**Calculations on a 250 Person-mpg Transit System**

by Galen J. Suppes, PhD, PE
Homeland Technologies, LLC
Columbia, MO  65203

## Abstract and Significance

A new mode of transportation using tethered gliders on a zipline guideway is able to attain fuel economies estimated at 5X that of intercity rail and airlines, which are reported as the most efficient current modes of transit. The primary factors leading to this high fuel economy reside in directly powering tethered-glider vehicles with grid electricity. This paper presents these fuel economy estimates based on documented airline fuel economies and a conversion equation.

## Introduction and Background

Since the commercialization of air transit, transportation options have primarily benefited from incremental improvements in air, vehicular, rail, and water modes of transit. In recent years, Hyperloop has emerged as a more-substantive change with significantly reduced transit times. Despite high implementation costs of over $40M per mile, there has been great public interest.

Clearly, society would welcome an alternative new mode of transportation that would supplement advantages in reduce total transit times, like Hyperloop, with reduced costs .

Terreplane (see Figure 1)[1] is an alternative mode of transportation based on glider-type vehicles using zipline-type guideways. At travel velocities greater than 100 mph, aerodynamic lift on the fuselage and short wings support the vehicle weight and allow for an inexpensive 1.5-inch to 2.25-inch diameter zipline infrastructure to enable transit faster than the fastest high speed rail.

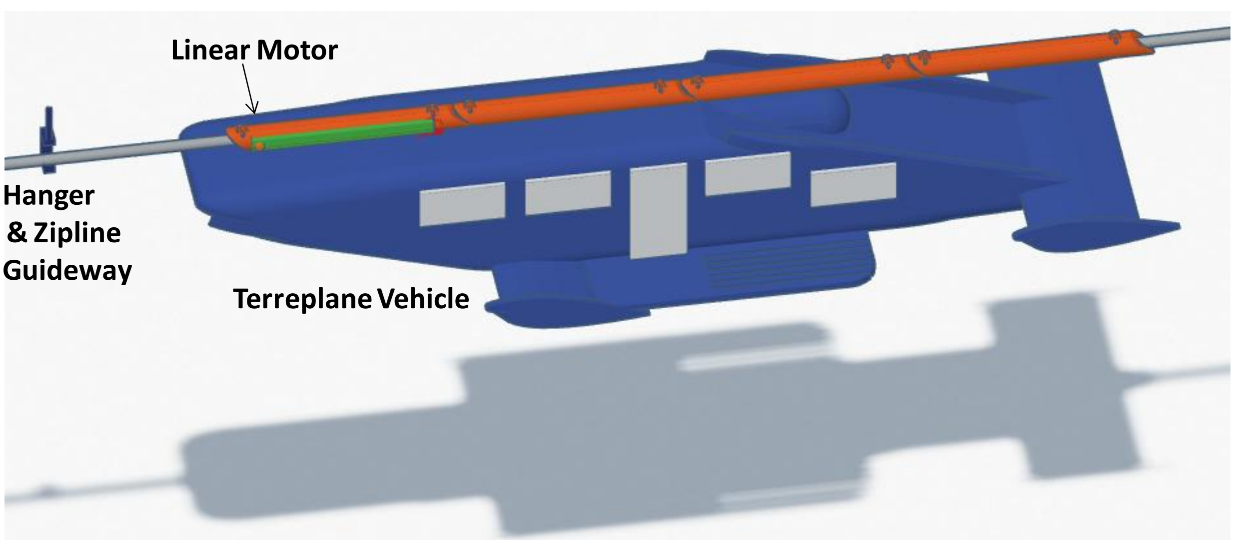


**Figure 1.** Illustration of prototype Terreplane vehicle attached to an overhead linear induction motor (stator) that pulls the vehicle along a wire rope (armature) zipline-type guideway.

A number of technologies emerged to support this approach to transit[2-4], including:

- linear motor propulsion based on an open-sided coil stator and the guideway as the armature,
- cable connectors/hangers that keep most of the cable diameter constant and unobstructed,
- suspended-towers that suppress/cancel guideway tension, and
- a vehicle-controlled high-speed switching method.

A 2018 Transportation Research Board (TRB) paper[5, 6] documented calculations on tension forces, guidway sag, vehicle lead times, and support spacing toward the goal of estimating the cost of the Terreplane guideway infrastructure. The base case infrastructure was comprised of towers spaced at 0.2 mile increments in a suspension guideway configuration, which is basically a suspension bridge where 1.5-inch diameter wire rope guideways are suspended rather than concrete slabs. Two cost estimate methods were used with both estimating costs at about $2M per mile in open country.

