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Urban Air Mobility: Viability of Hub-Door and Door-Door Movement by Air

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ABSTRACT
Owing to a century of innovation in connected and automated aircraft design, for the first time in history, air transport presents a potential competitive alternative to road, for hub-to-door and door-to-door urban services. In this article, we study the viability of air transport, for moving people and goods in an urban area, based on three metrics - enroute travel time, fuel cost and carbon dioxide (CO_2) emissions. We estimate the metrics from emission standards and operational assumptions on vehicles based on current market data and compare electric air travel to gasoline road travel. For passenger movement, air is faster than road for all distances. It fares better on fuel cost and emissions only for longer distances (specific transition distances are stated in the text). For consolidated movement of goods, air is at par with road. Finally, for movement of unconsolidated goods, air again fares better than road on all three metrics. It is also noteworthy that these results are based on a road friendly urban design. Changes in design that facilitate easier access to air based hub-to-door and door-to-door services, would only make the case stronger for Urban Air Mobility (UAM), especially with connected and automated aircraft, as the next revolution in urban transportation.

KEYWORDS
Urban Air Mobility; Unmanned; UAM; eVTOL

1. Introduction

Transportation systems move people, goods and services (henceforth collectively referred to as entities) via Air, Land (Rail and Road) and Water and other secondary modes like pipelines, cables and space. In a nutshell, all transportation operations can be classified into three types, namely - hub-hub, hub-door/door-hub, and door-door. Hubs handle large-scale movement of entities, such as airports, harbors, railway stations, bus terminals, gas stations, supermarkets, etc. Doors are places handling small-scale movement of entities, like individual houses, farms, offices and so on. Air, rail, road and water enable hub-hub operations. But hub-door and door-door operations are conducted till date, primarily via roads.

Founded by Henry Ford on June 16, 1903, the Ford Motor Company produced its first automobile - the Model T in 1908. The same year, the Wright Brothers made their first public flight and carried the first airplane passenger. Within two decades, Sikorsky Aero Engineering Corporation was founded by Igor Sikorsky on May 23, 1923. It produced the Sikorsky R-4 - the first stable, single-rotor, fully controllable helicopter to enter full-scale production. Yet over the past century, the automobile became a consumer product but the aircraft/helicopter did not. With one simple goal that a company should produce products that its employees can afford, Henry Ford's revolution changed the face of urban transportation (figure 1), putting every American home on a motorable road.

Figure 1. Columbus Circle New York City - 1905 to 2015, Image Courtesy: fineprintnyc (left), 2luxury2 (right)

Is air a viable alternative today for large scale hub-door and door-door urban operations? The revolution in small consumer aircraft design over the past decade has created an opportunity. Led by companies like DJI and 3DR, first the small Unmanned Aircraft Systems (sUAS) aka drones became a consumer product. Consequently with increasing automation, drone-based services like photography, package delivery, surveying, surveillance, search and rescue and so on are now within the reach of an average consumer. This industry, predicted by Forbes to be worth a billion dollars in 2015, produced a combined revenue (consumer and commercial) of \$4.5 billion in 2016 (Gartner, 2017), from the goods and services sector.

What about moving people? With rapid innovation in distributed electric propulsion and automated Personal Aerial Vehicle (PAV) (2-4 passengers) design, fuel efficiency and emissions have already improved and are expected to get better. For example, the electric Vertical Take Off and Landing (eVTOL) Airbus Vahana is expected to produce thrice the mileage of the most efficient gas powered Cessna and over seven times the mileage of the Robinson R44 Raven II helicopter. At the same time it will produce close to two-thirds the CO_2 emissions of either. eVTOLs are therefore expected to lead the UAM era (Mueller, Kopardekar, & Goodrich, 2017).

Parallely, automobiles or the connected cars of today have undergone a similar revolution. Electric and hybrid propulsion have made the automobile fuel economy five-fold and two-fold respectively and reduced CO_2 emissions compared to gasoline. However, they still make up only around 2% of automobile sales globally and in the USA. At the same time, automated technologies developed for these vehicles are simultaneously being incorporated into their gasoline counterparts. We therefore believe that they will take a long time to substantially replace the existing gasoline fleet on roads. In comparison, UAM enabling aircraft are primarily envisioned as electric. Hence, we use electric aircraft and gasoline automobile as the representative vehicles for air transport and road transport respectively.

We use three enroute metrics for comparison - 1) travel time (min), 2) fuel/energy cost (\$), and 3) CO_2 emissions (lbs). The trade-offs can vary based on whether the trip involves moving passengers, consolidated goods or unconsolidated goods. Hence, the above metrics are compared for each of these urban movement types. For each type, air transport is a feasible alternative if it fares at par or better on most of the metrics. The near future urban air traffic will enter an airspace which is pretty much devoid of any such traffic today. Road traffic on the other hand is already quite congested most of the time in urban areas. Hence, we also compare uncongested air travel to both uncongested and congested road travel. Section 2 and 3.2 together elaborate the assumptions made for each type of urban movement and section 4 presents the detailed analysis of the metrics. Section 5 summarizes our findings and identifies areas for further exploration.

2. Background

UAM studies have shown improvements in urban passenger air travel time for both hub-door(Alonso et al., 2017) like and door-door(Antcliff, Moore, & Goodrich, 2016) services with specific trip designs. Uber(Holden & Goel, 2016) estimates its future air taxis to be competitive to its current road based rideshare services based on time, direct operating costs and emissions. For passenger movement, our work complements these efforts.

The maximum permitted uncongested freeway speed in a US metropolitan region is usually 65 mph (104.6 kph). On congested roads, the speeds come down to about 30 mph (48.3 kph) (SFCTA, 2017). Similarly, the US average fuel economy for cars comes down from about 30 mpg (12.75 kpl) to roughly 20 mpg (8.5 kpl) due to congestion (US-EPA, 2018). In comparison, urban air travel is envisioned to be most fuel efficient at speeds of about 125-150 mph (200-240 kph) (Holden & Goel, 2016; Johnson & Silva, 2018) with operations at or below 5000ft altitude.

A Cessna 150 that can fly at a comparable cruise speed gives a mileage of close to 18 mpg (7.65 kpl) which is more than twice that of a helicopter like the Robinson R44. An all electric Airbus Vahana will give thrice that mileage (using an energy density conversion of 34.44 kWh/gal for aviation fuel(USDOE-EIA, 2001)) while producing less CO_2 per kWh. These improvements in aircraft motivate our work.

