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ON THE ECONOMIC IMPACTS OF TRANSPORTATION INNOVATIONS: A COMPREHENSIVE APPLICATION TO QUANTIFYING THE IMPACTS OF AN HYPERLOOP TECHNOLOGY

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ABSTRACT

The purpose of this paper is to quantify the economic impacts associated with an investment in transportation systems. Here, we apply the methodology to projected comprehensive economic impacts of an Hyperloop route. The methodology is a low-frequency economic growth model that includes cumulative gains in real GDP, cost savings and the greenhouse gas savings of the proposed Hyperloop technology. To calibrate the model, we consider a route spanning from Texas to Chicago and covering 1,575 miles across the proposed hyperloop system. The infrastructure investment is obtained from construction cost estimates presented in previous feasibility studies. Our contribution is to present a simple general equilibrium approach to quantifying transportation economic impacts. To our knowledge, our is the first quantitative assessment of the Hyperloop technology. We include an analysis of the public finance aspects of the route, thus adding an answer to the question regarding the national merits of such an investment project. Our findings suggest that for returns comparable to the interstate highway system, the project could be paid for out of the stream of future tax revenues. There are additional gains through lower fares and travel times. Lastly, the environmental gains, especially from reduced air travel, are quantitatively significant.

Contribution/Originality: In this paper, our main contribution is to carefully quantify the cost and the economic impacts associated with an Hyperloop system. The quantitative analysis is conducted at the macroeconomic level with calibration of the costs and additional income and tax revenues associated with such a transportation investment.

1. INTRODUCTION

Transportation plays a critical role in an economy. How inputs and consumer goods are transported from one location to another at the lowest cost depends on the technology available and the infrastructure upon which that technology operates. Policymakers depend on carefully measuring the costs and benefits of public infrastructure investment. Researchers have made significant contributions toward answering the merits of different infrastructure investments. Aschauer (1989), for example, calculated the returns to the interstate highway system. Though not exhaustive, the list of additional contributors include Finn (1993); Holtz-Eakin (1994); Nadiri and Theofanis (1996a); and Pereira and Jorge (2013).[1]

[1] For a more complete list of references, see Pereira and Jorge (2013).

Hyperloop is a technology that uses a near-vacuum condition combined with either air cushion or magnetic levitation to further reduce friction. With air resistance reduced, the Hyperloop Genesis paper argued that linear induction motors could propel either a passenger or freight capsule within an enclosed tube to theoretically reach speeds as high as 760 miles per hour (see Musk (2013)).

The purpose of this paper is to quantify the macroeconomic impacts that an investment in a Hyperloop route connecting cities from Texas to Illinois. Because we cannot assess the observed returns to this transportation system, we use a calibrated, general equilibrium model to assess the impacts. As such, our numerical results amount to projections. The general equilibrium methodology is a useful means of making projections that can be modified to incorporate externalities, multiple production sectors, heterogeneous consumers. The chief advantage of the approach developed here is that it is a fully dynamic system so that economic impacts are measured over time.[2] For our calibration experiments, we consider a Midwest Hyperloop route spanning from Chicago to Texas, with both San Antonio and Houston as terminal points. The proposed route spans 1,575 miles with major stops in Dallas, Oklahoma City, Wichita, Kansas City, and St. Louis. It is projected that the route would cost $63 billion to construct two parallel transport tubes for the full 1,575 miles.

The investment affects three measures of aggregate economic activity. First, the investment yields a return that is measured as the difference between the control and treatment path of aggregate income. The intuition is straightforward: with a larger quantity of productive capital, real GDP expands. In a dynamic setting, the difference between what the economy sans Hyperloop and the economy with Hyperloop captures the aggregate economic impact. Second, we compute the aggregate benefits in reduced travel time. With data on both air and auto travel times, projected fares are much lower than air travel and automobile operations. In addition, there are projected travel-time savings. We consider both fare savings and travel-time savings. Third, solar energy is the proposed source powering Hyperloop travel. As such, we compute the aggregate savings in reduced greenhouse gases associated with reduced air and auto travel.

Our findings are easily summarized. First, the aggregate economic impact depends critically in the calibrated return to the investment, If a Hyperloop investment yields the historical average return, the cumulative, discounted gain in additional real GDP over s 25-year period is $205.9 billion for a 10-year investment totaling $63 billion. If, however, the return on the Hyperloop investment is equal to the historical average return on the interstate highway system, which is 34 percent, the cumulative, discounted gain in additional real GDP increases to $933.9 billion over 25 years.[3] In the high-return experiment, the cumulative, discounted gain in federal tax receipts will pay for the infrastructure investment in 23 years. Second, travel cost savings come in two ways. Because it takes 10 years to complete the infrastructure project, we consider the first 15 years of operation. The projected cumulative, discounted sum of fare savings is $365 million. With reduced projected travel times, our projections indicate that annual aggregate travel-time savings are $116.9 million. Third, with solar panels used to collect the energy needed to propel the Hyperloop pods, there are significant reductions in greenhouse gases produced by air travel and autos. Our results indicate that the annual cumulative, discounted savings from reduced air and auto travel is equal to $25.8 million.

Our results are clearly very preliminary. There are significant engineering and design issues that still need to be worked out. Our read is that the existing literature is very microeconomic focused; the natural first step is to determine exactly how the technology works and what the construction costs are. We take as given the costs and speeds put forward in the existing literature and seek to contribute an understanding of the macroeconomic impacts.

[2] Ireland (1994) used a similar general equilibrium to project the existence of a dynamic Laffer curve with respect to income tax rates.

[3] The return to the interstate highway system is found in Nadiri and Mamuneas (1996b). In additional, Fernald (1999) provides estimates of the links between public capital expenditures and productivity.

These assumptions are likely to be modified as additional engineering studies are conducted.[4] However, by doing so in a fully dynamic economic setting, we provide a structure that can be easily updated as the additional data on this transportation system are discovered.