Even with a 100% contingency cost totaling $4M per mile, Terreplane costs less than 1/5th the cost of high speed rail's $30M per mile. The tower footprint is also a small fraction of highway and railway footprints on the environment. Routing can be above streets, trees, highways, railways, wetlands, rivers, mountain hollows and a host of possible obstacles. Easy routing, transit speeds of 100-450 mph, and inexpensive guideways enable reduced travel times.

Terreplane's stated goal of 1/5th the cost, 1/5th the time, and 1/5th the environmental footprint were largely substantiated, but energy costs have not been addressed adequately. This paper estimates the fuel economy of Terreplane in the consecutive steps of a) defining the constraints of the system for which energy costs are estimated, b) defining an equation that allows documented fuel economy for airlines to be transformed to an estimate of Terreplane's fuel economy, and c) estimating the equation's conversion factors.

## Analysis

**Constraints and Equations -** Constraints and their rationale, as selected for this fuel economy estimate, are as follows:

- 250 mph maximum speed as consistent with proven overhead catenary transfer of grid power,
- a neglecting of transit to/from full aerodynamic when starting/ending transit,
- near-zero battery, fuel, and engine weight on vehicle, and
- rideshare service that maximizes non-stop service close to origin and destination.

Stations spaced at 1.5 mile intervals in high-demand areas, high-speed vehicle-controlled switching, and cell-phone apps similar to those used for Uber would make performance within these constraints possible. The same guideways would be used for service from commuter transit to inter-city.

Equation 1 is a conversion factor equation to convert documented airline [average] fuel economy to a Terreplane fuel economy,

$$\frac{Terreplane\ Fuel\ Economy}{Airline\ Fuel\ Economy} = \boldsymbol{f_{eff} f_{Log} f_w f_{L:D}} \qquad \text{Equation 1}$$

where:

***f*** is the ratio of Terreplane's value to the average value of an airline,

***eff*** is efficiency for converting the fuel's energy to vehicle thrust (Joules thrust per Joule fuel).

***Log*** is a general logistics term accounting for the weighted actual miles traveled divided by geographical distance in miles,

***w*** is the average total payload weight divided by the average loaded vehicle weight, and

***L:D*** is the lift-to-drag ratio of the vehicle (Newtons lift per Newton drag).

The terms of Equation 1 are specific to transportation based on vehicles using travel velocity to provide full aerodynamic lift. The Equation 1 "*Airline Fuel Economy*" is 51 passenger-miles per gasoline gallon equivalent.[7] Values of the remaining factors are described and estimated by Table 1.

| **Table 1.** Factor descriptions, estimates, and confidence intervals. | |
|---|---|
| $\boldsymbol{f_{eff}}$<br><br>1.9 avg<br>(1.7-2.0) | Based on an NAL report, the fuel efficiency of jet aircraft and turboprops are about the same.[8] The efficiency of a turboprop gasoline engines are 20-25% less 3%-5% for conversion of rotational energy to thrust (prop inefficiencies). The efficiency for electrical power generation was taken as 38%, including transmission losses. Here, 38/20 is 1.9. |
| $\boldsymbol{f_{Log}}$<br><br>1.43 avg<br>(1.3-1.5) | This cumulative logistical factor accounts for actual miles traveled being greater than the geographical distance of origin and ultimate destination. It includes: a) travel to/from airport including impact of lower fuel economy of car transit, b) flights that use a transfer hub, and c) standby flight patterns in queue for landing. Terreplane is assumed to be used only if the route is more direct. A rough estimate of this factor is 1/0.7. |
| $\boldsymbol{f_{w*}}$<br><br>1.85 avg<br>(1.75 -<br>1.95) | For airlines, the takeoff weight of a jet is 32% fuel, 43% OEW (operating empty weight), and 25% payload.[9] Grid electricity eliminates the fuel, the OEW is reduced from about 43 to 22 due to: a) no cockpit, b) reduced/eliminated wings, and c) substantial reduction in hardware like landing gear and hydraulics. This results in a factor of (22+25)/(16+43+25) = 1.787. Autonomous Terreplane service would be without pilots or flight attendants, but includes some batteries. The resulting values is about 1.85. |
| $\boldsymbol{f_{[L:D]}}$<br><br>$\frac{[L:D]_{Ter}}{14}$ | The airline benchmark for Lift:Drag ratio is set at 14. The Cessna Cardinal RG II prop performs at 14.2 at near-atmospheric pressure; this 14.2 reference point does not account for inefficiencies of landing and takeoff where L:D ratios are typically around 4.0. |

For these factors, 1.9 X 1.43 X 1.55 = 5. Hence, Equation 1 can be simplified to that of Equation 2.

$$\frac{Terreplane\ Fuel\ Economy}{Airline\ Fuel\ Economy} = 5.0\,\frac{[L:D]_{Terreplane}}{14} \qquad \text{Equation 2}$$

## Discussion

**Tethered-Glider Fuel Economy -** The 5.0 cumulative factor term of Equation 2 indicates that Terreplane can attain fuel economies five (5.0) times those of the best alternatives, provided Terreplane can attain ***L:D*** ratios of 14:1 or greater. While this value was estimated based on comparison to an airline, the value is applicable to short commuter routes where the margin between Terreplane and alternatives is even greater.

