247 Person-MPG Terreplane Transit System - Fifth-Scale Demonstration
(An ARPA-E Proposal for $6M in R&D Funding)

ABSTRACT

Normally, a 20% increase in fuel economy for a travel mode would represent a decade-long industry-wide endeavor. Terreplane will provide more than 10X that 20% (200% to 400%) improvement for major transportation markets currently served by air, rail, bus, truck, and car travel modes; ready for private sector to commence commercialization at the end of this 3-year project.

That 200% to 400% improvement possible with passenger transit increases to up to 600% improvement for parcel transit (relative to current air parcel transit) that does not require a high a compartment as passenger transit. That parcel service can be same-day service in many markets.

These improvements are for a system having less than 1/5th the cost ($2M-$4M per mile) of alternatives like high speed rail ($30M per mile). This ARPA-E project is on the development and fifth-scale demonstration of this technology.

Terreplane is based around a glider-type vehicle that: a) pulls itself along a zipline-type guideway using a linear motor stator/chassis, b) is designed to travel with full support of the vehicle's weight by aerodynamic lift and c) is powered by transfer of grid electricity to the vehicle.

Compared to airlines, Terreplane has about: a) 0.57X the specific weight, b) 0.53X the fuel consumption per thrust generated, and c) 0.70X the specific logistics-related burden. Combined, these result in a 0.21X index factor on total energy input. Dividing airlines' 52 passenger-miles per gasoline gallon equivalent (pmpg) by this index factor puts the estimate at 247 pmpg. This value is 4.75X that of airlines (or 375% improvement) and 6.5X that of cars (at 38 pmpg).

Terreplane's pmpg is directly proportional to the Lift:Drag (L:D) ratio of Terreplane vehicles where L:D ratios greater than 14:1 would lead to further increased fuel economy. The study and development of Terreplane's L:D ratios is the first task of this project. There are both factors and design degrees of freedom that suggest L:D ratios greater than 14:1 can be attained.

The second task is the development of a series of fifth-scale battery-powered remote-control prototypes. The third (last technical) task is construction and testing on an eighth-mile test track.

Terreplane's abilities (see web site at terretrans.com) are referred to as the 20% metrics. These include: 1/5th the energy consumption, 1/5th the total transit time, and 1/5th the cost. If these are expressed as indices where higher is better (e.g. 5X, 5X, and 5X), this would represent a 125X cumulative/indexed improvement of the best current alternatives. Not all markets would realize a 125X indexed improvement, but the vast majority would realize a indexed improvement greater than 30X with each of the three individual factors greater than 2X.

This is a topic of great public interest. Hyperloop has stimulated national and international excitement (and headlines) of travel with much greater possibilities than present alternatives, but Hyperloop brings with it a prohibitive high construction/maintenance cost. Terreplane provides all the possibilities of Hyperloop and more; all with a price tag less than 1/5th alternatives like high speed rail.

In addition to the 30X to 125X index of improvement versus alternative modes of transportation, Terreplane has an unprecedented ability to evolve while preserving service in commuter to trans-continental markets. This evolution can include corridors having travel velocities in excess of 500 mph. More details are available at terretrans.com.

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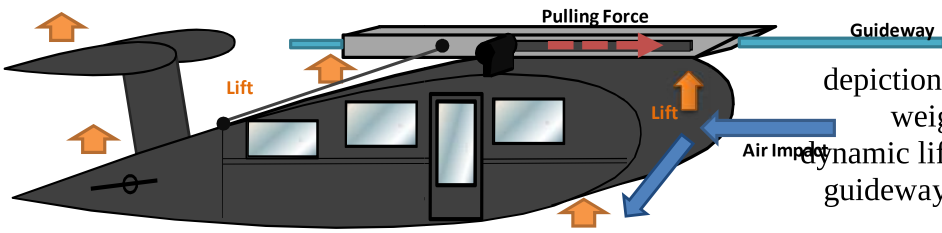
Category: Transportation (Non-Vehicular)
Proposed Funds: Fed: $5.2M/ Cost Share: $0.8M/ Total: $6M
Project Duration: 3 Years

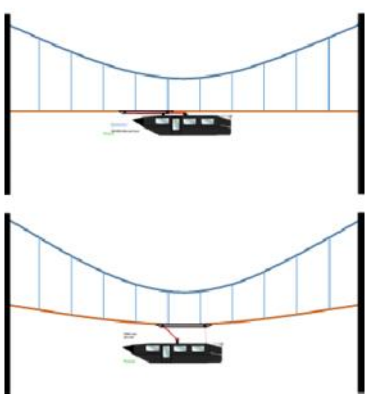
1. CONCEPT SUMMARY

Concept - Terreplane is a glider-type vehicle with a linear motor that pulls itself along a zipline-type guideway. Figure 1 illustrates 1) the vehicle, 2) guideway, and 3) unique performance due to the manner in which the chassis/carriage is connected to the vehicle. Terreplane meets the following FOA objectives: 1) substantial increases in fuel economy and 2) replacement of petroleum as used for jet transit and automobiles with grid electricity with all the advantages associated therewith. The broader impact versus alternative travel modes include: 1/5th the energy consumption, 1/5th the cost, and 1/5th the environmental impact.