Thus, there is a clear sequence of research questions that need to be addressed to rigorously determine how the Hyperloop system would serve the United States economy. Based on available projections, this paper indicates that the macroeconomic impacts are substantial. Conducting the necessary research to obtain better microeconomic data would supply better inputs for a future analysis, but the general gains from the investment in Hyperloop track infrastructure remain quite promising.

2. AGGREGATE ECONOMIC IMPACT

In this section, we specify the low-frequency model economy used to quantify the projected economic impact that an investment in a hyperloop route would have on the United States' economy. The economic impact is measured as the difference between a projected future path for an economy with a particular infrastructure investment—the treatment—and the projected future path for the same economy assuming no such treatment is applied, otherwise known as the control. The structural model economy is the Ak model. We calibrate this model to fit the historical growth rate of real GDP.[5] Rebelo (1991) and McGrattan (1998) provide theoretical basis for using the Ak model for such numerical analysis.

We assume that the representative household is infinitely lived and maximizes welfare with a composite consumption good. Formally, let:

$$\sum_{t=0}^{\infty} \beta^t \frac{c_t^{1-\sigma}}{1-\sigma} \qquad \text{(P1)}$$

$$s.t. \quad y_t = c_t + x_t$$

Where β is the subjective time rate of preference, c_t is the composite consumption good, k_t is the aggregate capital stock, y_t is disposable income and x_t is savings. Here, we assume the momentary utility is constant elasticity of substitution. We assume $0 < \tau_t < 1$ is the income tax rate. Each household has access to a production technology that converts units of capital to units of the final consumption good. Formally, $Y_t = Ak_t$. By construction, it follows that $y_t = (1-\tau_t)Y_t$. We assume the capital stock has a law of motion: $k_{t+1} = (1-\delta)k_t + x_t$ with $0 < \delta < 1$ is the capital depreciation rate.

For a balanced-growth path, the solution to (P1) is:

[4] For example, a viable Hyperloop system still needs to address security concerns since the tubes are required to maintain very low pressures. In addition, work on resiliency to natural disasters as well as prevention of electrical fires need to be demonstrated in a practical setting. In addition, further tests on passenger comfort are required since there are significant forces at work with elevation changes and starting and stopping. See Taylor, David, and Lawrence (2016) for a review of some of the most critical engineering challenges facing the Hyperloop system.

[5] We focus on the growth rate as the focal point because we are interested in generational, or low-frequency, measures of the economic impact. As such, business cycle fluctuations are omitted from consideration along the two projected economic paths.

$$\frac{Y_{t+1}}{Y_t} = g = \left(\beta R_t\right)^{1/\sigma} \quad (1)$$

Note that $R_t = \left(1 - \tau_t\right)A + 1 - \delta$. Equation 1 presents the equilibrium growth rate for the model economy. It describes the endogenous growth rate as a product of the subjective time rate of preferences and the equilibrium gross real return on physical and human capital. Throughout out numerical analysis, we assume the tax rate is constant.

2.1. Control and Treatment Paths

We begin by constructing the projected control path for the U.S. economy. The calibration begins with the historical average annual growth rate for United States' real GDP data. For the period 1990-2020, real GDP increased at a 2.27 percent average annual rate. With $g = 0.0227$ and evaluated at $t = 0$, the control path for real GDP is constructed as follows:

$$GDP_t^C = \left(1 + g\right)^t Y_0 \quad (2)$$

Equation 2 describes the equilibrium path for future real GDP when the economy is calibrated at the control settings.

Here, the treatment path is constructed by considering two possible changes. Case I considers the change in investment spending such that $k_t^T = k_t^C + \Delta k_t$. The infrastructure investment results in $\Delta k_t = \omega$ for $t = 0,1,2,\ldots J$ where J is the integer that represents the number of periods in which infrastructure investment is implemented. From the production technology, treatment real GDP is $Y_t^T = Ak_t^T$. Case II allows for the infrastructure to affect the marginal productivity of capital. Formally, let $Y_t^T = A'k_t^T$ where $A' > A$ captures differences in the increase in the return to the particular infrastructure investment. For the purposes of our numerical analysis, we assume that there is a time-to-build feature; specifically that the productivity gain is realized only after the infrastructure investment is complete.

For both cases, the economic impact is measured as the cumulative discounted sum of the differences in the treatment level and control level of real GDP. Formally,

$$\sum_{t=0}^{N} \beta^t \left(Y_t^T - Y_t^C\right) \quad (3)$$

Equation 3 is central to the economic impact analysis. Specifically, we measure the economic impact as the difference between the treatment path of future real GDP and the control path of future real GDP. With this setup we can quantify the economic impacts over N periods.

2.2. Calibration

The numerical analysis considers a proposed Hyperloop network that includes four of the nation's ten largest cities: Houston, Chicago, Dallas, and San Antonio. The proposed route has a segment running from San Antonio to Kansas City, following the Interstate 35 corridor. Next, from Kansas City, the proposed route parallels Interstate 70 to St. Louis and then travels along Interstate 55 to Chicago. In addition, the proposed route includes a spur that follows Interstate 45 between Houston and Dallas. The total distance covered by this proposed route is 1,575 miles.

With infrastructure distance, we need construction costs to compute the size of the investment needed to complete the project. Taylor et al. (2016) provides two measures of the construction costs. The first is a restatement of the construction costs put forward in the Alpha paper written by Elon Musk. The construction for the Los Angeles-to-San Francisco route would be $6 billion. At roughly 350 miles, the construction costs were estimated to be roughly $17 million per mile. The second comes from Hyperloop Technologies with estimates ranging from $25 million to $27 million per mile, excluding the cost of land acquisition. In addition, a feasibility study performed by Black and Veatch estimates a cost between $30 million and $40 million per mile, including right-of-way, for construction of the route between St. Louis and Kansas City.[6] In all cases, two parallel tubes are assumed, i.e., a dedicated tube is provided in each direction of travel.

