From Roads to Skies: The Next Revolution in Urban Transportation?

Vishwanath Bulusu and Raja Sengupta
University of California, Berkeley, CA, USA

***Abstract*—Owing to a century of innovation in 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) as the next revolution in urban transportation.**

I. 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.

Is air a feasible 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, drone-based services like photography, package delivery, surveying, surveillance, news-gathering, law enforcement, 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 [3], from the goods and services sector.

What about moving people? With rapid innovation in electric propulsion and Personal Aerial Vehicle (PAV) (2-4 passengers) design, fuel efficiency and emission numbers have already improved and are expected to get better. For example, the electric Vertical Take Off and Landing (eVTOL) Airbus Vahana produces 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 produces close to two-thirds the CO_2 emissions of either. (see section II for numerical details). As a result, eVTOLs are expected to lead the way for the era of UAM [4].

Parallely, automobiles have undergone a similar revolution. Electric and hybrid (part gasoline and part electric) 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 less than 1% of global automobile sales and less than 2% of sales in USA. 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 [5]. Hence, we use eVTOL and gasoline automobile as the representative vehicles for air transport and road transport respectively.

The primary mode of urban movement fundamentally defines what cities look like (see figures figs. 1, 5 and 6). 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 [6]. How would urban regions improve their space utilization, if they were built instead for significant transport by air? This is worth exploring only if the aforementioned advances make air a feasible alternative to road.

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 II lists all the assumptions made for each type of urban movement and section III presents the detailed analysis of the metrics. Section IV summarizes our findings and identifies areas for further exploration.

Fig. 1: Columbus Circle, New York City, from 1905 [1] to 2015 [2]

II. Background

UAM studies have shown improvements in urban passenger air travel time for both hub-door [7] like and door-door [8] services with specific trip designs. Uber [9] estimates its future air taxis to be competitive to its current road based rideshare services based on time, direct operating costs and emissions. Our work complements these efforts for passenger movement.

The average uncongested freeway speeds in a US metropolitan region are around 65 mph. On congested roads, the speeds come down to about 30 mph [10]. Similarly, the US average fuel economy for cars comes down from about 30 mpg to roughly 20 mpg due to congestion [11]. In comparison, urban air travel is envisioned to be most fuel efficient at speeds of about 125-150 mph [9] with a power consumption in the range of 70-80 kW (for a 2 passenger eVTOL in cruise at or below 5000 ft) [9], [12]. We use the above numbers for our enroute travel time and fuel cost analysis. Also for eVTOL, we add an additional 500kW of power for take off and landing occurring over a combined period of two minutes for 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 which is more than twice that of a helicopter like the Robinson R44. An all electric Airbus Vahana give thrice that mileage (using an energy density conversion of 34.44 kWh/gal for aviation fuel [13]) while producing less CO_2 per kWh. These improvements are expected to get better and therefore motivate this 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 [14] 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 that delivers roughly 200 packages a day against a drone that can deliver a similar package by air, normalizing the fuel and emission numbers by weight and distance. For unconsolidated goods, we compare a sedan trip to buy a gallon of milk from a grocery store a mile away from home against the same delivered by a drone.

Finally, we base our comparisons on the dimensions of time, energy and emissions. Our metrics, namely - travel time, fuel cost and CO_2 emissions analyze only enroute statistics to cover a broader class of operations agnostic to specific locations and network design.

III. Results

A. Passenger Trips

All our passenger movement results look at the comparisons in two ways - 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). Comparisons are made assuming the urban road distance is 1.35 times the haversine (great circle) distance on average [8], [9].

Figure 2 shows four comparisons for travel time - 125 mph by air (most fuel efficient air speed [9]) against uncongested (free) and congested road travel; and 150 mph by air (best speed with minimal reduction in fuel efficiency [9]) also against the same. Enroute travel time is reduced by one-third for air compared to free road conditions. This is in line with Antcliff et. al. [8] where they found a 3 times improvement in total trip time, accounting for first and last mile movement and take-off and landing times.

Congestion on roads more than doubles the advantage of air against roads. For example, for a 50 mile (haversine distance) long trip, enroute air time is 20 min compared to 62 min by road that increases to 135 min when the road is congested. This translates to a time saving of 42 min and 115 min for free and congested road conditions respectively.