Base-Case System - The contents of this Concept Paper are based on an example system defined as follows: a) 2.25" OD suspended wire rope guideways, b) overhead power lines in parallel with the guideways to provide current-collector transfer grid electricity as the power source, c) an inner pair of guideways operating at 200-300 mph, d) an outer pair of guideways operating at 90-120 mph, e) half-mile merge/diverge guidways to/from the 90-120 mph guideway at stations, and f) switch transfer lines between the inner and outer guideways.

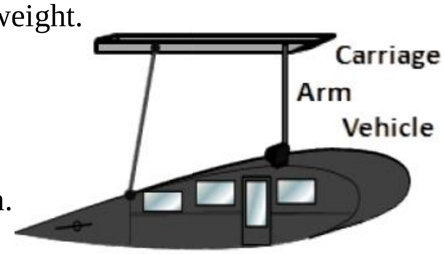


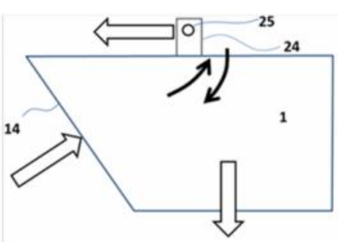
1) Flying vehicle depiction of Terreplane. Vehicle weight is supported by aero-dynamic lift. The only force on the guideway cable is a pulling force.



2) Cable Guideway illustration of suspended zipline-type guideway. The top image is with vehicle in flight with only longitudinal force exerted on guidewway.
The bottom image is of a stalled vehicle. Both the upper support cable and lower propulsion cable combine tensile forces to support stalled vehicle weight.

3) Aerial Tram depiction of Terreplane vehicle at rest. The Vehicle is connected to the Carriage with a Connection Arm.





... (left) a further (simplified) illustration shows the primary forces and torques on a vehicle representation during flight. The pulling force (from carriage) is at the top of the vehicle and is purely longitudinal since it is a point of rotation in line with the propulsion cable. This purely longitudinal force on a cable guideway is critical for stable transit on the cable.

Figure 1. Terreplane.

2. INNOVATION AND IMPACT

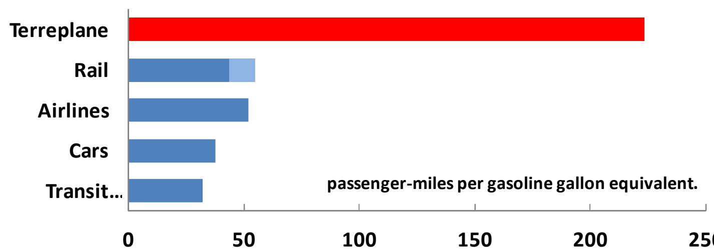


Figure 2. ORNL fuel economy (passenger-miles per GGE) of various travel modes with addition of Terreplane in red.

Terreplane's impact on fuel is depicted by Figure 2. Terreplane's 247 pmpg is basically off-the-scale of the Oak-Ridge Laboratory (ORNL) reported numbers of common transportation modes. For comparison, common modes of car, airlines, and rail range from 38 to 55 pmpg. Equation 1 summarizes how the pmpg was estimated using airline fuel economy as a reference. The overall improvement factor, f_{index}, is estimated as the product of four factors (see Table 1).

$$f_{index} = f_{eff}\, f_{Log}\, f_w\, f_{L:D} \qquad \text{Equation 1}$$

Table 1. Factors, descriptions and confidence intervals.

