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Low-Risk High-Reward Transition to Low Pressure Tunnel Transit

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ABSTRACT: Typical low-pressure tunnel transit concepts are based on the low-pressure tunnels as separate transit corridors with the disadvantage of the time and cost associated with passengers transferring to and from transit outside the tunnel infrastructure. A new multimodal ground-effect flight technology (GEFT) identifies a path for seamless connectivity between commuter and intercity rail and highway corridors. This paper considers and evaluates approaches to open-entry tunnel transit with engineering of tailwinds to increase speed and energy efficiency. Digital prototypes were evaluated using computational fluid dynamics with results identifying that as velocity is increased in tunnels, pressure can be designed to decrease at a magnitude equal to the change in air's dynamic pressure. When considering both tailwind and decreased pressures, the competitive advantage of open-entry lower-pressure tunnel transit extends to distances up to at least 1000 miles. To a first approximation, closed tunnel transit systems are able to achieve lower pressures and advantages at distances over about 2000 miles; however, when considering the opportunity for continuous improvement in the evolutionary path, the emergence of closed systems having advantages at any distance is not certain.

KEYWORDS: Tubes, Tunnels, Hyperloop, Ground-effect, low-pressure, L/D-Efficiency, multimodal

INTRODUCTION

In recent years, hundreds of millions of dollars have been spent on low pressure tunnel transit, typically under the term Hyperloop [1]. Endeavors include studies and prototypes by NASA, HyperloopOne, and institutes in Europe, India, and China [2-6]. Despite this, no clear core of knowledge has emerged to provide a foundation of technology for continuous improvement. All proposed systems suffer from high research and development costs, prolonged projected construction times before realizing revenue, and high total transit times associated with accessing projected limited station infrastructure [7].

An alternative "open-entry tube" approach seamlessly connects low-pressure tube transit to existing rail infrastructure as part of a multimodal transit network using tens of thousands of miles of existing transit infrastructure. The approach is low-risk and can be performed without the cost and delay of building and testing physical research and development prototypes.

This paper evaluates the approach of engineering a tailwind in tunnels to enable higher speeds and lower energy consumption. It is possible to simultaneously increase tailwind speed and decrease pressure; both leading to the viability of higher speeds. Additional data are presented on "tunnel effect" flight over railway tracks which uses the upper and lower surfaces of tunnels to block the loss of lift pressures and increase the lift-to-drag ratio of the vehicles. The discussion identifies a basis for tunnel effect flight being more efficient than maglev, pneumatic propulsion, or air skis for transit in low pressure tunnels.

BACKGROUND

Since a rise in popularity in the early 2010s, many startups arose to develop "hyperloop" technologies: high speed transit in a low-pressure tube to connect major cities [5]. The objective is to use low pressures in tunnels to reduce drag and enable higher travel speeds. The vehicles would be able to operate more efficiently without the inefficiencies of take-off and landing before getting to cruising conditions. Maglev is the most commonly considered approach to suspension [2]. Maglev and linear motor approaches have traditionally been the suspension and propulsion methods of choice since they do not rely on wheel traction and provide a clearance gap to prevent highspeed contact of the vehicle with guideway structures [8].

Ground Effect Flight – Ground-effect flight is also regularly considered to provide an alternative method to achieve high speeds in close proximity to the ground. Ground-effect flight uses the ground to block the downward dissipation of lift pressures, resulting in higher lift-to-drag ratio (L/D) efficiency. Much of the current research into utilizing ground effect focuses on use of wings in ground effect ("WIG") at 1-5m from the ground [9-19]. Another common application is over water which provides a relatively flat surface that is wide enough to accommodate wing spans greater than 6 m [20, 21]. Current examples of commercial efforts for this are the Liberty Lifter, Airfish 8, and Regent aircraft [20-25].

WIG aircraft are too wide to operate on railways, highways, and tunnels; likewise, WIG are not suitable for use in hyperloop-type systems.

Ground effect machines ("GEM") is another classification of ground-effect vehicles that include hovercraft and various GEM designs. GEM typically operate at clearances less than 0.5 m where L/D efficiency increases with decreasing clearance with the ground. Traditionally, GEM have used forward-section ducted fans to force air in a lower cavity which has advantages of providing lift at lower velocities where air's dynamic pressure is not sufficient to provide lift [26, 27]. GEM are lifting-body designs, generally absent lateral wing extensions and suitable for use in tunnel transit.

Traditional GEM have two features which limit utility:

1) L/D efficiency correlates with the ratio of ground clearance to vehicle length which makes vehicles excessively long to provide heights suitable for passenger transit, and
2) The frontal-section ducted-fan intake pulls overhead air downward resulting in increased upper-surface pressures and lower L/D efficiencies.

A recently-defined type of GEM referred to as ground-effect flight transit (GEFT) uses an upper-surface trailing-section ducted fan to: a) prevent boundary-layer separation over a truncated trailing section, b) create a more-robust trailing-edge stagnation point next to the ground which increases lift pressures in the lower cavity, and c) benefit from the ducted fan intake positions to create lower pressures on upper surfaces and induced thrust on frontal surfaces [28]. When wheel suspension is incorporated with cavity fences (see Figure 1), the wheels provide both suspension at lower speeds and guides for operation of fences in low clearance to highways or railway tracks.