Taylor et al. (2016) provide the most detailed breakdown of Hyperloop capital costs, including right-of-way along Interstate 5 for a Los Angeles-to-San Francisco route. In Table 11, they compute a projected capital cost equal to $5.4 billion.[7] Based on the cost estimates presented by Taylor et al. (2016), the construction costs would be $15.4 million per mile. In all cases, construction of Hyperloop segments in urban areas will be even more costly, as more expensive tunneled sections will be needed, along with additional parallel tubes for acceleration/deceleration sections and high-speed bypass segments. The cost of portals, or Hyperloop stations, can be considerable and will add to the overall infrastructure costs.

Thus, the cost estimates vary widely. Without completing the next step, the projections are challenging. And the next step is to fill-in the basic research needed to understand the actual construction costs for a safe, efficient Hyperloop system across a given geographical area, and with consideration of the urban areas where tubes and portals will be routed and placed. That said, we use the cost estimate of $40 million per mile to cover the investment infrastructure associated with our proposed route, including the cost of portal (stations) located in major cities along the route. At this cost estimate, the total infrastructure investment to cover the 1,575 miles would be $63 billion. At $15.4 million per mile—the Taylor et al. (2016), estimated construction cost—the total infrastructure investment would be $24.26 billion.

For parameters in the model economy, we use values from historical annual averages and standard values used in economic research. Table 1 reports the parameters used to construct the treatment path for real GDP. For unobserved parameters, like the productivity term, we use observed measures of growth (g), the tax rate (τ), the discount factor (β), and the elasticity of intertemporal substitution (σ) to derive the solution.[8] For Case II, we compute a weighted sum of the returns to all other capital and the return to this infrastructure investment to compute a new value of gross return to capital (R). It is straightforward to compute the new values of A' and g' consistent with the return on the infrastructure investment. Nadiri and Mamuneas (1996b) report the return to non-local highway investment between 1950 and 1989 was 34 precent. We use this value as the return to the Hyperloop investment after the infrastructure structure is complete. Hence, the values A' increases in year 11 after the investment begins.

[6] See Black and Veatch (2019).

[7] The breakdown of the construction material is 1) tube construction; 2) pylon construction; 3) tunnel construction; 4) propulsion; 5) solar panels and batteries; 6) station and vacuum pumps; and 7) permits and land. Note that the construction costs do not include operating and maintenance cost associated with the hyperloop system. These average variable costs are critical to determining the economic viability a proposed hyperloop system since the shut-down condition is that the marginal revenue per passenger mile is not less than then average variable cost per passenger mile for the project to make sense.

[8] We calibrate an average annual tax rate using federal income tax collections from the Economic Report of the President and divide by nominal GDP. This is a conservative estimate. Barro and Chaipat (1986) report average marginal income tax rates equal to 27 percent in 1983.

Table 1. Parameter values for the calibrated United States model economy.

Parameter	Value
g (computed)	1.0227
β	0.96
τ	0.1959
A	0.22439
δ	0.1
σ	1.5

Table 2 reports the results of the investment for Case I and Case II. In each case, we report the cumulative discounted gains in real GDP, the cumulative discounted gains in real federal tax collections, and the cumulative employment-years gains using the median annual wage for $N = 25$. (Note the median annual salary in the United States in 2019 was $63,688.) In addition, we report a measure of the federal breakeven level for the infrastructure investment. In other words, how many would it take for the cumulated discounted sum of real federal tax collections be no less than the cumulative discounted sum of the infrastructure investment costs.

Table 2. Projected economic impacts from the infrastructure investment.

Case	$\sum \beta^t \left(Y_t^T - Y_t^C\right)$	$\sum \beta^t \Delta T_t$	Cumulative employment-years	Breakeven number of years
I	$205.9	$35.0	3,233,179	43
II	$603.4	$102.57	9,473,946	23

Case I shows a cumulative, discounted gain in real GDP equal to $205.9 over 25 years. At the median annual wage, this would correspond to an additional 3.2 million workers over the 25 years. The projected breakeven period is 43 years. With the return equal to average annual return to the interstate highway system, the gains are much larger. Our calculations indicate that $A' - A = 0.00019$ and the increase in the average annual growth rate is one basis point. With the time-to build assumption, the cumulative gains in real GDP increase to $603.4 billion. Accordingly, cumulative real federal tax collections are projected to be $102.6 billion over 25 years. We further project the gains in employment-years are over 9 million and the breakeven time period shrinks to 23 years.

We start with a simple question: Could a federal government afford to finance a hyperloop investment project? The projections indicate that the gains in real GDP could breakeven from the perspective of additional cumulative, discounted federal tax collections equal to cumulative, discounted infrastructure expenditures. At normal returns, the investment would take 43 years. However, if the returns on the Hyperloop are close to the average annual return on the interstate highway system, then the breakeven period shortens to 23 years. Overall, the projections suggest that such an investment in the transportation system has a positive net present value for a country.

3. COST SAVINGS

Hyperloop studies propose high speeds and low fares. Using the same route as we did in the economic impact section, we consider two types of cost savings. One is proposed fares savings lower and the other are opportunity-cost savings that are realized because travel times are reduced.

Table 3 presents city combination along the proposed route. There are 27 city pairs listed and each is a unit of observation. Based on observed and projected values, we compute travel costs between each city pair by auto, by air, and by Hyperloop. Costs are measured by the actual fares charged to travel by plane or the projected fares for by Hyperloop, or the operating costs of travel by automobile. Fares are taken pre-pandemic. In addition, the additional time it takes to travel by air or by auto is used to compute the opportunity costs compared with Hyperloop.[9] The data

[9] Note that we omit rail travel since Hyperloop travel would strictly dominate existing rail travel both in terms of time and fares charged to customers.

sources are presented for the calculations that are performed. The distances reported in Table 2 range from 160 miles between Oklahoma City and Wichita to 1,375 miles to travel between San Antonio to Chicago.