For goods, we differentiate between consolidated (e.g. - mail delivery) and unconsolidated (e.g. - grocery trips) movement. Published research comparing urban goods movement by air and roads is quite limited. Goodchild and Troy(Goodchild & Toy, 2018) come closest with their comparison of emissions for drones vs delivery trucks. Following a similar approach for consolidated goods, we compare a standard UPS Diesel Truck against a drone that can deliver similar packages by air, normalizing the fuel and emission numbers by weight and distance. For unconsolidated goods, we compare a sedan trip to a grocery store a mile away from home against the same trip needs met by drones.

3. Modelling and Assumptions

3.1. Metrics

For passenger and goods (consolidated and unconsolidated) movement, we base our comparisons on - 1) Travel Time; 2) Fuel Cost; and 3) Emissions. We normalize these metrics as elaborated next. Only enroute statistics are analyzed to cover a broader class of operations, agnostic to specific locations and network design.

3.2. Assumptions

3.2.1. Passenger trips

For passenger movement, all comparisons are made - as a ratio of the metric (Road/Air, orange lines in figures); and as a difference of the metric (Road-Air blue lines in figures). For road movement, we assume uncongested speed(v_{Ru}), congested speed(v_{Rc}), uncongested fuel economy(M_{Ru}) and congested fuel economy(M_{Rc}) of 65 mph, 30 mph, 30 mpg and 20 mpg, respectively. For air movement, we assume a cruise speed(v_{Au}) of 150 mph and the airspace is assumed to be uncongested.

Market studies of eVTOL viability use highly optimistic power consumption numbers and Lift-to-Drag ratios (L/D), owing to the lack of data from real certified aircraft or feasible eVTOL models tested for design missions. L/D above 13 are considered in these studies(Holden & Goel, 2016; Kasliwal et al., 2019). A rather efficient fixed-wing general aviation aircraft (Cirrus SR22T) has a best-range L/D of 10. In consultation with aircraft designers and aerospace engineers, we found that it is highly unlikely that any eVTOL configuration for long range urban passenger movement will have better L/D than even current-technology fixed wing aircraft, let alone fixed wing aircraft with same level of advanced technology.

To explain this better, for an aircraft in level cruise, the L/D ratio is given as:

$$L/D = Wv/P \tag{1}$$

where, W is the weight of the aircraft, v is the cruise speed and P is the cruise power. If all three terms on the right are known, the L/D in cruise can be calculated. However, released specifications of eVTOL under development or tested only state the W and v values. They provide information on the total installed power but not on how much is actually used, nor do they provide the actual L/D numbers. If we assume the L/D values as projected in market studies (13 plus), the computed cruise powers typically tend to be less than 20% of the total installed powers of these designs. Hence, they don't seem realistic.

We instead use insights from eVTOL models as developed by Johnson and Silva at NASA Ames (Johnson & Silva, 2018) (henceforth referred to as NASA eVTOL models/designs) and combine those with design specifications of flight tested eVTOL aircraft to estimate the cruise power to use. The L/D of the all electric NASA eVTOL models vary from roughly 5.3 to 9.3, with the most optimal (design size + cruise efficiency) model's value at 7.2.

The Airbus A^3 Vahana Beta is the 2-seater version of the Vahana Alpha that has flown over 50 full scale test flights (News, 2019). Its design specifications include a maximum take off weight of 815 kg with an optimal cruise speed of close to 150 mph. It has 8 propellers each rated at 45 kW. Since aircraft are built with redundancy, we assume only half of this installed power (180 kW) is utilized during the hover phase of flight. For the cruise phase of flight since its L/D numbers are not available publicly, we assume the optimal NASA eVTOL number of 7.2 to compute the cruise power at 70.87 kW (substituting W, v and L/D in equation 1). We note that L/D of 13 (as per market studies), would give a cruise power of 41 kW, less than the power of a single propeller. A higher L/D would make this even smaller. Clearly, the L/D of this designed and flown aircraft is not as high. Yet, since we don't know the exact L/D, we also perform a sensitivity analysis by varying the L/D to 5 and 10 and utilizing the corresponding Vahana cruise power values of 102 kW and 51 kW.

We assume a flight profile as shown in figure 2. The eVTOL takes off hovering in place to 100 feet at 100 fpm. Then it ascends while cruising to its cruise altitude, cruises close to destination, descends while cruising to a hover and then lands while hovering. The in place hover take-off and landing phases therefore take overall 2 minutes while the extra energy utilized in slant ascent to the cruise altitude (4000 ft in the NASA eVTOL designs) while accelerating to the cruise speed is assumed to be offset by the energy saved in descent while decelerating to a hover for final landing. We compare statistics only for enroute travel. By enroute, we refer to portion of the journey from start of trip (take off for air and movement start for road) to end of trip (landing for air and movement end for road).

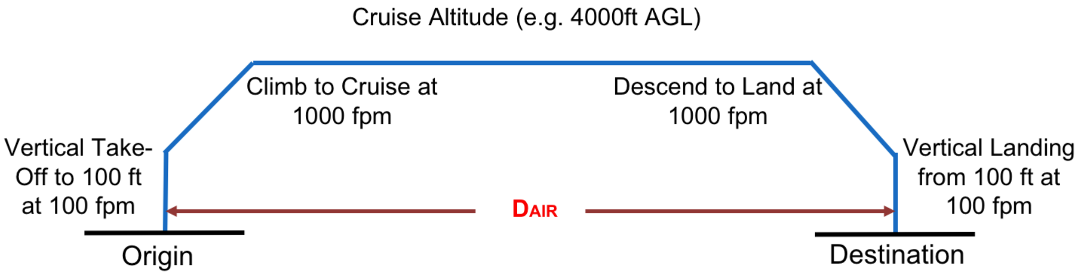


Figure 2. eVTOL flight profile for passenger movement.

Our first set of results only compare the vehicle configurations as is without accounting for the passenger occupancy. UAM passenger services as a shared transportation mode will tend to maximize utilization rates, unlike cars on the road today which are predominantly singly occupied. To account for this discrepancy, we perform a second sensitivity analysis by normalizing our fuel costs and emission numbers on a per passenger basis. For road movement, we use a US average passenger occupancy of 1.54 (O_R)(USDOT-FHA, 2017). The chosen aircraft (Vahana) is an automated pilotless 2-seater. Hence, we choose an occupancy of 2 (O_A) for it. Furthermore, the NASA eVTOL models were designed for 6 passengers, including the pilot. Such aircraft might be preferred even more to improve the utilization rates. Hence, we add that design to the list of test cases for comparison using an automated aircraft occupancy of 5 passengers. We note that the enroute distinction above ensures that the wait time constraint is not included, the assumption being that given the diversity of vehicle sizing, the vehicle appropriate to the available number of passengers will be used.

For gasoline and electricity we use fuel costs of \$3/gal(c_R) and \$0.13/kWh(c_A) respectively based on US averages. For electric fuel, we also account for the battery charge-discharge efficiency of 90%(η). In other words, the energy used by the eVTOL is assumed to be only 90% of the energy delivered while charging from the grid. Power consumption for electronics is assumed to be negligible compared to the propulsion power and hence ignored in the calculations.