GEFT are designed to be multimodal with exceptionally high efficiencies over smooth railway tracks due to operation at clearances less than 1 cm . When cruising with 95% of the lift provided by aerodynamic forces, the substantial absence of rolling losses results in less than half the energy consumption of traditional trucks [28].

In the optimization of GEFT designs, improved aerodynamic lift has great synergy coinciding with minimizing aerodynamic drag. This synergy is the result of higher pressures extending forward throughout the lower cavity to a leading edge stagnation point where the leading-edge stagnation point is adjacent to the ground and maximized induced thrust on the frontal defecting surface of the GEFT vehicle.

This paper evaluates the feasibility of extending the application of multimodal highway-railway GEFT to use in lower-pressure tunnels.

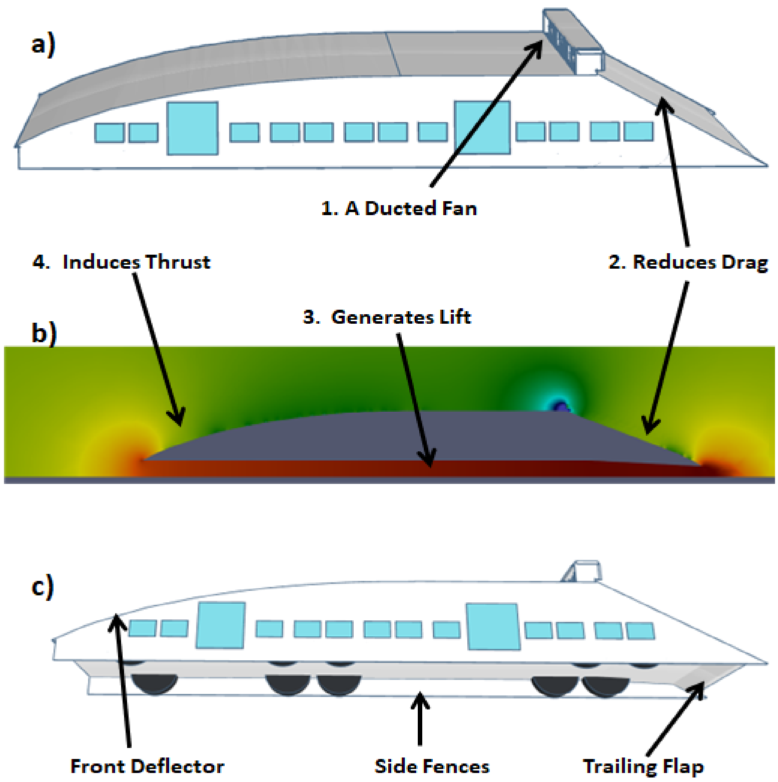

Figure 1. GEFT illustration including car and computational fluid dynamics (CFD) pressure profiles. Red is higher pressure, blue is lower pressure, and lime-green is zero p_{sig}.

Specification of Tunnel Pressure – Tunnel pressure is one of the most important parameters in low-pressure tunnel transit. A NASA report included methodology and rationale for selection of the pressure in tunnels based on energy to evacuate air from the tunnels versus vehicle drag [2].

Two components are considered for the optimization of operating pressure: pump down and steady state. The less critical, but more expensive, component is the pump down. Pump down is the energy needed to bring the tube from atmospheric pressure to operating vacuum pressures; Pump downs should occur rarely on initiation of the tube and any subsequent emergency pressurization. For long term expenses, the steady state cost is of more immediate importance for determining operating pressure as this is the regular pumping required to maintain the tube at operating conditions against air leaks into the tube, particularly during loading and unloading of transport pods. While previous research identified that 100 Pa was the ideal pressure at which to operate the tubes, NASA identified an optimal pressure of 200 Pa was identified as ideal to reduce energy costs of operation [2, 29, 30].

The NASA report also identified that to prevent build up of pressure in front of the vehicle, which would significantly increase the drag on the vehicle, the tunnel diameter must increase as the velocity of the vehicle also increased. The example provided was a tunnel 4m in diameter to support a vehicle travelling at 0.8 Mach [2, 29]. The necessary area has exponential growth. To overcome this hurdle, the NASA report recommends the addition of a compressor at the front of the vehicle.

The key feature limiting the diameter of tunnels remains the drag on the vehicle. Application of maglev in hyperloop tunnels adds another drag beyond aerodynamic drag in the form of magnetic drag. Magnetic drag is proportional to vehicle weight, yet inversely proportional to travel velocity, therefore, if aerodynamic drag is sufficiently dealt with for high velocities, maglev becomes a viable technology for suspension within hyperloop tubes [31]. Suppes identifies the optimal pressures per travel velocity at which to operate maglev suspension to balance the effects of aerodynamic drag vs magnetic drag [31].

A Divergence of Design Philosophy – In the work leading to GEFT, Suppes and Suppes identified three basic physics principles that describe how air flow creates aerodynamic lift [32]:

Principle 1. Impacting air flows create higher surface pressures.

