additional track is needed at Station 4. Multimodal GEFT would turn around using slabs or roads next to the rails. The service would provide higher passenger capacity and shorter commute times, both leading to higher ridership and increased profitability.

Multimodal capabilities would allow slabs and roads for GEFT to turn around at stations which would reduce costs and improve logistics relative to using only rail. Also, multimodal capabilities provide methods for expanding routes and increasing passenger loading and unloading options.

When replacing traditional trains on existing rails, a prominent non-stop passenger-oriented service could emerge with average speeds in excess of 120 mph on tracks otherwise only suitable for much slower trains. The operating schemes apply for both commuter and intercity rail systems with multimodality extending service to highway routing. Rail is preferred due to control of traffic enabling higher speeds.

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