The potential for major improvement exists, and that potential is firmly rooted in the lighter-weight Terreplane vehicles and use of grid power that is generated at higher thermal efficiency (than internal combustion engines). Also, the grid power can be produced from renewable resources as compared to aviation fuels that are essentially solely sourced from petroleum.

The highest known L:D ratios are for vehicles flying at atmospheric pressure are near 70 for gliders; these values are at relatively low altitudes. It is not true that the low pressures of high altitudes not being necessary for good fuel economy. Example L:D ratios are 15 for a hang glider, 14.2for Cessna Cardinal RG II prop airplane, 21 for the B2 bomber, 70 for the Eta glider, and 85 for a simple airfoil.[10]

A list of advantages and disadvantages of Terreplane toward attaining or surpassing an ***L:D*** of 14:1 includes:

**<u>Advantages</u>**

- As a tethered vehicle, some aerodynamic features difficult to control in free flight are easy to control.
- A lack of engine protrusion(s) and related higher velocity sheer.
- Ability to operate continuously at an optimal pitch for optimal ***L:D***.
- Several design degrees of freedom, including: increasing wingspan, increasing longitudinal length, use of walls to control pressure pockets, decreasing median fuselage height, and addition of more wings/spoilers.

**<u>Disadvantages:</u>**

- Short to zero wingspan with low aspect ratio.

In view of advantages associated with increasing vehicle wingspan and improved options on airfoil design for tethered gliders, Terreplane vehicle can attain and surpass a L:D or 14:1.[11] The primary issue is one of balancing the increase in guideway costs versus decrease in fuel costs as the wingspan increases; guidway costs increase because the width[1] of each guidway corridor must be slightly wider than the wingspan.

An example wing structure for use with Terrplane is that of the Flyox Mark II where a 35-foot wingspan support 8,800 pounds (250 pounds per ft)[12]. For an 8-passenger Terreplane vehicle having a loaded weight of 3,200 pounds, a 13-foot wingspan would be required. This 13 feet could be readily reduced with lift-generating vehicle surfaces and a rear wing/spoiler.

The optimal wingspan is between 5 (no wings) and 13 feet. The Figure 1 depiction is for a 5 ft wide vehicle with pairs of 2.5 ft wings extending on both sides (total of 10 ft). The vehicle also uses a diffuser between wings which doubles as a loading platform. The Figure 1 depiction is

---

[1] It is possible to stack guideways as an alternative to widening guideways.

the first prototype design specification for the Terreplane vehicle.

Application of the 5.0 factor to the Airlines fuel economy of 51 results in a fuel economy of 255 passenger-miles per gallon.  Figure 2 compares this value to those of other modes of transportation.  This value is directly comparable to the vales of cars and transit buses as may be used for commuter service since the result is essentially a "state property" comparable to thermodynamic efficiencies.