Principle 2. Diverging air flows create lower surface pressures.

Principle 3. Air expanding from higher to lower pressures at the speed of sound extends lift pressures along streamlines, dissipates lift pressures across streamlines, and interacts with air flow to turn streamlines.

These principles are presented based on fundamentals of continuum mechanics as basic principles so they can extrapolate towards innovation.

Traditional schools of thought identified pressures as a result of changes in air velocity or the turning of air streamlines. The new perspective is that turning of air and changes of air velocities are the result of pressure fields formed by the Three Principles. Concisely, the new perspective transposes the cause and effect of traditional schools of thought to improve innovation.

An extended implication of the Three Principles is that effective designs strategically create areas of lower and higher pressure toward design objectives. One resultant design approach is to use ducted fans to create lower pressures at intakes and higher pressures at discharges. For the Figure 1 GEFT design, the upper-surface trailing-section propulsor generates a desirable pressure field throughout the vehicle's surface. One beneficial aspect is the ability to truncate the length by using a higher pitch trailing taper. Another beneficial aspect is that extended lower-pressure surfaces can be created on the leading section which creates "induced thrust".

The approach of creating induced thrust on the front deflector surface substantially gets around the mentioned NASA design criterion that a "buildup of pressure" on the front of the vehicle dictates that both tunnel diameters must be increased and tunnel pressures lowered to accommodate high speed transit in tunnels, especially considering how the propulsor passes air through the vehicle length.

Tunnel Effect Flight and Multimodal Approach – The Three Principles teach toward increasing L/D efficiency by blocking the dissipation of lift pressures, a dissipation at the speed of sound. Ground-effect flight achieves higher L/D efficiency than airliners by blocking the downward dissipation of lift pressures [28]. The blockage of downward expansion of lift pressures generates lift on the lower surface, where for many designs the lower-surface lift significantly exceeds upper-surface lift.

An extended application of this approach identifies that "tunnel effect" flight is able to achieve higher lift pressures and higher L/D efficiency by blocking both upward and downward dissipation of lift pressures [33, 34]. Initial work on tunnel-effect flight successfully identified that GEFT's upper-surface ducted fan can be adjusted so that pressures within five vehicle lengths in front of and behind the vehicle were equal to the value of the tunnel entrance boundary condition. The simulations identified L/D efficiencies approaching 20; Good values, but less than potentially be achieved with further optimization. The results identify that a design specification relying purely on low pressure in tunnels to achieve high efficiency most likely teaches away from overall optimal designs.

The tunnel-effect simulations are iteratively intensive, requiring a simulation for each ducted-fan power setting to meet the convergence criterion that pressures be equal at five vehicle lengths in front of and behind the vehicle. The implication is that vehicle surfaces and sources (i.e., a ducted fan) can be further optimized to create laminar streamlines of air flow that depart/meet at leading/trailing surfaces with near-zero lost work due to turbulence or air velocity stratification, both of which are forms of lost work.

New Low-Pressure Transit Design Criteria – By overcoming the low-pressure tunnel design criterion that pressures must be low to avoid drag and the buildup of higher pressures in front of the vehicle, new design criteria emerge. Since air pressure does not have to be detrimental to tunnel transit, the designs with tailwinds emerge as key design parameter for tunnel transit.

This paper is on transit tunnel configurations to increase perpetual tailwinds toward a greater understanding of benefits and losses associated with these engineered tailwinds.

Methods

SimFlow CFD software was used to simulate tunnels prepared as STL files with a CAD program. The SimpleFOAM solver was used with the RANS k-ω SST turbulence model for converged steady state solutions. The tunnels were meshed with the boundary layer grids in proximity to the walls. Tunnels were simulated as about 0.01m wide with a total length of 3m. The ends of the tunnel system are exposed to atmospheric pressure with flow generated by pumps at the entrances to the tunnels or within bypass loops inside the system simulated as velocity sources. The sources are 0.01m in width across the tunnel and 0.002m deep. Pressure profiles are presented with blue as low pressures, red as high pressures, and a symmetric scale where 0 gauge pressure is green. Pressure reported within SimFlow is kinematic pressure, normalized by the density as an incompressible fluid. Figure 2 provides an example of the tunnels meshes with pump sources identified.

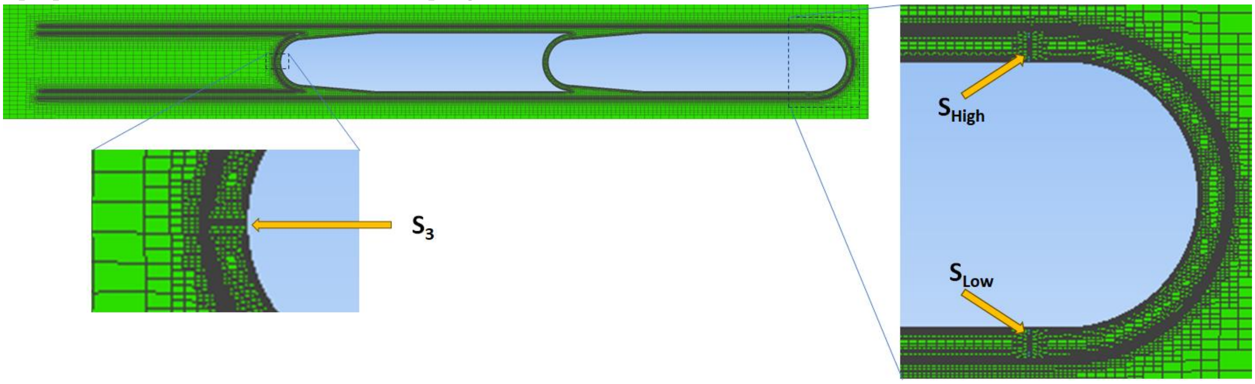

Figure 2. Example mesh showing three sources used to create air flow in the tunnel.