3.1. Cost Savings: Fare Prices and Operating Costs

Because there is no price data for Hyperloop, we have to make assumptions. Two alternatives are used to project fares for each city pair. One is a proportional fare based on the fare announced in the original white paper between Los Angeles and San Francisco. The other is based on rate-per-mile reported in the Mid-Ohio 2020 Mid-Ohio Regional Planning Commission (2020) report.[10] To estimate Hyperloop fares, this analysis uses data on the proposed fare from Los Angeles to San Francisco. At 382 miles, the proposed fare is $20. We assume that the Hyperloop fare for any city pair is proportional to the ratio of the distance for a city pair and the distance between Los Angeles and San Francisco; therefore, the distance from Dallas to Wichita is 370 miles and the proportional Hyperloop fare is $\frac{proj\ fare}{\$20} = \frac{370}{382} = \$19.47$. Alternatively, the Mid-Ohio Regional Planning Commission completed a report in which it uses $0.20 per mile for projected Hyperloop fares. For this alternative projection, the fare between Dallas and Wichita would be $\$0.20*370 = \$74$.

Table 3. Major city pairs along the proposed Hyperloop route and operating costs

City pair	Distance	Operating cost (auto)	Hyperloop fare (proportional)	One-way fare	Hyperloop fare (constant per mile)
San Antonio to Dallas	275	$ 127.60	$ 14.47	$ 46.50	$ 55.00
San Antonio to Oklahoma City	485	$ 225.04	$ 25.53	$ 83.50	$ 97.00
San Antonio to Wichita	645	$ 299.28	$ 33.95	$111.00	$129.00
San Antonio to Kansas City	825	$ 382.80	$ 43.42	$ 82.50	$165.00
San Antonio to St. Louis	1075	$ 498.80	$ 56.58	$112.00	$215.00
San Antonio to Chicago	1375	$ 638.00	$ 72.37	$ 64.00	$275.00
Houston to Dallas	240	$ 111.36	$ 12.63	$ 45.50	$ 48.00
Houston to Oklahoma City	450	$ 208.80	$ 23.68	$ 45.50	$ 90.00
Houston to Wichita	610	$ 283.04	$ 32.11	$ 83.50	$122.00
Houston to Kansas City	790	$ 366.56	$ 41.58	$ 73.50	$158.00
Houston to St. Louis	1040	$ 482.56	$ 54.74	$ 76.00	$208.00
Houston to Chicago	1340	$ 621.76	$ 70.53	$ 34.50	$268.00
Dallas to Oklahoma City	210	$ 97.44	$ 11.05	$ 90.00	$ 42.00
Dallas to Wichita	370	$ 171.68	$ 19.47	$ 89.00	$ 74.00
Dallas to Kansas City	550	$ 255.20	$ 28.95	$ 46.50	$110.00
Dallas to St. Louis	800	$ 371.20	$ 42.11	$ 66.00	$160.00
Dallas to Chicago	1100	$ 510.40	$ 57.89	$ 34.50	$220.00
Oklahoma City to Wichita	160	$ 74.24	$ 8.42	$121.00	$ 32.00
Oklahoma City to Kansas City	340	$ 157.76	$ 17.89	$ 97.00	$ 68.00
Oklahoma City to St. Louis	590	$ 273.76	$ 31.05	$132.50	$118.00
Oklahoma City to Chicago	890	$ 412.96	$ 46.84	$ 83.00	$178.00
Wichita to Kansas City	180	$ 83.52	$ 9.47	$116.00	$ 36.00
Wichita to St. Louis	430	$ 199.52	$ 22.63	$ 63.00	$ 86.00
Wichita to Chicago	730	$ 338.72	$ 38.42	$ 76.00	$146.00
Kansas City to St. Louis	250	$ 116.00	$ 13.16	$100.00	$ 50.00
Kansas City to Chicago	550	$ 255.20	$ 28.95	$ 45.50	$110.00
St. Louis to Chicago	300	$ 139.20	$ 15.79	$ 45.50	$ 60.00

[10] The figure for the fare comes backing out proposed fares in the Mid-Ohio Regional Planning report. There is very little written on the fares set for proposed Hyperloop routes and nothing official is yet set forth. However, we consider this rate as a check for the robustness of savings.

In the final four columns of Table 3, we present the cost estimates of traveling between each city pair by auto, by air, and by Hyperloop. Both the proportional fare method and the constant fare per mile method are reported. Here, the minimum air fare for air travel between the city pairs is estimated using data from skyscanner.com.[11] The operating cost column for auto travel is computed as the product of the mileage (see Table 3) and $0.464, which is the operating cost per mile for automobiles.[12] For each city pair, the low-cost travel mode is highlighted in Table 3. For the proportional-fares method, Hyperloop has the lowest direct cost in 24-of-the-27 city pairs. Interestingly, airfares are the lower than the Hyperloop projected fare for three city pairs: San Antonio-to-Chicago, Houston-to-Chicago, and Dallas-to-Chicago. In addition, there are two city pairs: Oklahoma City-to-Wichita, and Wichita-to-Kansas City, in which the operating cost of the automobile is less than the air fare. The lowest airfares represent the city pairs that are the greatest distance apart. These are the four largest cities along our proposed route in terms of population. For the constant-per-mile method, Hyperloop is less expensive than a one-way airfare in only eight of the 27 city pairs. The direct cost savings per trip can be substantial, especially when the proportional fare is implemented. Table 3 shows that the projected Hyperloop fare is over $100 less than traveling between Oklahoma City and St. Louis. Over short hauls, like Kansas City-to-St. Louis, a traveler could save over $86 by taking Hyperloop instead of flying. We use the low-cost option as the basis for computing the aggregate savings that could be achieved by having Hyperloop instead of one of the other modes of travel. We assume that some fraction of people that would have travelled by air or by auto would switch to the low-cost Hyperloop option.[13]

Table 4. Annual aggregate direct-cost savings per city pair for air travel.