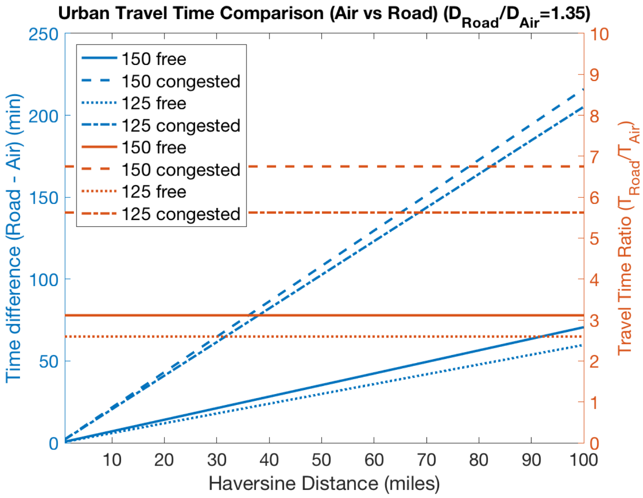

Fig. 2: Enroute Travel Time Comparison - Road vs Air. Orange - Travel Time ratio, Blue - Travel Time difference

Energy/fuel cost comparison is shown in figure 3. For gasoline and electricity we use fuel costs of $3/gal and $0.12/kWh respectively. Air fares better enroute compared to roads for longer travel segments. These savings are almost tripled with congestion on road. For example, for a 50 mile air trip, fuel spent enroute costs $2.41 and $5.79 less than uncongested and congested roads respectively. However, for uncongested trips under 20 miles and congested trips under 10 miles, road fuel costs beat air.

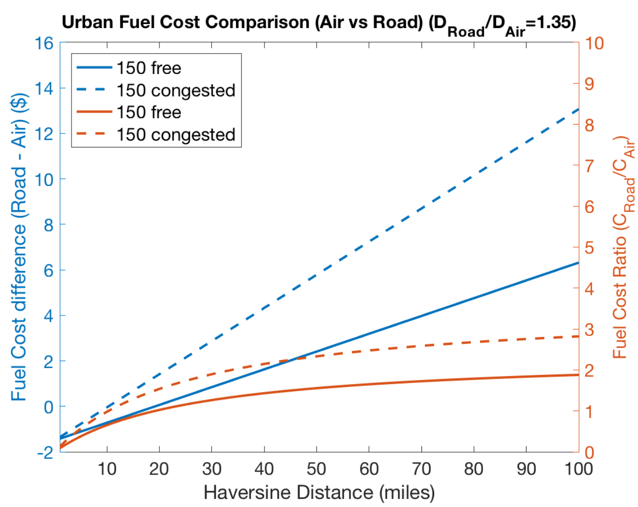

Fig. 3: Enroute Fuel Cost Comparison - Road vs Air. Orange - Fuel Cost ratio, Blue - Fuel Cost difference

We use CO_2 emission rates of 19.59 lbs/gal and 0.524 lbs/kWh for gasoline and electricity respectively, to compare emissions as shown in figure 4. We find that beyond 10 miles, it is greener to travel by air. If the roads are congested, this becomes true beyond 5 miles. Again for a 50 mile trip example, air produces 25.13 lbs less of CO_2 enroute on average with the savings almost doubled to 47.17 lbs when the roads are congested.

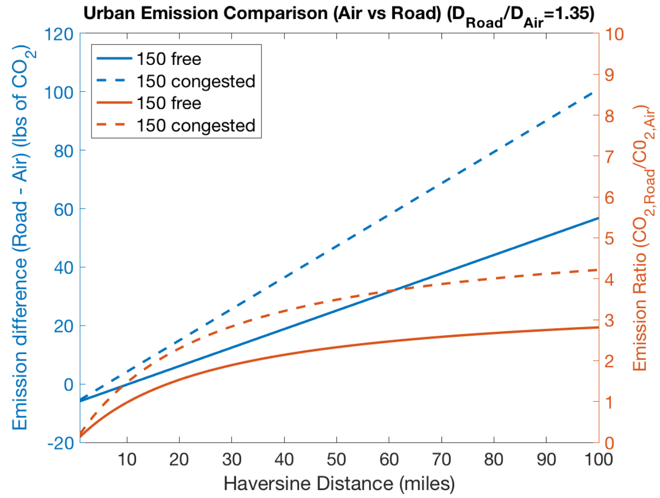

Fig. 4: Enroute CO_2 Emissions Comparison - Road vs Air. Orange - CO_2 Emissions ratio, Blue - CO_2 Emissions difference

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

B. Consolidated Goods Trips

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

A standard diesel UPS truck weighing 11000 lbs. with a maximum storage capacity of 12000 lbs. moves 200 packages 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 of fuel. If we assume that it moves only 5000 lbs of packages daily on average, it spends about 6.517kJ/lb/mile of energy and 0.001 lbs of CO_2/lb/mile of emissions.