Figure 3 compares a mesh used for CFD simulation to the tunnel it is intended to represent. Implicit in the estimation is that extended main tunnel corridors would have a means to compensate for viscous losses in kinetic energy, such as vehicles pushing air through the system. In practice, different vehicle traffic in adjacent tubes would result in minor fluctuations of the steady-state pressures; the simulations of this work are for equal traffic resulting in equal and opposite air flow for an adjacent entrance and exit.

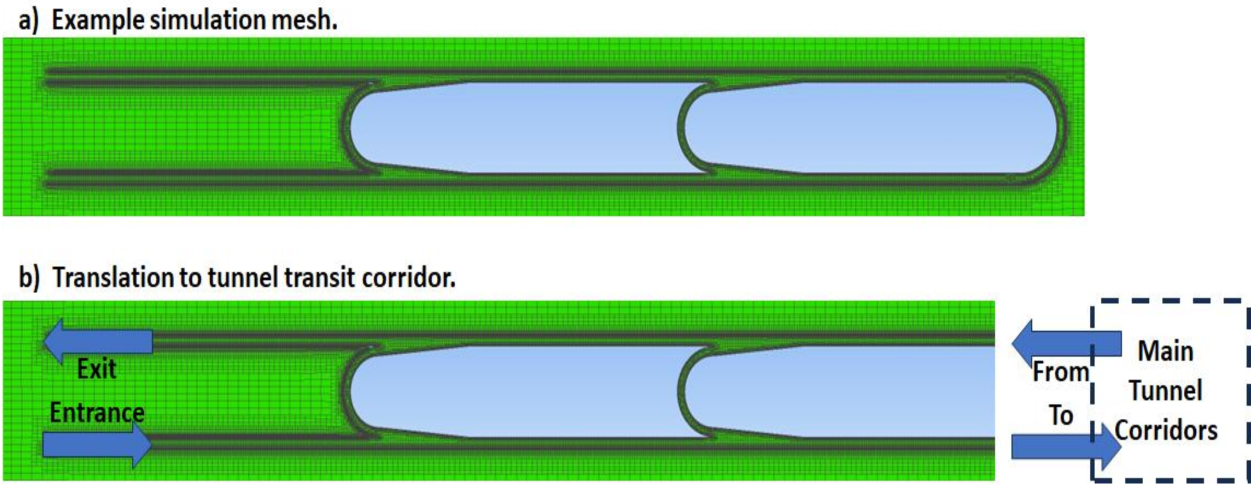

Figure 3. Comparison of mesh configuration with the tunnel system being simulated.

RESULTS

Pressure profiles of a control tunnel and four variations of connected tube configurations are provided by Figure 4. Entrances are at the lower left and exists are at the upper left for each configuration. Extended tunnel sections are simulated by a U-turn in the tube to simulate an entrance adjacent to an exit under the constraint of equal and opposite air flow.

The velocity profiles of Figure 5 illustrate high velocities on the U of each configuration, illustrating high velocity throughout the transit tunnels. The actual length of the transit tunnel sections may be as long as needed: vehicles pushing air would supplement flow and compensate for the drag along the tunnel walls.

Figure 4. Comparison of pressure profiles (from -1000 to 1000 m^2/s^2) for four configurations of tubes connecting adjacent tunnel entrances and exits. From top to bottom: a) control, b) single recirculation tube, c) two recirculation tubes in series, d) a recirculation paired with a- entrance-exit tube, and e) two pairs recirculation with entrance-exit tubes.