City pair	Savings with 10% substitution	Savings with 50% substitution
San Antonio to Dallas	$ 3,023,667	$ 12,752,216
San Antonio to Kansas City	$ 188,516	$ 795,058
San Antonio to St, Louis	$ 534,699	$ 2,255,075
Houston to Dallas	$ 6,840,567	$ 28,849,872
Houston to Oklahoma City	$ 1,292,932	$ 5,452,900
Houston to Wichita	$ 1,027,124	$ 4,331,863
Houston to Kansas City	$ 1,209,891	$ 5,102,676
Houston to St, Louis	$ 952,462	$ 4,016,976
Dallas to Oklahoma City	$ 4,624,480	$ 19,503,596
Dallas to Wichita	$ 2,012,356	$ 8,487,047
Dallas to Kansas City	$ 1,161,234	$ 4,897,468
Dallas to St, Louis	$ 1,531,410	$ 6,458,673
Oklahoma City to St, Louis	$ 978,758	$ 4,127,879
Oklahoma City to Chicago	$ 1,420,314	$ 5,990,128
Wichita to St, Louis	$ 389,472	$ 1,642,585
Wichita to Chicago	$ 1,476,134	$ 6,225,548
Kansas City to St, Louis	$ 1,675,694	$ 7,067,185
Kansas City to Chicago	$ 1,619,801	$ 6,831,460
St, Louis to Chicago	$ 3,194,047	$ 13,470,790
Cumulative across all city pairs	$ 35,153,558	$ 148,258,995

To compute the aggregate direct-cost savings, we assume that each flight has the number of seats in a Boeing 737. We assume a 65 percent load factor for each flight. The direct cost savings per passenger seat are taken from

[11] Specifically, the data are obtained for one-way flights between the city-pair as of June 1, 2020.

[12] This operating cost is reported by AAA. See https://newsroom.aaa.com/tag/driving-cost-per-mile/. Operating cost is used here because it ignores occupancy issues. In this section, we are not comparing the low-cost alternative for multiple travelers. In each city pair, there is a break-even cost in which the automobile is the low-cost mode of travel. For example, if you have nine people traveling from Houston to St. Louis, it is less expensive to travel by auto ($482.56) than by Hyperloop (9*$54.74 = $492.66).

[13] Skyscanner.com reports on the number of flights between each city pair when a direct flight exists. There are some city pairs that have zero direct flights: namely, San Antonio-to-Oklahoma City, San Antonio-to-Wichita, Oklahoma City-to Wichita, Oklahoma City-to-Kansas City, and Wichita-to-Kansas City.

Table 3, so we multiply the forecasted number of seats for each city pair by the savings per passenger. Table 4 presents the annual aggregate savings when 10 percent of the air passengers substitute air travel for Hyperloop. In addition, we include a column in which 50 percent of the air passengers substitute from air travel to Hyperloop. The final row in Table 4 is the annual aggregate savings, summing across all the city pairs. If only 10 percent of the air city of destination the annual savings are $148.3 million if 50 percent of current air travelers switch to Hyperloop. The travel-cost savings are only $35.1 million if ten percent of air passengers switch to Hyperloop.

When compared with auto travel, the aggregate direct-cost savings are even more substantial. Based on Federal Highway Authority data, we reports the aggregate number of non-business and business trips by auto for adjacent city pairs in Table 5.[14] We include a column for miles between each city pair. So, the aggregate miles travelled is the product of the aggregate number of non-business trips plus the aggregate number of business trips multiplied by the miles between cities. With these data, we begin to construct the annual travel cost savings for recorded auto travelers compared with what they would have spent to travel by Hyperloop.

Table 5. Annual auto travel report for city pairs

City pair	Non-business trips	Business trips	Miles	Total miles travelled
Chicago - St, Louis	40648	7322	300	14,391,000
St, Louis - Kansas City	29306	7136	250	9,110,500
Kansas City - Wichita	34204	7924	180	7,583,040
Wichita - Oklahoma City	70430	19958	160	14,462,080
Oklahoma City - Dallas	44578	12305	210	11,945,430
Dallas - San Antonio	74702	16412	275	25,056,350
Dallas – Houston	151776	41370	240	46,355,040

Source: Federal highway administration.

If the operating cost is $0.464 per mile, then we compute the total miles travelled between each city pair and multiply by $0.464. We start with the proportional Hyperloop fare.[15] In addition, we recognize that the average number of auto passenger for a non-business trip is 2.183 persons. So, the annual total cost of moving people between each city pair is the represented by the formula.

$$(NBT*2.183*hf)+(BT*hf) \quad (4)$$

Where *NBT* stands for number of nonbusiness trips by auto a year, *hf* is the proportional Hyperloop fare, and *BT* is the number of business trips by auto. From Equation 4, we get the cost of moving people between these city pairs at the proportional Hyperloop fare. In other words, the total Hyperloop fares is computed by using Equation 4 when we compare the cost of traveling by Hyperloop with the operating cost of traveling by auto. Table 6 reports the operating costs for aggregate miles travelled between each city pair along with the Hyperloop fare and the aggregate savings.

Based on the calculations, auto operating costs are greater than the proportional Hyperloop fares. Indeed, Table 6 presents the annual direct-costs savings range for each city pair, ranging from $2.7 million between Wichita and Kansas City. This result is driven primarily by the relatively small number of trips recorded between these cities. The annual savings between Dallas and Houston are projected to be $16.8 million, owing chiefly to the relatively large number of trips between the two Texas cities. If each of those auto travelers switched from auto to Hyperloop, the annual aggregate direct-cost savings from reduced auto travel would be $46.6 million. With 100 percent substitution

[14] Note that the city pairs represented are most-adjacent pairs and represent the number of autos travelling by the interstate highway system. The data include longer trips by including in each segment travelled. For example, a non-business trip between San Antonio and Wichita would be included in three segments: San Antonio-to-Dallas, Dallas-to-Oklahoma City, and Oklahoma City-to-Wichita.

[15] For the interested reader, we have tables for the constant-fare-per-mile method available upon request.

from auto to Hyperloop, the amount saved annually would be $4.7 million and with 50 percent substitution annually from auto-to-Hyperloop, the direct-cost savings would be $23.3 million.

Table 6. Comparison of annual auto operating cost and Hyperloop fare for city pairs (proportional Hyperloop fare).