f_{eff} 1.9 avg (1.7-2.0)	This factor is on efficiency of conversion of fuel to thrust [thrust]/[fuel]/k_{eff} (both in energy/time) where k_{eff} is this ratio for the airline reference. Here, the fuel efficiency of jet aircraft and turboprops are about the same (NRL Report) where the efficiency of the turboprop engine is 20-25% while the efficiency for electrical power generation is taken as 38%. The propeller's efficiency (mechanical to thrust) takes about 3-5% from that 25. Here, 38/20 is 1.9.
f_{Log} 1.43 avg (1.3-1.5)	This factor is on operational logistics and is based on the following diversions from the most-direct path that occur during air travel: a) travel to/from airport, b) flights that use a transfer hub, and c) standby flight patterns in queue for landing. Also included are seats occupied by pilots and flight attendants. The factor takes into account easy access to Terreplane stations and non-stop transit. (f = 1/0.7)
f_{w*} 1.75 avg (1.65 - 1.8)	This factor is on weight per-passenger, that when divided by the L:D ratio yields a factor of desired dimensions. For airlines, the takeoff weight of a jet is 32% fuel, 43% OEW (empty weight), and 25% payload. Grid electricity eliminates the fuel, the OEW is reduced from about 43 to 22 due to: a) no cockpit, b) eliminated wings, and c) substantial reduction in hardware like landing gear and hydraulics.
$f_{[L:D]}$ **1.0**	The airline benchmark for Lift:Drag ratio is 18 for a cruising jet with takeoff and landing at 4.0. The Cessna Cardinal RG II prop performs at 14.2 at near-atmospheric pressure. This factor is $[L:D]_{Terreplane}$ / $[L:D]_{AirlineBenchmark}$.

For these factors, 1.9 X 1.43 X 1.75 = 4.75; a fuel economy 4.75X that of Airlines and 6.5X that of Cars. A cabin height of 1.5' for parcel service versus 6.5' for passenger allows for increase L:D ratios and fuel a fuel economy >7X that of airlines. Other factors to consider are:

- Initial applications can focus on markets able to achieve these improvements.
- The electrical power would be a domestic energy source with an emphasis on renewable or sustainable per national and local priorities.
- Terreplane's flexible operation allows parcel service to occupy empty seat weight.

Impact & The 20% Metrics - This 1/5th the Energy meets Terreplane's 20% metric goal. The 1/5th the Time metric is summarized by Figure 3. The combination of high speed travel and improved accessibility make Terreplane faster than alternatives, even faster than Hyperloop. The 1/5th the Cost metric (summarized by 2018 TRB paper, see terretrans.com) is based on $2M-$4M per mile guideway costs (versus $30M for HSR). In addition, Terreplane will provide an unprecedented ease of routing (above streets, trees, rivers, wetlands, railways).

Over a dozen patents are pending on this technology; these allow the technology to be published. The Terretrans.com site provides a summary of summaries, documents, and the latest findings on Terreplane. Terretrans.com provides a site for international public forums to review, adopt, and advance this technology.

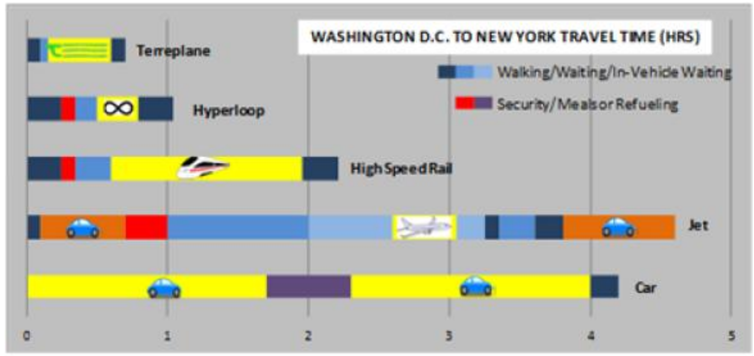


Figure 3. Estimate of total door-to-door transit times for DC to NY corridor. Terreplane speed is 450 mph; which when adjusted to 250 mph brings the travel time to about 1 hour.

3. PROPOSED WORK

Goal - Of the four Equation 1 factors, the greatest unknown is associated with the L:D factor, $\mathbf{f_{[L:D]}}$. The goal of this project is to definitively lock in what is possible for wingless tethered glider vehicles. The project will include test track demonstrations of fifth-scale vehicles.

Deliverables - Deliverables will be: a) L:D performance curves for substantially wingless vehicles as optimized for use with the Terreplane System and b) a fifth-scale demonstration of the vehicle and guideway on an eighth-mile test track.

Alternatives - The technology is divided into three categories for consideration of alternatives:

- **Guideway -** Terreplane's inexpensive guideway is based on large segments (e.g. half-mile long) of wire rope (or flexible tubing) able to be released/strung from reels as a suspended guideway between 0.4-mile-spaced towers. This infrastructure can be installed for $2M to $4M per mile. No alternative comes close to these low costs.
- **Linear Induction Motor -** The open-sided coil short stator technology is well under way to being reduced to practice. No alternative comes close (see terretrans.com).
- **Vehicles -** If the goal is to have a L:D ratio of at least 14:1; the alternative to an airfoil-shaped vehicle is a vehicle with at least some wings.