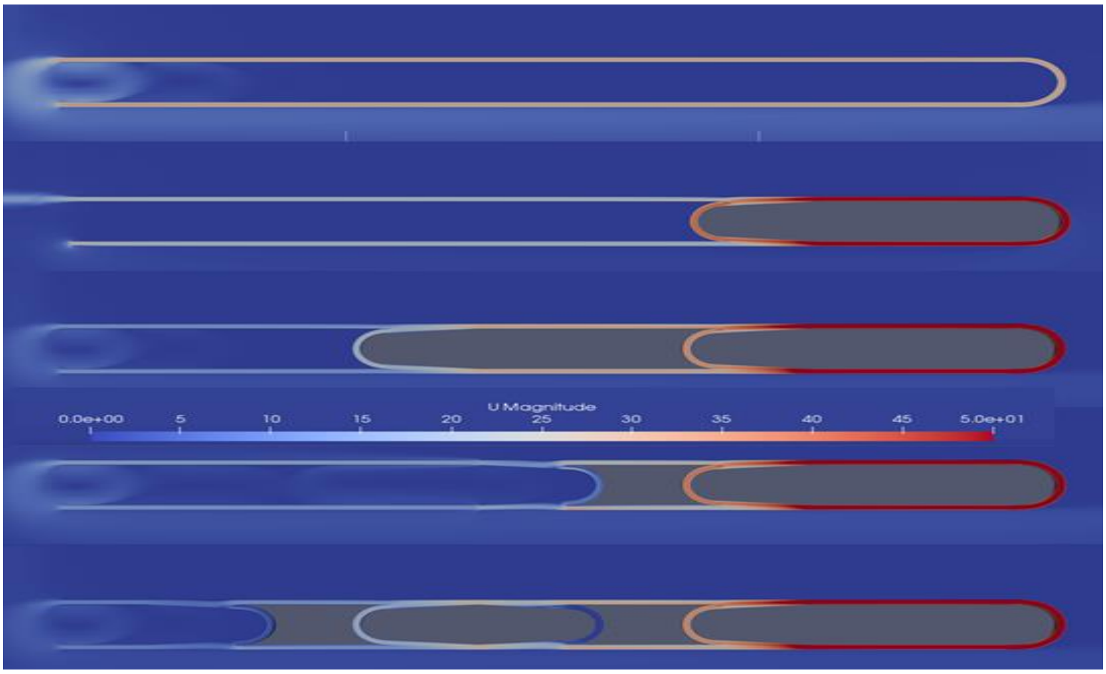

Figure 5. Comparison of velocity magnitudes of the tube configurations of Figure 4 scaled at 0 to 50 m/s.

Dependent on the configuration, air flow exiting the tubes varies from 10 to 25 m/s. This compares as 15-45% of the peak velocities near 60 m/s in the main transit sections. To achieve conditions of zero exit velocity, a third velocity source was simulated in the leftmost recirculation tube. Figure 6 provides example velocities vectors in the X and Y directions for a simulation developing near zero flow at the exit.

Table 1 summarizes the differences in pressures between the entrance and exit sections as a function of the setting of the third velocity source in the left recirculation tube. The velocities reported are the velocities at the U which simulates the transit corridor. The power placed in the third source incrementally increases the air velocity in the main tunnel corridors.