Finally, for emissions, we use CO_2 emission rates of 19.59 lbs/gal (2.347 kg/l) (e_R) and 0.474 lbs/kWh (0.275 kg/kWh) (e_A) (California ISO (CaISO)) for gasoline and electricity respectively. We also account for the additional emissions in moving fuel from primary source to delivery by multiplying the above emission rates by primary-to-delivery ratios of 1.28 (ArgonneLab, 2018)(μ_R) and 1.67 (CaISO grid system efficiency)(μ_A), respectively.

Road movement is typically more circuitous compared to direct aerial routes. Hence, for air movement, we use the haversine (great circle) distance(D_{Air}), while for road movement we assume circuity factors (f) of 1.20 (US average (Ballou, Rahardja, & Sakai, 2002)), 1.35 (Silicon Valley average (Antcliff et al., 2016)) and 1.42 (Uber average based on their trip data(Holden & Goel, 2016). Hence, the road distance $D_{Road} = f.D_{Air}$.

The metrics for comparison are computed as follows:

The travel time, T for each mode is given by -

$$T = D/v \tag{2}$$

where, D is substituted as is for air and as $f.D$ for road.

The energy consumed for road in gallons is given by -

$$E_{Road} = D_{Road}/M_R \tag{3}$$

where, M_R is substituted for uncongested and congested conditions as needed.

The energy consumed for air in kWh is given by -

$$E_{Air} = (P_{Hover}.T_{Hover} + P_{Cruise}.T_{Air})/\eta \tag{4}$$

where, the hover/cruise power, travel times and the charging efficiency are as stated earlier.

Given each of the energies, they are multiplied by the respective unit energy costs to get the total energy cost in dollars.

The emissions for each mode are given by -

$$CO_2 = E.e.\mu \tag{5}$$

where, e and μ are the respective emission rate per unit energy and primary-to-delivery ratios, respectively.

Results are first presented for the three metrics, using the Vahana design based assumptions above, for a circuity factor of 1.35 for direct travel distances from 1 to 100 miles (1.6 to 160 kilometers). We then discuss the sample results for a typical urban commuter distance of 50 miles (80 km). It is to be noted that the US average accounts for more direct road routes in rural areas and Uber's average is for a very specific niche of trips. The Silicon Valley average is the best representative among the three of circuity factors in a metropolitan area. Hence, we perform a sensitivity analysis in two steps. First we vary the circuity factor to 1.20 and 1.42 and present the results in comparison to the 1.35 case. Next we vary the L/D and vehicle occupancy numbers for the circuity factor of 1.35. The numbers are all presented for the sample distance of 50 miles. Also, we do not analyze distances shorter than a mile.

3.2.2. Consolidated Goods Trips

We assume a standard diesel UPS truck(Lammert, n.d.). It weighs 11000 lbs (5000 kg) with a maximum storage capacity of 12000 lbs (5450 kg) and makes 200 stops per day on an average. With a mileage of 10.2 MPG and about 80-100 miles driven per day, it consumes roughly 10 gallons (38 litres) of fuel. We further assume that it moves 5000 lbs (2270 kg) of packages daily on average.

Since, there is sufficient specification data in the market for an efficient drone that can deliver packages over long distances from hub to door, we choose DJI S900 as a representative. We pick the necessary values from its specification sheet(DJI, 2019). It produces 12A current at 24V for 18 min of flying time and can carry a payload of 10 lb (4.5 kg). At its maximum speed it can cover a distance of 10 miles (16 km) in that time.

3.2.3. Unconsolidated Goods Trips

Unlike a big truck delivering packages, there are other hub-door and door-door trips that move consumer goods in smaller quantities. An Uber Eats trip, a pizza delivery, a quick shopping trip to buy groceries or other household products, delivery of emergency medical supplies and so on are all examples of such smaller unconsolidated goods trip that typically originate and end within the confines of an individual city within a larger metropolitan region. At least one fifth ($\tilde{2}0\%$) of vehicle trips in the US fit this criteria as per the US Department of Transportation(USDOT-FHA, 2017).

We use the same DJI S900 drone as above to evaluate a typical unconsolidated goods trip. For road movement, an average gasoline based Sedan with a mileage of 25 MPG is assumed (average of the congested and uncongested road mileages)(US-DOE, n.d.). We first evaluate a consumer trip to a store a mile away for a gallon of milk (8.6lbs or 4 kg) and present our travel time, fuel cost and emissions analysis for that.

A typical shopping trip or a food/essentials delivery via a car would still have some consolidation effect, albeit not to the extent of a UPS truck per se. For example, a person might shop for multiple items in the same trip. Unlike the car, a single drone has limited capacity. So those multiple items need to be delivered by multiple drones. To account for this mini consolidation advantage from the car, we also analyze our metrics by varying the car trip goods weight from 1 to 50 pounds (1 to 23 kg).

4. Results

4.1. Passenger Trips

Figure 3 shows two comparisons for travel time - 150 mph by air (best speed with minimal reduction in fuel efficiencyHolden and Goel (2016)) against uncongested (free) and congested road travel. We are only analyzing distances from 1 mile to 100 miles. Air travel time is less by around one-third compared to free road conditions across the three circuity conditions.

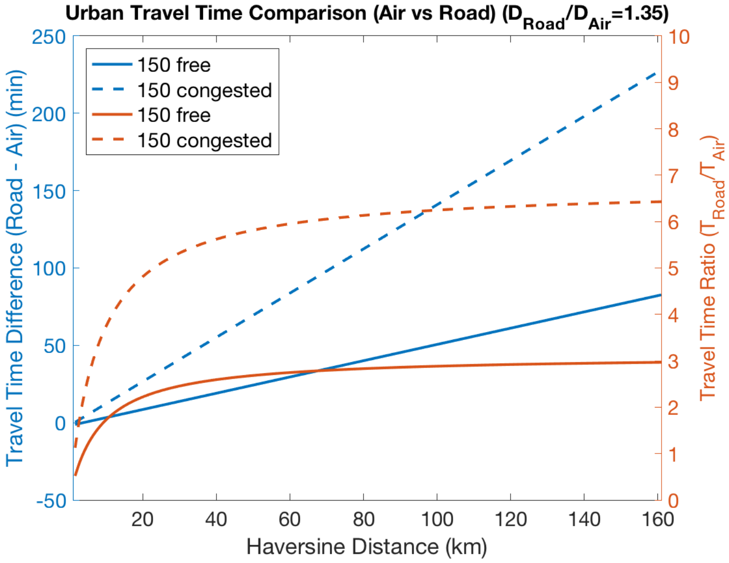


Figure 3. Enroute Travel Time Comparison - Road vs Air. Orange - Travel Time ratio, Blue - Travel Time difference

Congestion on roads more than doubles the advantage of air to road. For example, at a circuity factor of 1.35, for a 50 mile (haversine distance) long trip, movement by air saves 40 min and 113 min compared to free and congested road conditions respectively. If the circuity factor is reduced to 1.20, the time savings are reduced to 33 min and 98 min respectively. However, if the circuity factor is increased to 1.42, the corresponding time savings are more pronounced at 42 min and 115 min (see Table 1). However, it is noteworthy that air only has a time advantage over distances of roughly 2 miles. This is because these distances are covered by road in the time the eVTOL takes to take-off and land.