City pair	Auto operating costs	Total Hyperloop fares	Direct-cost savings
Chicago - St, Louis	$ 6,677,424	$ 1,516,733	$ 5,160,691
St, Louis - Kansas City	$ 4,227,272	$ 935,821	$ 3,291,451
Kansas City - Wichita	$ 3,518,531	$ 782,140	$ 2,736,391
Wichita - Oklahoma City	$ 6,710,405	$ 1,462,610	$ 5,247,795
Oklahoma City - Dallas	$ 5,542,680	$ 1,211,287	$ 4,331,392
Dallas - San Antonio	$ 11,626,146	$ 2,597,169	$ 9,028,977
Dallas – Houston	$ 21,508,739	$ 4,707,163	$ 16,801,575

3.2. Cost Savings: The Value of Time

Because people can travel faster by Hyperloop than air or auto, there is an opportunity cost associated with using the slower travel modes. We quantify the travel-cost savings that a person could realize by choosing Hyperloop.

Tine savings are measured using three data points. First, what is the projected travel time on the Hyperloop. Given the distance between city pairs, we use data reported in the Taylor, Hyde and Barr study; they use 35 minutes to get 382 miles from Los Angeles to San Francisco. By a simple proportion equation, $\frac{dist}{382} = \frac{x}{35}$. We use proportional travel time throughout these numerical analyses. Second, we need the time it takes to travel by air. We use data from skycanner.com as values for direct flights between city pairs. Third, we need the time it takes to travel by auto. For simplicity, we assume the auto traveler will average 60 miles per hour. Hence, the distance is also the projected number of minutes between city pairs for an auto traveler.

We present the projected travel times for each mode and for each city pair in Figure 1. In each case, the projected Hyperloop travel time is the fastest. In three cases, auto travel time is less than air travel time. In each case, Oklahoma City-to-Wichita, Oklahoma City-to-Kansas City, and Wichita-to-Kansas City, there are no direct flights and the distances are short enough that auto travel is faster than air.

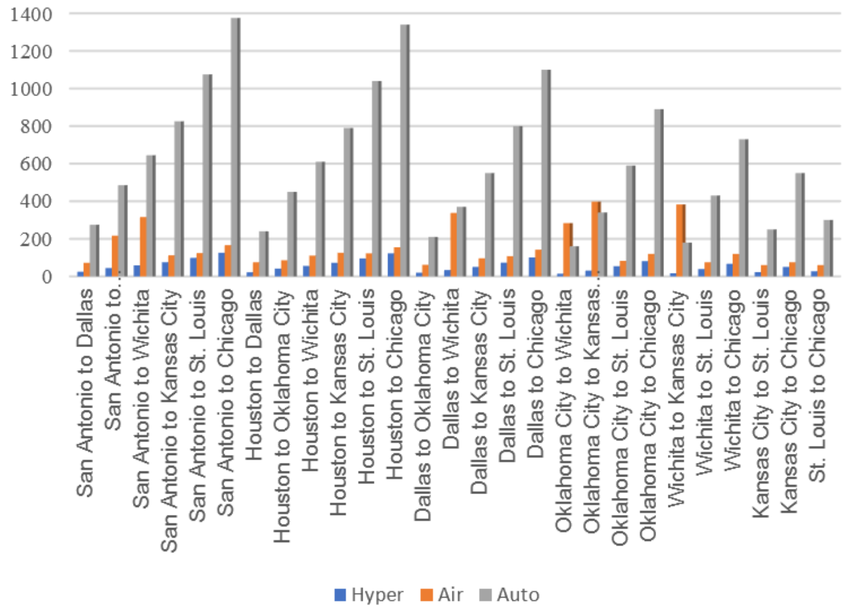

Figure 1. Projected travel times by mode for each city pair.

Figure 2 reports the travel time savings for each city pair. With respect to air travel, the projected travel-time saving is, on average, slightly greater than one and-one-half hours (95 minutes). The minimum amount is 24.6 minutes between Kansas City and Chicago. The maximum travel-time savings is greater than six hours (366.8 minutes) compared with air travel between Oklahoma City and Kansas City. Compared with auto travel, the average gains are substantial; the sample mean is more than nine hours (558.5 minutes) while the minimum time saving is more than two hours (145.3 minutes) for the trip between Oklahoma City and Wichita. Not surprisingly, the maximum time save is for the Houston-to-Chicago trip, with Hyperloop saving nearly 21 hours (1,249 minutes).

Travel-time costs savings are measured using the median hourly wage. Formally, we take the average of the two cities median hourly wage and use that as the opportunity cost per hour for each city pair. We compute the time saving by comparing only minimum of air travel time and auto travel time, subtracting Hyperloop travel time. In this way, there is no double counting since the traveler is assumed to take the mode with the shortest travel time. Figure 2 presents the time saving for each city pair. To compute the aggregate annual opportunity cost, we multiply the per person opportunity cost by the number of travelers. For air travel, we assume the flight is a 737 airplane with a 65 percent load. The number of annual flights for each city pair was obtained from skyscanner.com data. For auto travel, we know the number of autos traveling for business and non-business purposes that are counted between adjacent city pairs.[16] After aggregating, our calculations indicate that the annual opportunity cost of traveling by auto or air rather than Hyperloop is $116,688,187. For the 15-year period after construction is completed, the cumulative, discounted sum of the aggregate annual opportunity cost is $876,466,462.

