External Supplement

"Shared Mobility for Last-Mile Delivery: Design, Operational Prescriptions and Environmental Impact"

Appendix E: Parameter Settings

E.1. Service Region Setting and Baseline Results

Table 1 lists the zip codes of the 15 areas considered in Section 6 along with their population densities and mean distances to the depot. Also listed are the baseline results, including the service zone design in terms of zone density as well as zip-code-specific costs of the shared-mobility system and the benchmark truck-only system.

Table 1: Population densities, distances to the depot and baseline results of the 15 zip-code areas.

Zip-code Area	Population density (km^{-2})	Distance to depot (km)	Zone size (km^2)	Cost with shared mobility ($)	Cost with trucks only ($)
1 (94710)	1171.6	5.29	1.721	64.3	68.4
2 (94702)	5022.5	4.83	0.402	75.9	67.5
3 (94703)	5890.5	5.29	0.342	96.1	83.7
4 (94709)	7842.7	9.78	0.257	55.7	47.5
5 (94720)	348.5	11.73	5.786	19.4	22.6
6 (94704)	8015.7	8.28	0.252	128.4	108.3
7 (94705)	2565.1	8.05	0.786	81.8	79.8
8 (94608)	4046.7	2.65	0.498	141.0	128.7
9 (94609)	4654.1	5.98	0.433	106.3	96.0
10 (94618)	2674.5	8.63	0.754	100.4	97.6
11 (94706)	5438.1	9.20	0.371	100.8	89.9
12 (94707)	2690.4	12.31	0.750	81.4	79.2
13 (94708)	1286.2	15.07	1.568	99.8	104.4
14 (94607)	1678.5	8.97	1.201	191.8	196.2
15 (94612)	5628.1	9.20	0.358	85.2	75.6

E.2. Vehicle-Related Parameter Estimates

Cost parameters: Cost parameter values are calibrated based on empirical evidence. To consider both the economic and the environmental objectives, the total cost refers to either operating costs or GHG emissions, denoted by c and c^e, respectively:

1. Operating costs of trucks consist of vehicle costs and driver wages.

    (a) The vehicle costs break down into components of fuel consumption, maintenance, and distance-related depreciation. On September 14, 2015, the average prices of diesel in

the U.S. was $p_t = \$0.664$ L^{-1} (http://www.eia.gov/petroleum/gasdiesel/). According to Lammert (2009), the fuel efficiency of a UPS delivery van (Freightliner P70) is 10.6 miles per gallon of diesel, or $f_t = 0.222$ L/km. The truck fuel cost estimate is thus $0.664 \times 0.222 = \$0.147$ km^{-1}. From the same report, the maintenance cost is $\$0.130$ mile^{-1}, or $\$0.081$ km^{-1}. From Barnes and Langworthy (2003), distance-related depreciation cost of a van under city driving conditions is $\$0.081$ mile^{-1}, or $\$0.050$ km^{-1}. Collectively, adjusting for annual inflation of 2.5%, the 2015 vehicle cost of a truck is $o_t = f_t p_t + u_t + l_t = 0.147 + 0.081 \times 1.025^3 + 0.050 \times 1.025^{12} = \$0.301$ km^{-1}, where u and l denote per-km costs of maintenance and depreciation, respectively.

(b) Concerning per-km wages, a truck driver's hourly wage in 2003 was $b_t = \$30$ hour^{-1} as Barnes and Langworthy (2003). The inflation-adjusted 2015 value is $b_t = \$40.3$ hour^{-1}. The truck speed depends on operating status. First assume the average vehicle driving speed to be 29.9 miles per hour, or $s = 48.1$ km/hour, which is the simple average of driving speeds in 50 U.S. cities (http://infinitemonkeycorps.net/projects/cityspeed/). According to Lammert (2009), the average driving speed of a UPS delivery van is 22.7 miles per hour. In the shared mobility scenario, trucks do not stop at demand destinations. Their average speed is assumed to be the simple average of the preceding two speeds, namely $s_t = (29.9 + 22.7)/2 = 26.3$ miles per hour, or 42.3 km per. The per-km wage is $w_t = \frac{b_t}{s_t} = \$0.95$ km^{-1}. In the benchmark truck-only scenario, assume the bulk transport speed to be equal to s_t. The calculation of the last-mile speed needs to take trucks' frequent stops into account. Using estimates from Lammert (2009), the speed is determined as $s'_t = \frac{\text{travel distance (75mi)}}{\frac{\text{travel distance (75mi)}}{\text{driving speed (22.7 mph)}} + \text{average duration of a stop (97s)} \times \text{number of stops (197)}} = $ 8.7mph $= 14.0$ km/hour. The per-km wage is $w'_t = \frac{b_t}{s_t} = \$2.88$ km^{-1}.

(c) Combining vehicle costs and driver wages, the per-km operating cost for trucks in the shared mobility scenario and in the bulk transport state of the truck-only scenario is $c_t = o_t + w_t = \$1.26$ km^{-1}. The per-km operating cost in the last-mile state of the truck-only scenario is $c'_t = o_t + w'_t = \$3.18$ km^{-1}.