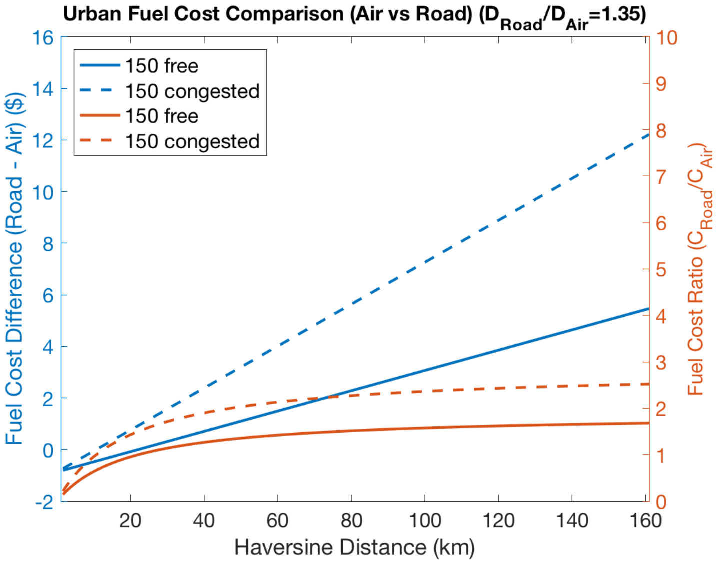


Figure 4. Enroute Fuel Cost Comparison - Road vs Air. Orange - Fuel Cost ratio, Blue - Fuel Cost difference.

Energy/fuel cost comparison is shown in figure 4. Air fares better enroute compared to roads for longer travel segments. These savings are more than doubled with congestion on road. For example, for a 50 mile air trip, at a circuity factor of 1.35, fuel spent enroute costs \$2.30 and \$5.67 less by air than uncongested and congested roads respectively. At a circuity factor of 1.20, these savings are reduced to \$1.55 and \$4.55 but increased to \$2.65 and \$6.20 at a circuity factor of 1.42 (Table 1). However, at a circuity factor of 1.35, for uncongested trips under 13 miles and congested trips under 6 miles, road fuel costs beat air. We call these the transition distances. As the circuity factor is increased, air becomes cheaper than road at shorter transitions distances and vice versa.

Next we compare CO_2 emissions as shown in figure 5. We find that beyond 8 miles, at a circuity factor of 1.35, it is greener to travel by air. If the roads are congested, this becomes true beyond 4 miles. A higher circuity factor reduces these transition distances and vice versa. Again for a 50 mile trip example, at a circuity factor of 1.35, travel by air generates 13.36 kg less of CO_2 emissions with the savings almost doubled to 26.19 kg when the roads are congested. At a circuity factor of 1.20, the savings against uncongested and congested roads are 10.51 kg and 21.92 kg, respectively. These savings are improved to 14.69 kg and 28.19 kg at a circuity factory of 1.42.

For the rest of our analysis, we only consider a circuity factor of 1.35 as a best measure of travel distance extension (road vs air) in metropolitan areas.

The fuel cost and emission trade-offs depend on the L/D ratio of the eVTOL. We demonstrate this by varying the L/D ratio (figure 6). The assumed design weight and cruise speed are kept unchanged for the Vahana. For a very low cruise efficiency (L/D

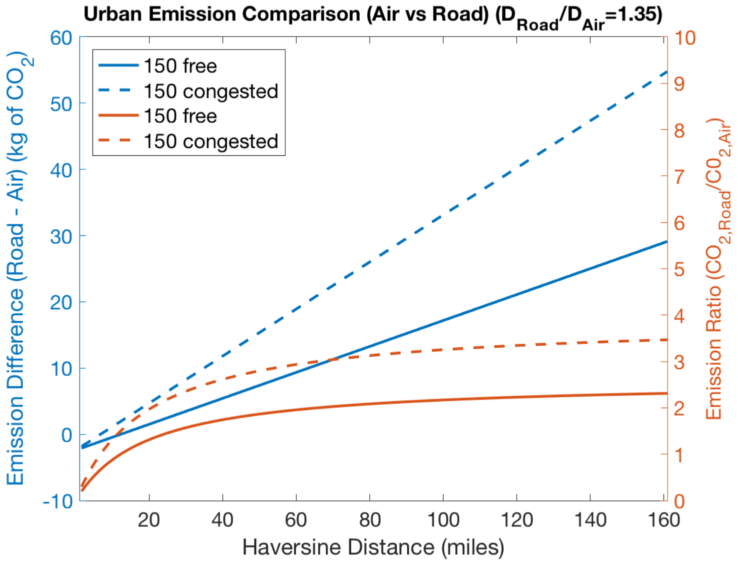


Figure 5. Emission Comparison - Road vs Air. Orange - Emission ratio, Blue - Emission difference.

Table 1. Sensitivity Analysis for a 50 mile (80 km) trip. Varying the circuity factor f

	T_{ratio}		T_{diff}(min)		C_{ratio}		C_{diff}(\$)		$CO_{2,ratio}$		$CO_{2,diff}$(kg)	
f	UnC	Con	UnC	Con	UnC	Con	UnC	Con	UnC	Con	UnC	Con
1.20	2.51	5.45	33.38	98	1.35	2.02	1.55	4.55	1.85	2.78	10.51	21.92
1.35	2.83	6.14	40.30	113	1.52	2.27	2.30	5.67	2.09	3.13	13.36	26.19
1.42	2.97	6.45	43.54	120	1.60	2.39	2.65	6.20	2.20	3.29	14.69	28.19

*Road condition: UnC - Uncongested, Con - Congested.