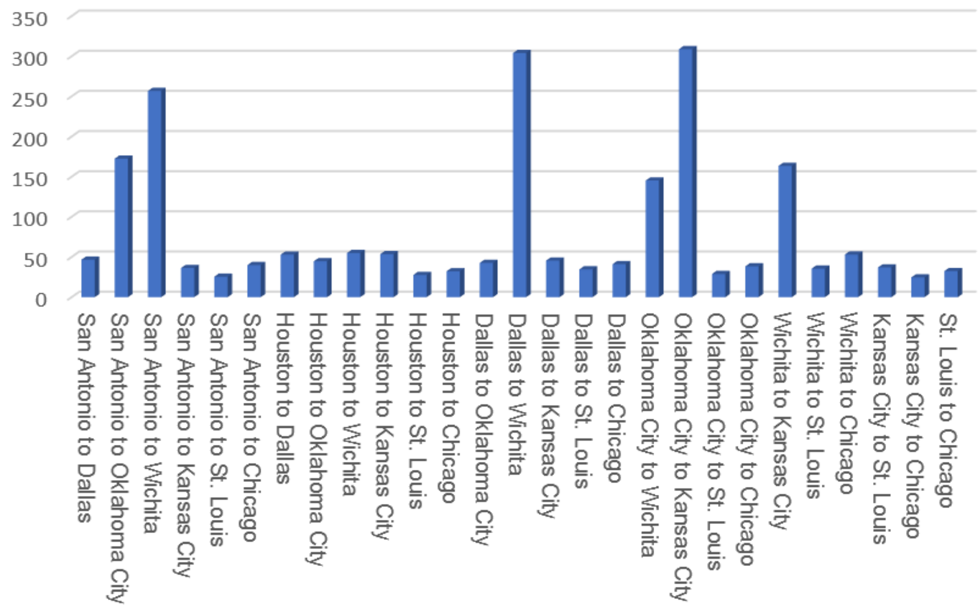

Figure 2. Projected time savings when using Hyperloop compared with the next-best travel mode.

4. COST SAVINGS: GREENHOUSE GAS REDUCTIONS

Proposed Hyperloop systems have a significant advantage over other modes of transportation in terms of the energy source. According to Hyperloop Alpha, the technology is completely powered by solar cells atop the tubes. Compared with auto travel and air travel, the operations of hyperloop technology would transport passengers and freight between Point A and Point B with zero emissions.

[16] Here, the term adjacent refers to city pairs that lie along a particular interstate highway and are close enough for the Federal Highway Administration to collect data on auto travel between the two points. The upshot is that we lose three city pairs in our calculations of aggregate time saving. For San Antonio-to-Oklahoma City, air travel is the next fastest mode, but there are no direct flights between the two cities. Consequently, we cannot compute the aggregate opportunity costs because we do not know the number of passengers traveling between this city pair. Similarly, there are no data on the number of passengers between San Antonio and Wichita. Based on the travel time estimates, auto travel is the next fastest alternative model to Hyperloop between Oklahoma City and Kansas City. Unfortunately, these cities do not meet both "adjacent" criteria. So, we do not know the number of autos travelling between this city pair.

Thus, the purpose of this section is to quantify the social cost savings associated with travel by hyperloop technology instead of air and auto travel. We ignore any greenhouse gases produced during the construction of the hyperloop route. In other words, our calculations are based strictly on cost savings compared with operations.

We begin by constructing the social costs savings for air travel. There are two ways to compute the amount of CO_2 produced by airplanes. Blue Sky is an open access model, an airplane produces 53.3 pounds of CO_2 per mile.[17] According to the European Environment Agency EMEP Corinair (2001) manual, 3.15 grams of CO_2 are produced for each gram of fuel burned. Using data on the fuel burned for a typical 737 aircraft with a 65 percent load factor, 90 kg of CO_2 is produced per hour of flight.[18] We compute the amount of CO_2 produced by air travel based on flight times taken from skyscanner.com and the quantity of kgs produced per hour of flight.

Our analysis is built on city pairs in which there are direct flights. Moreover, we include city pairs in which the flights are less expensive than travelling by Hyperloop. In short, we report only those city pairs with direct flights. Table 7 presents the city pairs with direct flights, the flying time (in minutes), and the kilograms produced per flight. We then multiply column 3 in Table 7 by the total annual number of flights between city pairs and compute the annual quantity of CO_2 produced by air travel along our proposed Hyperloop route. By summing the values in column 4, we find that air travel for these city pairs totals 14,364,012 kg of CO_2 each year. Or, air travel in the direct flights between cities on our route produces 14, 364 metric tons of CO_2 each year.

Table 7. Annual CO_2 emissions for city pairs with direct flights.

City pair	Minutes per flight	kg of CO_2 per flight (based on 90kg per hr.)	Total annual kg of CO_2
San Antonio to Dallas	72	108	769392
San Antonio to Kansas City	152	228	82992
San Antonio to St. Louis	124	186	135408
San Antonio to Chicago	166	249	660348
Houston to Dallas	75	112.5	1766700
Houston to Oklahoma City	86	129	576888
Houston to Wichita	111	166.5	251082
Houston to Kansas City	126	189	540540
Houston to St. Louis	123	184.5	623610
Houston to Chicago	155	232.5	1886040
Dallas to Oklahoma City	62	93	411060
Dallas to Kansas City	96	144	718848
Dallas to St. Louis	108	162	783432
Dallas to Chicago	142	213	2226276
Oklahoma City to St. Louis	83	124.5	90636
Oklahoma City to Chicago	120	180	533520
Wichita to St. Louis	75	112.5	81900
Wichita to Chicago	120	180	533520
Kansas City to St. Louis	60	90	131040
Kansas City to Chicago	75	112.5	830700
St. Louis to Chicago	60	90	730080

The National Academies of Science, Engineering and Medicine (2017) computed the social costs of carbon dioxide. The cumulative, discounted sum of the social cost is $42 per metric ton of CO_2 when discounting at a three percent rate.[19] The social cost projections takes into account a wide range of impacts, including net changes on agricultural productivity, human health, property damages from increased flood risks, and changes in energy system costs, such as the reduced costs of heating and the increased costs of air conditioning. We compute the aggregate air

[17] See https://blueskymodel.org/air-mile.

[18] See European Environment Agency EMEP Corinair (2001).