2. Car drivers' wages depend on driving speeds. The terminal-bound speed is assumed to be the aforementioned average vehicle driving speed $s = 48.1$ km/hour. The average speed during the outbound delivery services depends on driving speed and delivery speed. Assume that the average driving speed is 18 miles per hour, which is smaller than the aforementioned driving speed of a delivery van (22.7 miles per hour), considering that the lat-

ter speed has a fast bulk-transport component. On the other hand, the delivery speed of car drivers is assume to be twice the speed of truck drivers (i.e., the average duration of a stop is $\frac{97}{2} = 48.5$s), since a car is easier to maneuver in local residential areas and its limited package load is easier to handle. Therefore, the outbound delivery speed is given by $s_o = \frac{\text{travel distance (75mi)}}{\frac{\text{travel distance (75mi)}}{\text{driving speed (18 mph)}} + \text{average duration of a stop (48.5s)} \times \text{number of stops (197)}} = 11.0$mph $= 17.7$ km/hour.

3. When the cost refers to GHG emissions, the per-km estimates are $c_t^e = e_t f_t = 0.597$ kg/km for trucks and $c_c^e = e_c f_c = 0.369$ kg/km for cars, where EPA (2014) estimates that CO2 emissions are $10,180$ grams from a gallon of diesel (i.e., $e_t = 2.69$ kg/L) and $8,887$ grams from a gallon of gasoline (i.e., $e_c = 2.35$ kg/L).

Capacities: UPS (2013) reports that a similar P70 delivery van has capacity of up to 20.8 m^3 with 110 kg m^{-3}, which amounts to $2,288$ kg. Hence, let truck capacity $v_t = 2,000$ kg. For cars, interior space is not a realistic estimate of the loading capacity for home delivery services. Instead, suppose the car capacity is $v_c = g \cdot 15 = 150$ kg, where $g = 10$ kg is assumed to be the mean weight of goods demanded at each designation. This value of g is smaller than the estimate of 18 kg in Cachon (2014) for the amount of goods that the average consumer carries with each shopping trip.

Also consider a heavy-duty scenario where heavy-duty trucks are in place of P70 delivery vans. From Burton et al. (2013), the Freightliner M2-106 has load capacity of about $6,000$ kg and fuel efficiency of 550 g/mile (6.3 miles per gallon). Repeating the above procedure yields the estimates of its per-km operating cost for bulk transport as $c_h = \$1.36$ km^{-1} and the per-km emission rate as $c_h^e = 1.0034$ kg/km.

E.3. Shared Mobility Supply and Wages

Exogenous information pertaining to supply and wages of shared mobility includes $\{w_b, w_m, \nu, \bar{m}, \bar{\mu}, F(\cdot)\}$. Set the base fare $w_b = \$1.65$ and the trip-dependent fare $w_m = \$40.85$ hour^{-1} based on the data from the official Uber website (https://www.uber.com/cities/san-francisco), considering that Uber takes 25% commissions. Set $\nu = 4.07$ hr^{-1}, which is the average of its values in ten major cities in the U.S. in 2015 (SherpaShare (2016)). Directly estimating $\bar{m}$ and $\bar{\mu}$ is difficult and prone to obsolescence, as Hall and Krueger (2016) shows that the numbers of registered Uber drivers and total ride-share service requests are increasing rapidly. Since the operating cost model (14b) crucially depends on $\tilde{\mu}$ instead, it is reasonable to choose $\{\bar{m}, \bar{\mu}, F(\cdot)\}$ such that the endogenized $\tilde{\mu}$ generates the expected car drivers' earning rate that is consistent with its empirical estimates. Following

this consideration, set $\bar{m} = 0.36\% \times$ population density, which has the same driver-to-population ratio with the case in New York City ($30,000$ registered Uber drivers and 8.4M population as of February 2016 according to Digital Marketing Ramblings (2016)), $\bar{\mu} = 0.33\% \times$ population density, and assume $F(\frac{\mu(\nu w_b + w_m)}{\mu+\nu}) = 1 - exp(-0.026 * \frac{\mu(\nu w_b + w_m)}{\mu+\nu})$. For all zip-code areas in the baseline scenario, the resulting $\tilde{\mu}$ is 3.43 hr^{-1} and $\tilde{m}$ varies by location. The resulting long-run average earning rate $\frac{\mu(\nu w_b + w_m)}{\mu+\nu} = 22.0$ \$·hr^{-1}, which is within the range of median hourly earnings of Uber driver-partners in six major cities of the U.S. (from \$16.23-\$23.87 by Hall and Krueger (2016)).

The validity of the assumption that enough cars are available to pick up packages (i.e., $m > \frac{m_z}{A} = \frac{gn}{v_c}$): It can be inferred from Equations (5) and (6) on page 13 that this assumption holds if and only if the density of demand destinations n and the density of potential supply of shared mobility $\bar{m}$ satisfies $n < \frac{v_c}{g}\bar{m}$. From parameter estimates in Appendix E.2 (i.e., $v_c = 150$ kg, $g = 10$ kg, and $\bar{m} = 0.36\% \times$ population density), n needs to exceed $5.4\% \times$ population density to violate the assumption. Suppose that the logistics service provider does four dispatches each day, the considered level of shared mobility supply is able to satisfy the daily demand for delivery services at the level of $4 \times 5.4\% \times$ population density, which represents a high penetration of home delivery activity. This threshold level of n to maintain the validity of this assumption will further increase as the shared mobility supply $\bar{m}$ grows due to the growths of the ride-share service market and the delivery service market. On the other hand, if n is large enough to violate this assumption, back-to-back delivery trips will be needed, or trucks need to be engaged in last-mile deliveries.

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