Table 2. Sensitivity Analysis for a 50 mile (80 km) trip. Varying L/D and Occupancy. f = 1.35

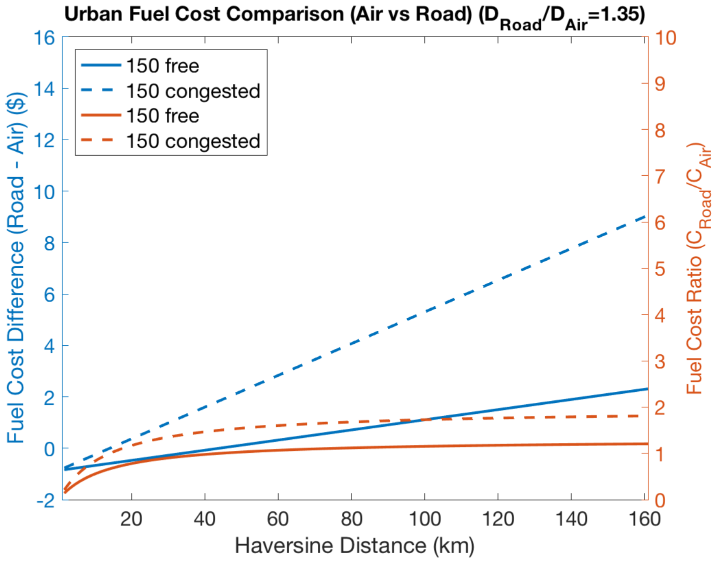
	C_{ratio}		C_{diff}(\$)		$CO_{2,ratio}$		$CO_{2,diff}$(kg)	
Parameter	UnC	Con	UnC	Con	UnC	Con	UnC	Con
L/D = 5	1.11	1.67	0.72	4.09	1.54	2.31	9	21.83
L/D = 10	1.95	2.94	3.30	6.68	2.69	4.04	16.14	28.96
Occupancy: Road = 1.54, Air = 2	1.96	2.95	2.15	4.34	2.71	4	10.51	18.84
Occupancy: Road = 1.54, Air = 5	2.22	4.41	2.02	3.04	2.79	4.18	10.69	19.02

*Road condition: UnC - Uncongested, Con - Congested.

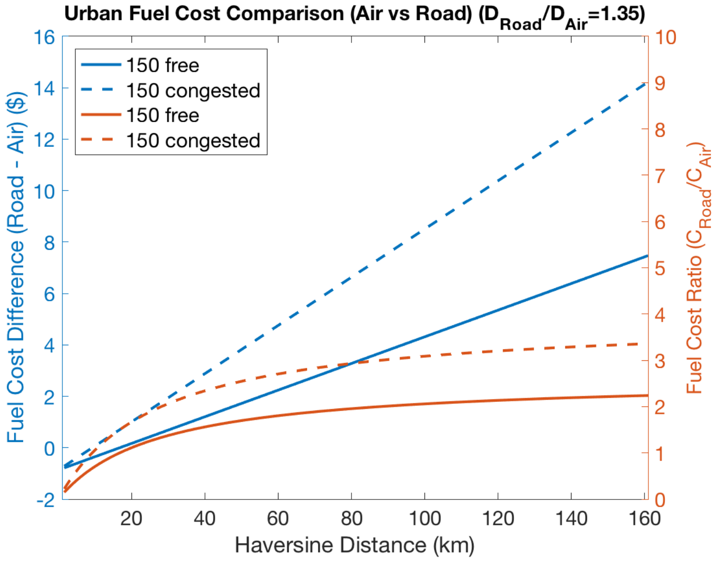
= 5), a 50 mile travel by air only saves \$0.72 and \$4.09 over uncongested and congested road travel, respectively (compared to \$2.30 and \$5.67 earlier at L/D = 7.2 in figure 4). A high cruise efficiency with L/D = 10 increases these savings to \$3.30 and \$6.94.

A similar trend is seen for CO_2 emissions too but the differences are more pronounced (figure 7). Low cruise efficiency saves 9 kg and 21.83 kg of CO_2 for a 50 mile trip by air against uncongested and congested road, respectively. Earlier (L/D = 7.2 in figure 5) these savings were 13.36 kg and 26.19 kg. A very high cruise efficiency makes the aircraft quite greener by saving 16.14 and 28.96 kg of CO_2.

All the results till now used a vehicle to vehicle comparison. The savings therefore can be thought of as pertaining to the operator side. However, as stated earlier, eVTOL aircraft are expected to operate at much higher utilization rates than cars on roads today. Hence we want to understand the trends as pertaining to the consumer or the



(a) L/D = 5.

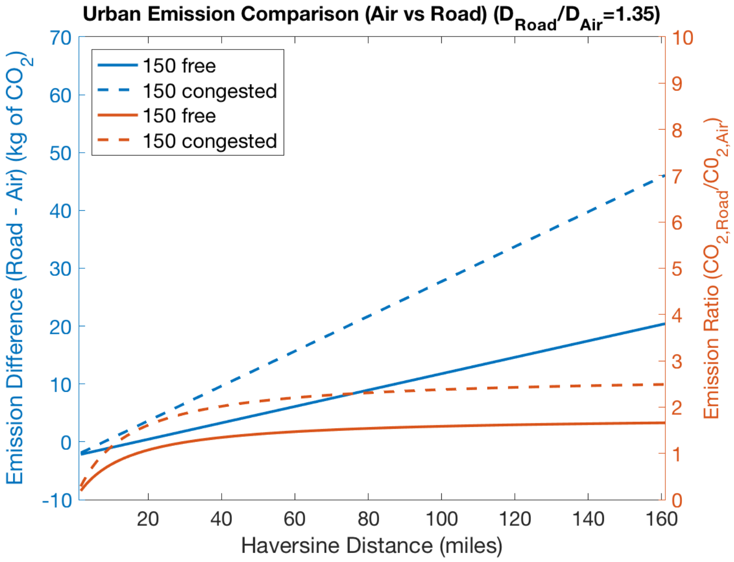


(b) L/D = 10.

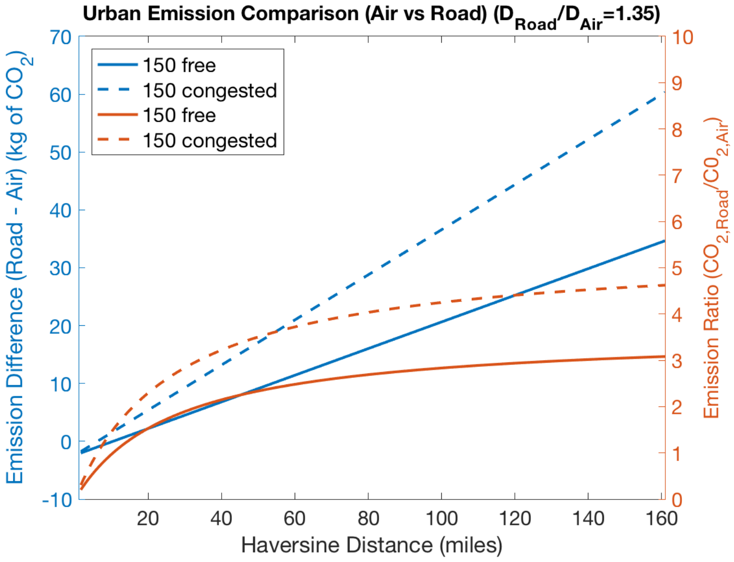
Figure 6. Enroute Fuel Cost Comparison - Road vs Air. Orange - Fuel Cost ratio, Blue - Fuel Cost difference

customer by computing the metrics on a per passenger basis. Since we are looking at only enroute statistics (take off to land by air and wheels move to wheels stop by car), the travel time comparison only depends on speed which remains unchanged with occupancy. Hence, the savings are as before. We only analyze the impact on fuel cost and emissions. We keep the design parameters of the base case unchanged with L/D = 7.2.