Since, no efficient drone exists in the market currently that can deliver packages over long distances from hub to door, we choose DJI S900 as a representative. It produces 12A current at 24V for 18 min of flying time and can carry a payload of 10lb. At its maximum speed it can cover a distance of 10 miles in that time. It spends about 3.11 kJ/lb/mile of energy and 0.00045 lbs of CO_2/lb/mile 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. [14] studied the tradeoff between delivery by drones and trucks based on Vehcile 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 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.

C. Unconsolidated Goods Trips

We use the above information to evaluate a typical shopping trip. Assume a consumers trip to a store a mile away for a gallon of milk (8.6lbs). 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 the gallon of milk (in addition to the driver and the roughly 3000 lb sedan) consuming $0.24 in fuel costs and producing 1.5674 lbs of CO_2 emissions. In comparison, the above drone for the same trip would spend 26.75kJ, consuming $0.0009 in electricity costs and produce on average 0.004 lbs of CO_2. Hence, the car spends and produces, roughly 300 times the energy and 400 times the emissions respectively, compared to a drone on the same trip. Air therefore beats road even for unconsolidated goods movement.

IV. Conclusions and Future Research

We presented an analytical process to study the feasibility of urban travel by air compared to road. 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 42 min and 115 min longer on average than air depending on whether it is uncongested or congested. A consumer also saves $2.41 and $5.79 respectively in fuel costs and produces 25.13 pounds and 47.17 pounds less CO_2 emissions respectively for the same trip. However travelling by road is cheaper for a 20 mile or shorter movement in uncongested conditions and for a 10 mile or less movement in congested conditions. Similarly, it also produces less CO_2 for an uncongested trip under 10 miles and a congested trip under 5 miles.

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, a small drone is about 350 times better than an average sized sedan both in terms of fuel cost and emission benefits.

The value of the above benefits to a consumer will however vary based on individual preferences and 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.

Fig. 5: Roads in Amsterdam, Netherlands redesigned for bike travel

Fig. 6: Houses in Giethoorn, Netherlands connected by canals instead of roads

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? 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. Amsterdam (figure 5) in the Netherlands was redesigned to accommodate bike travel [15]. Giethoorn (figure 6) 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 (figure 7).

Therefore, to summarize the findings on airspace feasibility and answer the opening 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*.

V. Acknowledgements

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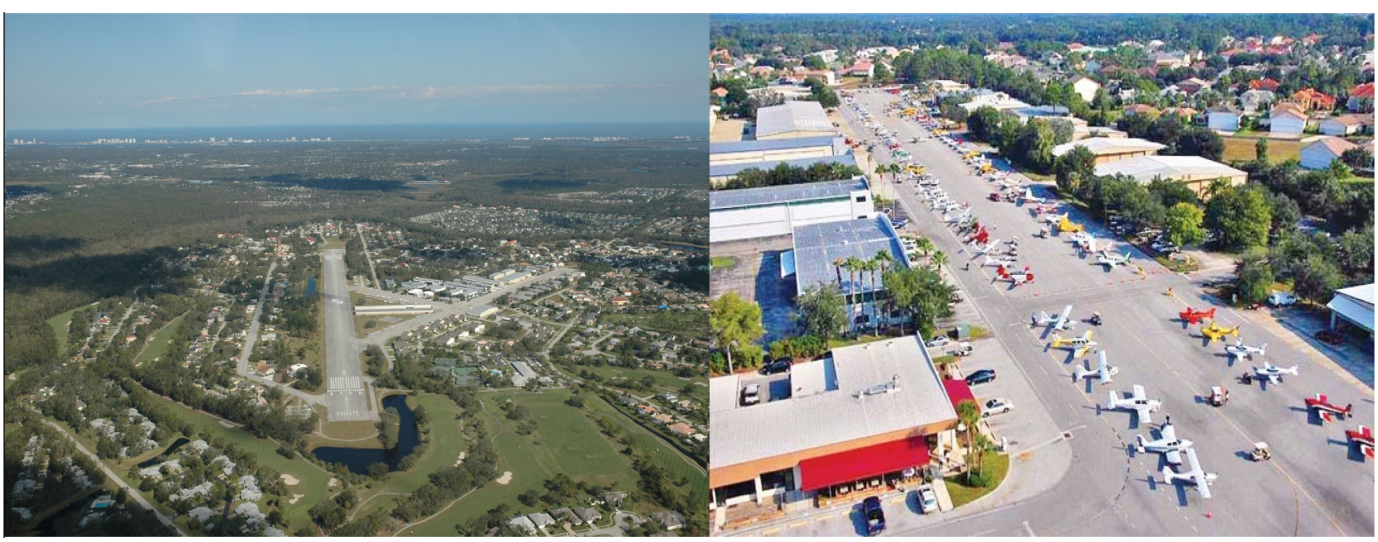

Fig. 7: Fly in Community - Spruce Creek, Florida, USA