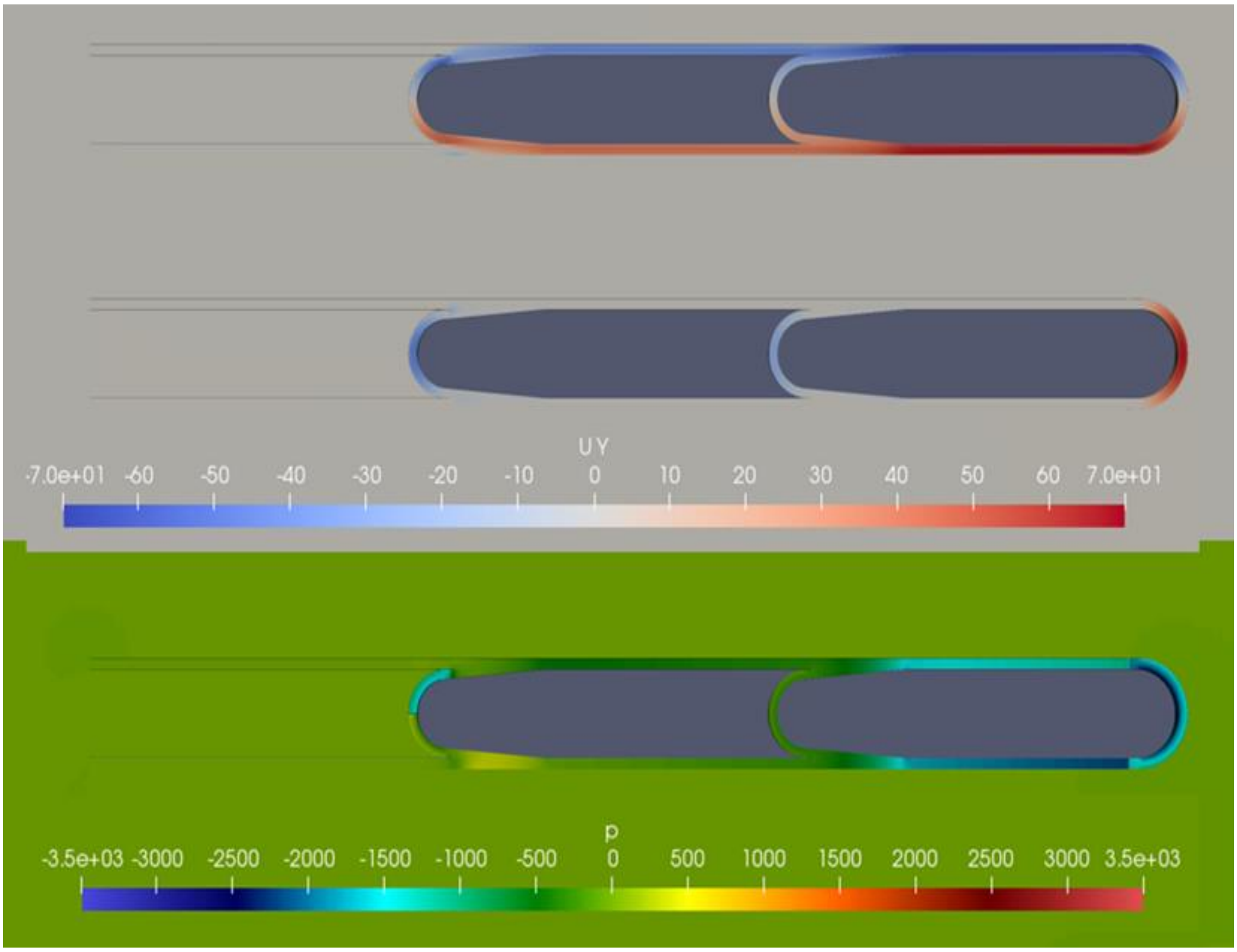

Figure 6. Tunnel profiles with upper and lower sources at 0.1 m^4/s^2 and S_3 = 0.15 m^4/s^2 (source in left recirculation tube), including: X-dimension velocities (top), Y-dimension velocities (middle), and pressure profiles (bottom).

Table 1. Conditions for convergence on zero flow into tunnel at S_{top} = -0.1 m^4/s^2 and S_{bot} = 0.1 m^4/s^2.

S_3 (m^4/s^2)	ΔP (m^2/s^2)	U_{max}
0	16	64
-.1	12	69
-.15	-0.1	71
-.2	-0.4	72.5

Impact of Source Setting on Air Velocity – Work summarized to this point in figures 3-6 has been with the upper and lower sources set at magnitude 0.1 m^4/s^2. Table 2 summarizes the impact of increasing the source settings on the main transit corridor pressure and velocity. Calculated dynamic pressure is compared to the simulated pressure. The results are compared to systems summarized by Figures 4 and 5.

CFD simulations identify that pressure is reduced by an amount equal to the dynamic pressure corresponding to the increase in velocity. Staged loops create slightly greater increases in velocity at given source settings.

Table 2. Impact of source setting on velocity and kinematic pressure. R is the recirculation tube, E is the entrance tube The $S_{top} = S_{bot}$ at the values listed in the table. $S_3 = 0$.

	S	U	0.5 U^2	P/ρ
	(m^4/s^2)	m/s	(m^2/s^2)	(m^2/s^2)
1XR	0	57	-1624	-1800
2XR	0	63	-1984	-2200
1XR, 1XE	0	59	-1740	-1900
1XR, 2XE	0	64	-2048	-2200
2XR	0.1	63	-1984	-2200
2XR	0.2	91	-4140	-4500
2XR	0.3	112	-6272	-6800
2XR	0.4	130	-8450	-9300

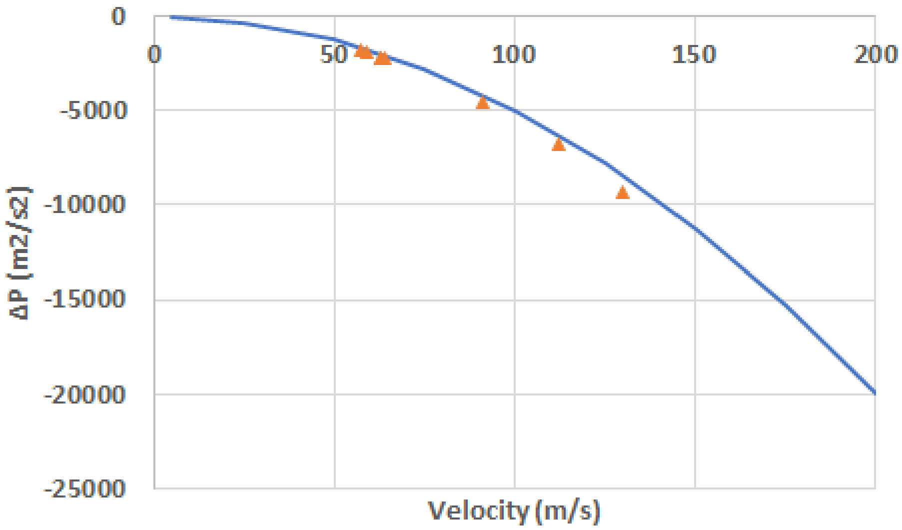

Figure 7. CFD calculated maximum velocities versus maximum change in kinematic pressure magnitude.