Assuming an occupancy of 1.54 for cars and 2 for the 2-seater automated/pilotless aircraft, compared to uncongested and congested road, air again performs better albeit now at even shorter distances (figure 8). There are fuel cost and emission savings for all distances beyond a mile. Both the fuel cost and emission savings double with congestion on roads. For example for a 50 mile trip, \$2.15 (uncongested road) and



(a) L/D = 5.

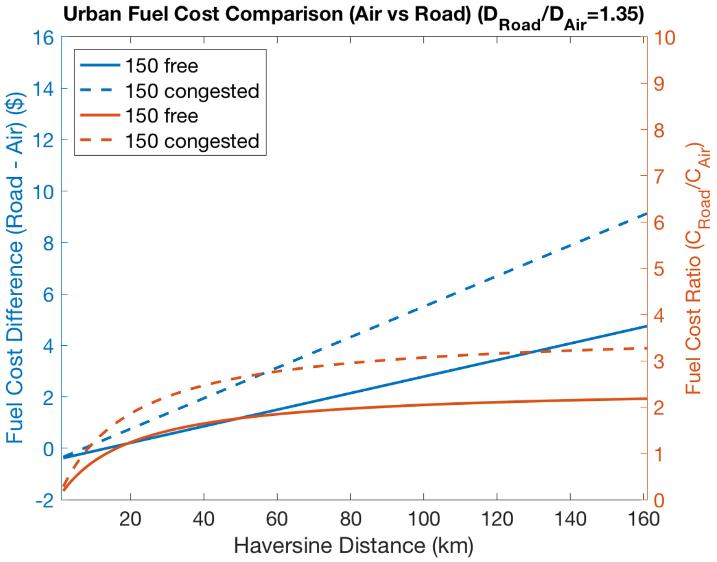


(b) L/D = 10.

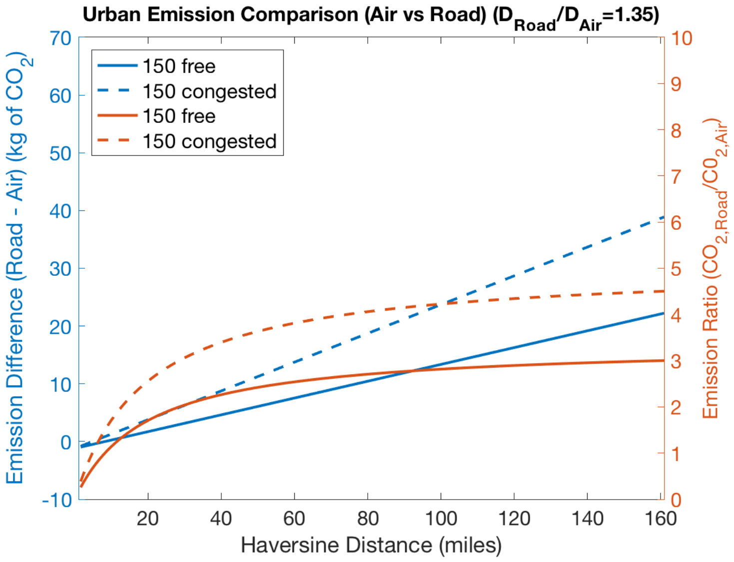
Figure 7. Emission Comparison - Road vs Air. Orange - Emission ratio, Blue - Emission difference

\$4.34 (congested road) are saved in fuel costs and the corresponding CO_2 emissions are less by 10.51 kg and 18.84 kg per passenger.

The chosen aircraft design is only a 2-seater. Automated aircraft that can carry a lot more passengers might produce more savings per passenger from consolidation. But they are also bulkier and these savings could get offset by increases in electric aircraft weight due to larger batteries needed. To test how the trends change, we perform the same analysis with the 6 passenger NASA eVTOL model that had an L/D of 7.2. However that aircraft design assumes a pilot. This pilot could be replaced instead by automated technologies in future. Hence, we assume that the weight advantage gained by removing the pilot is overcome by additional structural weight for automation and there only use an occupancy of 5 to evaluate per passenger fuel costs and emissions



(a) Enroute Fuel Cost per Passenger Comparison.

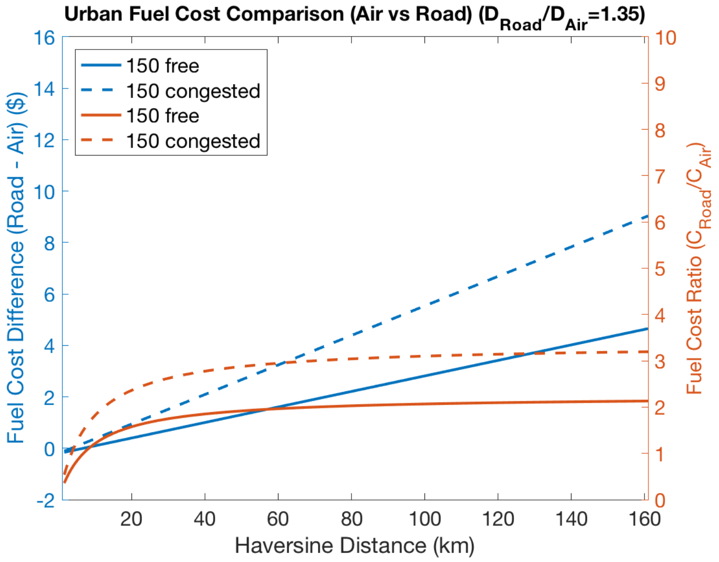


(b) Emission per Passenger Comparison.