Risk Analysis - The following summarize the risk of the L:D research in terms of comparison to established aircraft performance:

- **Neutral -** Operating at 1.0 atm versus 0.2 atm (40,000 ft elevation) is not a disadvantage for moderate velocities (note that gliders have highest L:D ratios and operate at 1 atm.).
- **Advantages -** a) No propeller or protruding jet engine which increase drag, b) stability over a range of pitch angles is not necessary (as is for aircraft), and c) spoiler-type wings and air ducts on vehicle are allowed.
- **Disadvantages -** a) A low aspect ratio is needed and b) constraint on use of laterally extending wing (e.g. less than 1 ft).

The backup plan to address this risk includes: a) use of short laterally-extending wings and b) accepting a lower L:D ratio resulting in only a 2X or 3X improvement in fuel economy.

Background - Most of the more-developed theories in aerodynamics serve the primary purpose of either a) providing convenient equation formats for teaching and quick calculations or b) supporting known trends of aircraft that have been well studied. The topic of tethered, wingless, glider vehicles has not been well-studied; nor can performance be usefully characterized by equations such as Bernoulli's equation.

The useful theory is the *momentum theory of lift* (Newton's third law of motion). More-specifically, in a control volume taken around a horizontally-flying vehicle (where the net momentum of air entering/leaving the control volume is zero), the lift force on the vehicle is the volume integral of $-\rho v^2$ where ρ is the density of air and v is air's vertical velocity.

From a practical perspective, this theory dictates that the vehicle (and/or wings) needs to pull/push air downward with minimal generation of turbulence. Specifically, the vehicle induces a higher velocity in the air going downward than the upward velocity of air around the vehicle which replaces the upper air that was pulled/pushed downward. This practical interpretation can be translated into vehicle shapes/surfaces that push/pull air rapidly downwards while minimizing: a) turbulence, b)pushing of air upward by vehicle surfaces, and c) the vortexing of air from high pressure surfaces below the vehicle to low pressure surfaces above the vehicle.

Work Plan - The following three tasks comprise the work plan:

1. **L:D Wind Tunnel Studies -** Vehicle designs will be computer generated and 3D printed. L:D ratios of these designs will be determined in a wind tunnel experiments to meet the goal of L:D ratios greater than 14:1 without use of wings.
2. **Vehicle Prototype Fabrication -** A self-contained remote-controlled fifth-scale vehicle will be fabricated with battery power and controls on the vehicle. The vehicle will include a linear motor chassis capable of engaging a test track with a half-inch diameter guideway. Risk can be mitigated by reducing weight by reducing the size of the battery pack.
3. **Test Track Construction and Testing** - An eighth-mile test track will be constructed comprised of four posts/towers at the corners of a rectangular section. Support cables will be strung from this towers below which a horizontal guideway will be hung for testing. The primary method of mitigating the risk here is the low cost of footprint of four posts; a number of cable technologies (including suspended posts) can be used to use relatively inexpensive cables to provide the desired support. A base case guideway is half-inch copper pipe (reactive plate of linear motor) with a steel cable (tensile strength) inside the pipe.

A base case system does not rely on development of new technology; however, ample opportunities (and incentive) exist to develop and implement new technology. Topics of new technology include: a) improved vehicle shapes/designs and b) improved guideway designs. The test track will allow testing of these new vehicle designs and guideway designs.

Techno-Economical Challenges - The challenge is to demonstrate that L:D ratios greater than 14 are possible for tethered wingless vehicles.

Project Costs - The total project cost is estimated at $6 million, $2 million for each of three consecutive years. Federal funds requested are $5.2 million (no cost share required year 1).

4. TEAM

Galen J. Suppes, PhD, PE:

Background: Chief Scientific Officer, **Homeland Technologies**, LLC. Chemical Engineer, Fellow AIChE.

Expertise: applied physics, thermoset polymers, batteries (energy storage), prototype fabrication (various methods), and experimental studies.

Responsibilities: project management, experimental studies, system fabrication.

Thomas G. Engel, PhD:

Background: Consultant, Electrical Engineer.

Expertise: Applied magnetic theory, machining and fabrication, circuit theory, and system control.

Responsibilities: Design of linear motor, control unit, and experimental systems.

TBD - Additional collaboration to be determined.