Example Transit Time Calculations – High-speed tube transit systems have been identified to be preferable over air transit for short-haul trips in both efficiency and customer time. A survey of nonstop flights from Washington-Reagan airport to locations ranging New York (short-haul) to Los Angeles (long-haul) correlates with gate-to-gate times as expressed by Equation 1.

$$Gate\ to\ Gate\ time\ (hours) = \frac{Distance(miles)}{554} + \frac{50}{60} \quad (1)$$

This does not include boarding times, disembarking times, security, or intra-airport travel. A typical recommendation is to arrive at the airport two hours before departure time. This translates the Equation 2 approximation:

$$Airport\ Entry\ to\ Exit\ time\ (hours) = \frac{Distance(miles)}{554} + 3 \quad (2)$$

Based on Equation 2, a 200 mph train can travel 600 miles before the non-flight time consumption for air travel is accounted for. A train traveling at 200 mph relative to a 50 mph tunnel tailwind would travel 750 miles while accounting for an airliner's non-flight time requirements. Adding half an hour for embarking and disembarking from a 200 mph train provides a comparison equation for tailwind tunnel transit to equation (2) with a modification factor U_T for the tailwind velocity:

$$Tube\ Train\ Entry\ to\ Exit\ time\ (hours) = \frac{Distance(miles)}{200+U_T} + \frac{30}{60} \quad (3)$$

Whereby, with the example 50 mph tailwind, achievable independent of exterior weather conditions, it is faster to travel between locations 1100 miles apart by train. 1100 miles is over a third the width of the United States and over two thirds the maximum height, providing any coastal tube systems a significant advantage over aircraft travel.

Multimodal transit with seamless connectivity to tunnel corridors would provide further advantage over the fastest alternatives including air transit and highspeed rail. Conservative assumptions translate multimodal transit that includes open entry/exit to have reduced transit times at distances up to at least 2000 miles. These distances would increase as the system evolves and improves to cover most any intra-continental transit.

DISCUSSION

CFD simulations identify that it is possible to simultaneously increase air velocities and decrease pressures in transit tunnels by utilizing recirculation tubes. The most effective designs use recirculation tubes that enable air's dynamic pressure to pump air from an exit tunnel section into an entrance tunnel section. To a first approximation, the use of recirculation tubes to increase tailwind velocity results in a decrease in pressure of magnitude equal to the change in air's dynamic pressure.

Staging multiple recirculation tubes in series increases efficiency as identified by lower lost work in the form lower air velocities exiting the tunnel. Without recirculation, the kinetic energy of the exiting tube would exit the tunnel system and irreversibly mix with surrounding air.

A prominent form of energy degradation for air flow in tunnels is viscous degradation of velocity to thermal energy. Without periodic pumping of air through the main tunnel corridors, the air would reduce in velocity with the kinetic energy converting to low-quality, undesirable thermal energy.

Sources of velocity from simulated blowers generated air flow in CFD simulations. Blowers may be used in tubes connecting vehicle corridor tunnels. Vehicles traveling in the tunnels could also operate with a net positive pressure in front to push air through the tunnel.

The transformation between pressure and velocity energy is more complex as they are both considered higher forms of energy, approximately equal in quality—relative to thermal energy which is lower quality from a thermodynamic perspective. Preliminary studies identified that a gradual increase in tunnel diameter at the approach to a sweep-radius effectively converted kinetic energy to velocity in the recirculation tubes; this is a design consistent with reducing frictional losses for elbows in pipes.

Lost Work Analysis – On a per vehicle basis, the lowest lost work occurs when the vehicle passes through air in streamlined flow such that the condition of the air immediately behind the vehicle is the same as the condition of the air immediately in front of the vehicle except for a slight increase in temperature behind the vehicle due to viscous losses [28]. In optimal designs, streamlined flow from the surfaces of a vehicle converge at the vehicle's trailing section without the formation of turbulence or stratification of velocities (i.e. without jetwash).

From a tunnel system perspective, flow exiting the tunnel exit mixes with adjacent air resulting in lost work, and so, the lowest lost work is with no air exiting the tunnel. A mass balance for this condition adds the constraint that no air must enter the tunnel either.

Combining the lost work analysis of the vehicle and tunnel system identifies that each vehicle passes through air of zero velocity at tunnel entrances and exists. In the tunnel, vehicles pass through tailwinds from zero to tens of meters per second. Efficient design dictates that the vehicle design forms streamlines in a manner that does not cause turbulence of stratified velocities other than laminar flow stratification of velocities.

Therefore, while paired entrance tubes and recirculation tubes performed well, the use of a series of tubes designed to recirculate air in the tunnels has performance advantages for both reducing lost work and reducing construction costs.

Impact of Fans on Lost Work – Strategically-place fans on a vehicle are able to prevent boundary layer separation and can streamline the convergence of air at aft surfaces. Thus, the use of fans increases overall efficiency. In recirculation tubes, the fan's energy input increases the kinetic energy of air in the transit tunnels.

A conclusion is that the strategic use of fans resulting in reduced work is a preferred design for overall improved energy efficiency. This conclusion is based on deductive reasoning rather than a directly measured increase in efficiency.

Optimal Tunnel Air Velocities – Chemical engineering routinely considers air flow in pipes, and in that process a design heuristic of 10 m/s for air flow is recommended. This value tends to be an optimum of lower capital costs for lower-diameter pipes versus higher operating costs to provide higher air flow velocities. Among the other reasons for not using higher velocities is aerodynamic noise.

For transit in tunnels, the velocity next to the vehicle will typically be greater than 50 m/s. Therefore, tunnel air velocity noise is the lesser of the noise reduction issues. Thus, higher velocities are more reasonable.