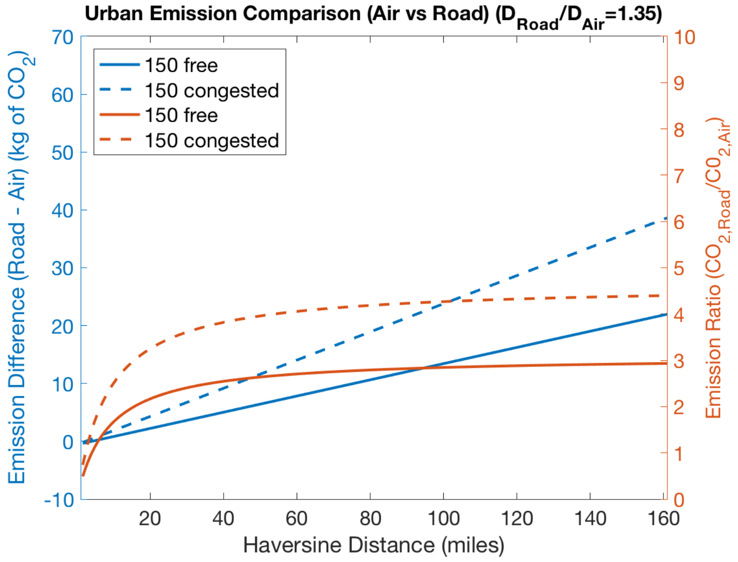
Figure 8. Road (Occupancy = 1.54) vs Air (Occupancy = 2). Orange - Metric ratio, Blue - Metric difference

(figure 9).

We find the per passenger trends strikingly similar. For example, for a 50 mile trip, fuel cost savings per passenger by air compared to uncongested and congested road are slightly reduced to \$2.02 and \$3.94, respectively. (For the 2-seater the corresponding numbers were \$2.15 and \$4.34). The CO_2 emissions difference per passenger is mildly increased to 10.69 kg and 19.02 kg (10.51 kg and 18.84 kg for the 2-seater). Either way, the per passenger fuel costs and emissions are better by air than road for all distances. There are at least two implications of this. First, a per passenger normalization seems a better way to compare the feasibility of different vehicle designs. Second, a bulkier aircraft may not necessarily gain the benefits of consolidation with respect to our chosen metrics with a similar design efficiency, with or without automation.



(a) Enroute Fuel Cost per Passenger Comparison.



(b) Emission per Passenger Comparison.

Figure 9. Road (Occupancy = 1.54) vs Air (Occupancy = 5). Orange - Metric ratio, Blue - Metric difference

Overall, air fares better compared to roads for moving passengers based on enroute transit times, energy costs and emissions.

4.2. Consolidated Goods Trips

We assume that instead of a delivery truck distributing packages over a network, the package can be carried directly from the distribution center to any address. Hence, the travel time benefit of air vs road becomes trivial. For the remaining two metrics, we evaluate as below.

A standard diesel UPS truck with the aforementioned assumptions in section 3.2, spends about 8.96 kJ/kg/km of energy and 0.00079 kg of CO_2/kg/km of emissions. The metrics here are normalized by package weight and distance. We also express the fuel cost directly in terms of energy here instead of the dollar value for comprehensibility as otherwise the number becomes quite negligible.

A stated in under assumptions, we choose DJI S900 as a representative. It spends about 4.26 kJ/kg/km of energy and 0.00046 kg of CO_2/kg/km of emissions. Hence, on face value drones have the potential to fare better in terms of energy consumption and emissions.

However, a delivery truck is more efficient in terms of vehicle miles traveled and hence the above benefit may not be necessarily existent if we sum up the fuel costs and emissions over total distances traveled (which themselves will vary based on the specific distribution network). For this we look at the results of Goodchild and Troy. Goodchild and Toy (2018) studied the tradeoff between delivery by drones and trucks based on Vehicle Miles Travelled (VMT) and Emissions. They divided LA County into 330 service zones with a main depot at the center. They used truck emissions from California Air Resources Board (CARB) database for a standard diesel truck and compared with drones with varying Average Energy Consumption (AEC) (Wh/mile). The study found that even though trucks would travel 98.45% less distance per recipient than drones on average, drones would still produce less emissions if their AEC is less than 25 Wh/mile. Our representative vehicle above has an AEC of roughly 9 Wh/mile for carrying a 10 lb (4.5 kg) package. Hence, our analysis also fits a specific network design study. Therefore, we can again conclude that air is at par or better than roads for consolidated goods movement.

4.3. Unconsolidated Goods Trips

Food, household items, groceries, emergency medical supplies, etc. are a few examples of a vast variety of unconsolidated goods that are frequently moved in an urban area. We therefore study a simple example and then extend the results to range of goods weights to cover the above variety.

First, we evaluate a sample shopping trip. Assume a consumer trip to a store a mile away for a gallon of milk (8.6 lb or 3.9 kg). As explained for consolidated goods movement, travel time benefits here are also trivial. Now an average gasoline based Sedan with a mileage of 25MPG, spends about 10466 kJ for carrying that gallon of milk (in addition to the driver and the roughly 3000 lb or 1360 kg sedan) consuming \$0.24 in fuel costs and producing 0.91 kg of CO_2 emissions.

In comparison, the above drone (as used in the previous section) for the same trip would spend 26.75kJ, consuming \$0.001 in electricity costs and produce on average 0.003 kg of CO_2. Hence, the car spends and produces, roughly 250 times the energy and 300 times the emissions respectively, compared to a drone on the same trip.

However, unconsolidated goods with a wide variety of weights can be moved by a car. But a drone is limited in capacity. There is also a mini consolidation effect in a car. For example, in the example of the shopping trip, a consumer could buy a few different items instead of just a gallon of milk. For movement by air, each item has to be separately moved. Again the time benefit here is trivial. We show the variation in fuel cost and emission ratios in figures 10 and 11, respectively.

The goods weight difference is negligible compared to the car weight. So the difference in fuel consumption of the road trip will also be negligible for a given distance. The fuel cost and emissions by road practically stay the same. However, each item

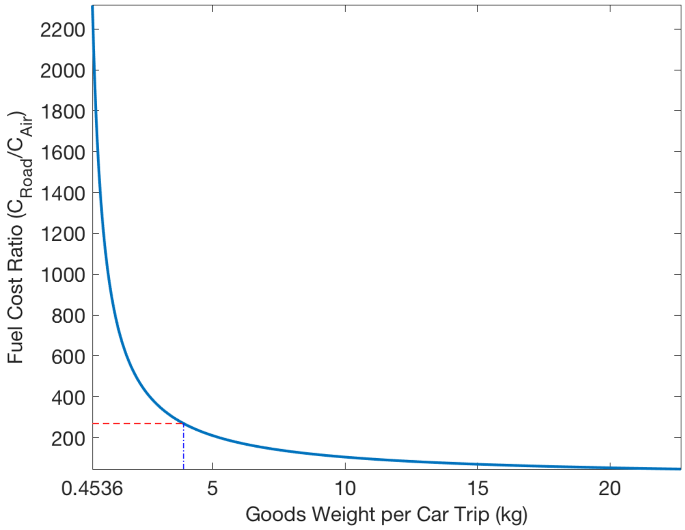


Figure 10. Fuel Cost comparison with varying Goods Weight - Road vs Air. The red and blue dotted lines show the sample shopping trip in text.