[19] See https://www.epa.gov/sites/default/files/2019-06/documents/ace_co2_trends_6.18.19_final.pdf

travel social cost by multiplying the number of kg of CO_2 produced by each city-pair annual flights by $42 per metric ton. For the annual aggregate savings in reduced CO_2 for air travel, our results indicate that Hyperloop would save $24.9 billion if 100 percent of the air travelers switched to Hyperloop. Correspondingly, the greenhouse gas cost savings would be $12.4 billion if 50 percent substituted and $2.5 if only ten percent of the air travelers switched to Hyperloop. For auto travel, we assume that cars average 23.4 miles per gallon. We know the distance between city pair, so it is straightforward to compute the gallons burned per auto between each adjacent city pair. A 2016 United States Energy Information Administration report says that 8.89 kgs of CO_2 are produced for each gallon of gasoline.[20] With the quantity of CO_2 produced by the average auto for each adjacent city pair, we can compute the total volume of CO_2 produced annually using the Federal Highway Administration data on the number of nonbusiness and business trips. The data indicate that over 5.5 million gallons burned for the seven city pairs considered in Table 8. The social cost of greenhouse gas saved is equal to $2.1 million per year by reducing auto travel as the maximum number of auto travelers switch to Hyperloop.

Table 8. Annual aggregate CO_2 emissions by auto travel.

City pair	Total miles travel (non-bus + bus)	Annual aggregate gallons of fuel	Quantity of CO_2 (in kgs)
Chicago - St, Louis	14,391,000	615,000	5,465,505.00
St, Louis - Kansas City	9,110,500	389,338	3,460,043.31
Kansas City - Wichita	7,583,040	324,062	2,879,934.89
Wichita - Oklahoma City	14,462,080	618,038	5,492,500.21
Oklahoma City - Dallas	11,945,430	510,488	4,536,710.96
Dallas - San Antonio	25,056,350	1,070,784	9,516,059.08
Dallas – Houston	46,355,040	1,980,985	17,605,010.28

The Mid-Ohio Regional Planning Commission released a report that projects a much larger gain in terms of reduced greenhouse gas emissions. The key difference is that the Mid-Ohio Regional Planning Commission accumulates the cumulative discounted sum of greenhouse gas cost savings over a 30-year period while we report the cumulative, discounted losses by year. If were to accumulate over years, our cost savings would be much greater. In addition, the Mid-Ohio report assumes that the cumulative number of auto passengers switching to Hyperloop travel will be equal to 1.9 billion travelers. On average, this corresponds to roughly 63 million automobile trips a year will switch to Hyperloop trips. The data source for this projection is unknown.

Overall, we urge the reader not to simply add up the various economic impact and cost savings measures. By construction, the economic impact values are constructed to take into account behavioral shifts owing to the different prices and returns. Resources freed up by Hyperloop cost savings are permitted to be used in other activities like greater consumption of other items and more savings. We report the values of the costs savings in order to provide a concrete example of the various ways in which a new technology can yield additional benefits to citizens.

5. SUMMARY

In this paper, we propose a dynamic general equilibrium model economy that can be used to quantify the effects of transportation infrastructure investment in the economy. Our application is to quantify three different areas in which a proposed Hyperloop route would affect economic outcomes. We consider a route with terminal points in Chicago, Houston and San Antonio. The route would follow Interstate 55 from Chicago to St. Louis, Interstate 70 from St. Louis to Kansas City, Interstate 35 from Kansas City to Wichita, Oklahoma City, and Dallas, then branching and continuing along Interstate 35 to San Antonio or along Interstate 45 to Houston. The proposed route would be just shy of 1,600 miles.

[20] See https://www.eia.gov/environment/emissions/co2_vol_mass.php .

In terms of the aggregate economic impact, our results show that the return on the Hyperloop determines whether federal tax collections will be sufficient to pay for the investment expenditures. If the return to the Hyperloop is equal to the normal return on capital, the discounted cumulative sum of additional real GDP is $205.9 billion over a 25-year period. The discounted sum of the investment expenditures is projected to be $53.1 billion. At the average federal tax collection rate, the Hyperloop investment would not pay off over the 25-year period. However, if the return on the Hyperloop investment is equal to the historical average return on the interstate highway system, which is 34 percent, the cumulative, discounted gain in additional real GDP increases to $933.9 billion over 25 years.[21] In the high-return experiment, the cumulative, discounted gain in federal tax receipts will pay for the infrastructure investment in 23 years.

In addition, we calculate the travel cost savings in terms of reduced fares compared with air and auto travel and in terms of the value of travel-time savings. For the analysis, we assume the project is not servicing riders for 10 years. After which, we consider the first 15 years of operation. With 50 percent of air passengers switching to Hyperloop, the fare savings would be $148.3 million annually. For auto travelers, Hyperloop fares are compared with operating costs. The annual travel-cost savings would be $23.3 million if 50 percent of auto travel switched to Hyperloop. For auto travel, the key feature is reduced travel time. We compute the annual value of travel time for air and auto travel compared with Hyperloop travel. Our calculations indicate that the annual value savings of travel time using Hyperloop instead of auto or air is $116,688,187. For the 15-year period after construction is completed, the cumulative, discounted sum of the aggregate annual opportunity cost is $876,466,462.

With solar cells providing the energy to propel Hyperloop pods, there are substantial savings in the form of reduced greenhouse gases. With 50 percent of air passengers switching from air travel to Hyperloop, the greenhouse gas cost savings would be $12.4 billion per year. Compared with auto travel, the greenhouse gas savings are much lower. Annual maximum greenhouse gas savings from switching to Hyperloop from auto travel for seven city pairs would greenhouse gas saved is equal to $2.1 million per year.

There is still much work to be done to make Hyperloop operational. One, for example, there remain a number of technical questions that must be answered before the full-scale operations can begin. The safety of the system is paramount, which can be rigorously studied in controlled experiments, followed by freight-only commercial operations. Federally-funded research centers are clearly needed, which would provide the rigorous, unbiased assessments needed to further hone estimates of the economic benefits of Hyperloop, to assess and ensure its safety, resiliency and role in transportation equity in the US. In conclusion, the main contribution of this study is to provide quantitative answers with respect to the macroeconomic consequences associated with an investment in the Hyperloop system. Such quantitative effects are necessary as the nation moves forward to determine the benefit of this new, game-changing transportation mode.

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