Efficiency, Transit Time, and Cost – A critical advantage of GEFT technology relative to past work on transit in lower-pressure tunnels is extremely that low pressures are not needed to avoid the energy of pressure buildup at the front of the vehicle and pushing air through tunnels. Pressure fields can be created around vehicles which induce thrust of magnitude similar to the drag on the front and rear of vehicles. As a consequence, and to a first approximation, lower pressures are not necessary to achieve energy efficiencies and speeds comparable to airliners or highspeed trains. A sequential consequence is that extensive experimental prototypes for research and development of highly-efficient tunnel transit are not necessary; rather, existing tunnels can be modified with the addition of air recycling tubes to achieve real-time data and new benchmarks for further improving transit infrastructure for easier testing.

Compared to the development of hyperloop technologies, these systems have significant advantages:

1) Testing may use pre-existing open access tunnels with minor modifications rather than highly expensive 5km tubes which will require even more expensive 30km tubes before approval of full-length systems.
2) The tunnels use moderately lowered pressures with tailwinds rather than 100-200 Pa vacuums which are significantly less expensive to maintain while retaining the open access for vehicles to freely enter and leave. This both improves passenger loading

efficiency and allows for expansion of the system into a multimodal venture.

3) The use of tailwinds and ground effect flight allows for similar improved velocities to compete with airlines for short-haul routes as ground effect flight or maglev technologies within hyperloops.

Initially, gains on reduced transit times and increased efficiency will emerge from perpetual tailwinds rather than lower pressures. Multimodal connectivity with existing railway and highway infrastructure will avoid time delays associated with changing modes of transportation and the limited locations of ports such as airports. Back-of-the-envelope calculations identify that total transit times and costs would be less for distances up to a thousand miles. The information to be gained from initial shorter routes will allow for optimized approaches to significantly longer routes and networks. The information gathered will also allow municipalities to optimize the speed vs cost of tunnels (dependent on tailwind velocities and pressures) that suit the value of the route to be developed, allowing for wider implementation than planned hyperloop routes.

An Author's Perspective – Author G. Suppes has been writing on low-pressure tunnel transit for over three decades. The early work recognized that rudimentary low-pressure tunnel transit prior to 1990 had two issues: 1) an absence high-speed switching between high-speed tunnel sections of different routes and 2) the time and cost of accessing stations designed to board vehicles positioned in low-pressure tunnels. Instant work evaluates the prospect of two enhancements to lower-pressure tunnel transit: 1) open-entry/exit transit where tailwinds and minor reductions in pressure to increase effective velocities beyond that considered without tailwinds and 2) multimodal capabilities able to seamlessly connect existing railway and highway to low-pressure tunnel sections.

Instant work also identifies that a critical error has been made in past work on where low tunnel pressures were considered necessary to prevent pressure buildup in front of vehicles which would lead to increased drag. Many past works teach toward intake fans at the front of tunnel-transit vehicles to compensate for pressure buildup; however, simulations on the GEFT design identify that upper-surface trailing-section fans more-efficiently alleviate pressure buildup along with providing higher L/D efficiencies than possible with fan intakes at the front of vehicles. For these GEFT, maglev suspension is not needed since aerodynamic lift increases with decreasing drag toward optimal designs. The aerodynamic lift substantially eliminates rolling losses towards achieving efficiencies greater than rail or airliner alternatives.

CONCLUSIONS

Past work on lower-pressure tunnel transit has primarily considered vehicle designs with concepts such as using of intake fans at the front of vehicles to reduce pressure buildup and increase efficiency. This has led to conclusions that low pressures (e.g. 100 Pa) were necessary to achieve efficient highspeed transit in tunnels. GEFT vehicles use induced thrust on frontal surfaces to avoid the high drag from pressure buildup. As a consequence, engineered perpetual tailwinds in tunnels provide a means to achieve higher speeds than highway or railway alternatives. GEFT are able to use existing railway infrastructure and are compatible with multimodal transit over highways and railways, both in and out of tunnels.

This paper's simulations on tubes connecting tunnel entrances to adjacent tunnel exits identifies that recirculation of air from tunnel exit sections to tunnel entrance sections leads to both higher velocities and lower pressures in the main tunnel corridors. Recirculation tubes that increase velocity in tunnels also reduce pressure in a magnitude approximately equal to the change in air's dynamic pressure.

Direct calculation of efficiency is an elusive objective. However, lost work analysis is straight forward and allows meaningful conclusions to be drawn. Tunnel surfaces block significant dissipation of energy in vertical and lateral directions, with the remaining lost work in the form of viscous heat, turbulence, velocity stratification, and pressure gradients at locations including: a) in front of the vehicle, b) behind the vehicle, and c) at tunnel entrances/exits. Recirculation fans in recycle loops are able to be adjusted to substantially eliminate lost work in the form of air velocity entering or exiting tunnel entrances/exits.

Existing tunnel infrastructure can be retrofitted with recirculation loops in a low-risk, high-reward evolution of transportation. In this evolutionary path, vehicle designs emerge as critical to effectively induce thrust, avoid the turbulence of boundary layer separation, and avoid jetwash in lieu of streamlined laminar flow from rear surfaces.

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