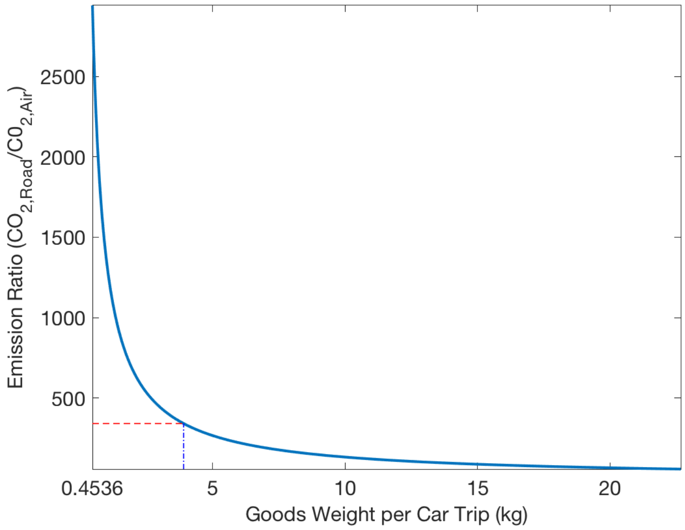


Figure 11. Emissions comparison with varying Goods Weight - Road vs Air. The red and blue dotted lines show the sample shopping trip in text.

has to be separately delivered if a drone is used. Therefore, the advantage of drones reduces as the total weight of unconsolidated goods moved increases. Yet, even for 50 pounds (22.68 kg) of unconsolidated goods, a car would spend 45 times more fuel costs and produce 60 times more emissions than if the same goods were moved by air. We note that over 200 single deliveries by drone would still amount to lesser energy costs and emissions than a single car trip. This clear advantage owes to the fact that for unconsolidated goods movement by cars and other light and heavy motor vehicles, extensive energy is spent on moving the vehicle itself. Drones on the other hand provide the advantage of fitting form to need. Air therefore beats road even for unconsolidated goods movement.

5. Conclusions and Discussion

This article presented an analytical process to determine the viability of urban travel by air compared to road. As the realm of connected and automated vehicles penetrates the roads further and dawns in the urban air, such an analysis helps gauge the direction for the evolution of our urban landscapes and identify the challenges to realize that evolution.

The results show that for each of the three different kinds of movement, namely - Passenger trips, Consolidated Goods trips and Unconsolidated Goods trips, electric air travel fares at par or better than gasoline road travel, in an *uncongested airspace.* Since, aircraft are more than twice as fast as automobiles on uncongested roads, enroute travel time is improved across the board.

For a 50 mile passenger movement, road takes at least 33 min and 98 min longer than air depending on whether it is uncongested or congested. An operator also saves at least \$1.55 and \$4.55 respectively in fuel costs and produces 10.51 and 21.92 kilograms less CO_2 emissions respectively for the same trip. However travelling by road is cheaper, for an under 15 mile movement in uncongested conditions and for a roughly 8 mile or shorter movement in congested conditions. It is greener for up to 8 mile distance in uncongested conditions and up to 5 miles in congested conditions. These results are for the lowest circuity factor of 1.20. The savings are increased and the transition distances (when air becomes at par or better than road) become shorter as the circuity factor of road travel compared to air travel increases.

Additionally, we also performed a sensitivity analysis by varying the aircraft cruise efficiency and also compared different aircraft by normalizing the metrics on a per passenger basis. We found that improving the L/D of the aircraft has a pronounced effect on the fuel cost and emission savings. Normalizing the metrics on a per passenger basis proved effective for comparing aircraft with different designs.

Consolidated goods movement by small aircraft also fares at par or better than diesel delivery trucks, if the average energy consumption of the aircraft is less than 25 Wh/mile. For unconsolidated goods movement, air is about 250 times and 300 times better than road in terms of fuel cost and emission benefits respectively.

Therefore, to summarize the findings on airspace feasibility and answer the opening question of the chapter - Air is a feasible alternative to roads for hub-door and door-door urban movement, as it fares at par or better on enroute travel time, fuel costs and CO_2 emissions, *when the airspace is uncongested.*

The value of the above benefits to a consumer will however vary based on individual preferences and the travel demand pattern. This is a good direction for further exploration. For example, a 42 min time saving could be valued differently based on whether it is a work or leisure trip. When it is valued high, the consumer's willingness to pay will determine how much overhead costs can be tolerated by an air service provider, in addition to the fuel costs. A similar analysis comparing direct operating costs of air vs road would than become feasible.

The primary mode of urban movement fundamentally defines what cities look like (see figures 1). Major urban centers in the US devote 50 to 60 percent of their real estate to vehicles, roughly half of which is used for parking ("We Are the 25%: Looking at Street Area Percentages and Surface Parking", 2011). How would urban regions improve their space utilization, if they were built instead for significant transport by air, especially via automated aircraft? This becomes worth exploring now since air seems a viable alternative to road.

It is also noteworthy that these benefits are in an urban area designed today to be highly efficient for road travel. What if the cities of tomorrow were designed to be highly efficient for movement by both air and road or just air? What if vehicles could travel in closer proximity owing to the fast inter vehicle data exchange and on board technology automation. This work therefore also motivates exploring newer urban designs and policy changes that support UAM. There are examples of cities which have already redesigned themselves to sustain non-automobile travel modes as shown in figure 12. Amsterdam in the Netherlands was redesigned to accommodate bike travel(Van der Zee, 2015). Giethoorn in the same country, developed itself around canals instead of developing roads. Even redesigning for air is not that far fetched an idea as proven by the already developed fly in community at Spruce Creek, Florida.

Therefore, to summarize the findings on the future of connected and automated vehicles in air vs road and answer the introductory question - Air is a feasible alternative to roads for hub-door and door-door urban movement, as it fares at par or better on enroute travel time, fuel costs and CO_2 emissions, *when the airspace is uncongested.*

Figure 12. Top: Left - Roads in Amsterdam, Netherlands redesigned for bike travel. Right - Houses in Giethoorn, Netherlands connected by canals instead of roads. Bottom: Fly in Community - Spruce Creek, Florida, USA

Notes

Since a lot of the data was taken from US sources, British units have been used to state the numbers as listed/used in specifications, reports, flight levels, etc. However, wherever appropriate, the SI unit conversion has been provided. This work is an abstraction of the second chapter of the doctoral thesis work of Dr. Bulusu (2019) and the thesis with the entire set of detailed results can be accessed here.

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