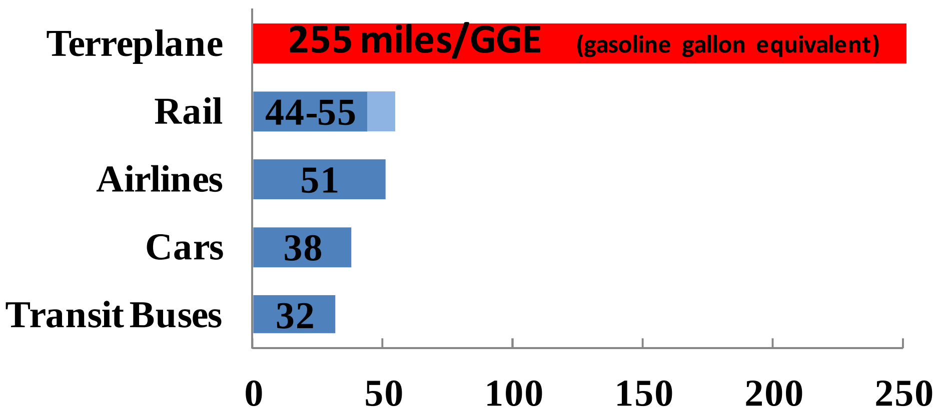


**Figure 1.**  ORNL fuel economy (passenger-miles per GGE) of various travel modes with addition of Terreplane in red.

A typical passenger Terreplane vehicle would have dimensions of 6.5 X 10 X 30 (Height X Width X Length, in feet).  A parcel vehicle could operate at a height of 2 to 2.5 ft with a significant increase in L:D since an airfoil's L:D (vehicle as an airfoil) is a strong function of height (thickness) to length (cord) ratio.  Parcel service vehicles could have L:D ratios in excess of 7.5 X the best available alternative or high-speed service.

**Initial Applications -** The best initial applications for Terreplane would complement current transportation infrastructure.

Bridges across rivers are particularly attractive due to the high cost of bridges (about $400 million per mile) and the low cost of Terreplane.  For bridges that tie into existing transit on both sides of a river/bay, the initial application can save hundreds of millions of dollars versus building a bridge to relieve traffic.

One of the highest-impact applications of Terreplane is the enabling of "superports".  An example superport is a NYNY-DC network connecting 7+ airports, 4+ railway stations, and 10+ city center locations by what functionally resembles a horizontal elevator.  On-demand service between any of the 600+ aircraft/train gates would have a median travel time of less than 20 minutes.

These superports can break current transportation paradigms, including:

1. Substantially improved availability of non-stop air service to/from superports as compared to the

individual airports.
2. A new standard of "home departure to aircraft takeoff" times of less than 40 minutes as opposed to current times often more than 2 hours.
3. Same-day shopping/parcel delivery within a superport area and with neighboring superports.
4. Easy resolution of delayed takeoffs and landings due to the large number of airport runways and gates in the superport network.

Superport networks would initially extend include more-comprehensive commuter traffic service. Ultimately, neighboring superports would be connected by guideways.

## Conclusions

Land-based, tethered-glider passenger aircraft are able to achieve efficiencies considerably greater than powered aircraft when propulsion is powered by grid electricity. This benefit is a direct result of reducing vehicle/fuel weight and increasing efficiency of electrical power production as compared to internal combustion engines. In a transportation environment where the most-common modes of transportation have a relatively narrow range of fuel economies from 38 to 55 passenger-miles / GGE; these modifications provide an alternative with a fuel economy in excess of 150 passenger miles / GGE.

The Terreplane Transportation System provides a means to achieve tethered glider service for both passenger and parcel service through use of linear motors pulling the glider vehicles along a zipline-type guideway. Logistical advantages associated with the easy-to-route and inexpensive guideway system, potentially, further extend the fuel economy to in excess of 250 passenger-miles/GGE.

## References

1. Suppes, G.J. *Terreplane Transportation System*. 2018; Available from: http://www.terretrans.com/.
2. Suppes, G.J., *Terreplane transportation system, Patent Application US/20160355194*. 2016.
3. Suppes, G.J., *Glider Guideway System, 15808966*. May of 2018 publication, November of 2017 filing.
4. Suppes, G.J., *Glider Guideway System, PCT/US17/61003*. November, 2017.
5. Suppes, G.J. *(poster) Reimagining Transportation - Base Case Calculations on Flying Aerial Tram System*. in *Transportation Research Board Annual Meeting*. 2018. Washington, D.C.
6. Suppes, G.J., *Reimagining Transportation - Base Case Calculations on Flying Aerial Tram System.*, in *Transportation Research Board Annual Meeting*. 2018: Washington, D.C.
7. Davis, S.C., S.E. Williams, and R.G. Boundy, *Transportation Energy Data Book: Edition 35*, O.R.N. Laboratory, Editor. 2016.
8. Peeters, P.M., J. Middel, and A. Hoolhorst, *Fuel efficiency for commercial aircraft, An overview of historical and future trends.*, N.A.L. NLR, Editor. 2005: The Netherlands.
9. Alshayef, M. *Schematic of relative aircraft takeoff weight components*. 2014; Available from: https://commons.wikimedia.org/wiki/File:Takeoff_weight_diagram.svg.
10. Abbott, I.H. and A.E. von Doenhoff, *Theory of Wing Sections*. 2017, New York: Dover. 693.
11. Suppes, G.J. *Chemical Engineering Insight On Theories of Flight (paper in review for per-*

*refereed publication)*. 2018; Available from: http://www.terretrans.com/flight-theory-paper.html.

12. Macovei, D., *Utility drone built by Singular Aircraft to start US flight tests.* Platform Unmanned Cargo Aircraft, 2018. **February 19**.