Appendix A - Equations for cost estimation and assumed distributions

Fare per mile

$$\begin{aligned} fare\_per\_mile = (&vehicle\_financing + technology\_financing + \\ &licensing + insurance + maintenance + cleaning + \\ &fuel + profit + labor + general\_and\_admin) \\ &\times \frac{1}{utilization\_rate} \end{aligned}$$

Vehicle Financing and Technology Financing

Variable Name	Value	Source
vehicle_price	$28,000	Compostella et al. (2020)
tech_price	$150,000	Moreno (2021)
annual_interest_rate	7%	Nunes and Hernandez (2020)
vehicle_financing_lifespan	3 years	Nunes and Hernandez (2020)
vehicle_lifespan	5	Nunes and Hernandez (2020)
payment_periods_per_year	12	Assuming monthly payments
mileage_annual	65,000	Schaller Consulting (2006)

Equations:

$monthly\_loan\_payment = \frac{vehicle\_price}{([(1+i)^n - 1] \div [i(1+i)^n]}$

$$n = payment\_periods\_per\_year \times vehicle\_financing\_lifespan$$

$i = \frac{annual\_interest\_rate}{months\_per\_year}$

$total\_loan\_payment = monthly\_loan\_payment \times months\_per\_year \times vehicle\_financing\_duration$

$financing = \frac{total\_loan\_payment}{miles\_per\_year \times vehicle\_lifespan}$

Licensing It is currently unclear whether robotaxis will be regulated under taxi or Transportation Network Company guidelines, which have differing licensing costs. See below for the calculation of taxi and TNC licensing fees.

Taxi Licensing - Chicago

The following costs are on a **per vehicle** basis

Variable Name	Value	Source
taxi_licensing_taxi_medallion_license	$500 per 2 years	BACP (2020)
taxi_licensing_ground_transportation_tax	$98/month	BACP (2020)
taxi_licensing_accessibility_fund	$22/month	BACP (2020)
taxi_licensing_advertising_fee	$100/year	BACP (2020)

Equations:

$$annual\_licensing\_taxi = taxi\_licensing\_taxi\_medallion\_license$$
$$+(taxi\_licensing\_ground\_transportation\_tax + taxi\_licensing\_accessibility\_fund) \times months\_per\_year$$
$$+taxi\_licensing\_advertising\_fee$$

$$licensing = \frac{annual\_licensing\_taxi}{miles\_per\_year}$$

TNC Licensing - Chicago

The City of Chicago identified 148,351 unique TNC drivers in a recent study BACP (2023). Only a fraction of these drivers, however, were categorized as full-time drivers. We assume robotaxis would operate on a full-time basis and thus use the mean number of full-time TNC drivers (1,313) as the fleet size for TNC licensing calculations.

Variable Name	Value	Source
tnc_licensing_admin_fee_per_year	$10,000/year per company	BACP (2020)
tnc_licensing_admin_fee_per_trip	$0.02/trip	BACP (2020)
tnc_licensing_ground_transport	$1/trip	BACP (2020)
tnc_licensing_access_fund	$0.10/trip	BACP (2020)
tnc_licensing_advertising_fee	$100/year per vehicle	BACP (2020)
fleet_size	1,313 vehicles	BACP (2023)
miles_per_trip	3.09 miles	City of Chicago (n.d.)

$$licensing\_tnc = \frac{tnc\_licensing\_admin\_fee\_tnc\_per\_year}{miles\_per\_year \times fleet\_size}$$
$$+\frac{tnc\_licensing\_admin\_fee\_tnc\_per\_trip + tnc\_licensing\_ground\_transport\_tnc + access\_fund\_tnc}{miles\_per\_trip}$$
$$+\frac{tnc\_licensing\_advertising\_fee}{miles\_per\_year}$$

Taxi Licensing - New York City

In New York City, taxi licensing occurs through the purchase of a taxi medallion. A down payment of 20% is applied with 25% of the down payment paid upfront and the remainder of the down payment financed over 5 years. The remaining balance is financed over 7 years.

Variable Name	Value	Source
taxi_medallion_price	$225,000	New York City Taxi & Limousine Commission (n.d.)
downpayment_percent	20%	Nunes and Hernandez (2020)
downpayment_upfront_percent	25%	Nunes and Hernandez (2020)
financing_period_downpayment	7 years	Nunes and Hernandez (2020)
financing_period_remainder	5 years	Nunes and Hernandez (2020)
medallion_interest_rate	5.4%	Nunes and Hernandez (2020)
payment_periods_per_year	12	Nunes and Hernandez (2020)
medallion_lifespan	20	Nunes and Hernandez (2020)

Equations:

$$n_d = payment\_periods\_per\_year \times financing\_period\_downpayment$$

$$n_r = payment\_periods\_per\_year \times financing\_period\_remainder$$

$i = \frac{medallion\_interest\_rate}{months\_per\_year}$

$$downpayment\_total = downpayment\_percent \times taxi\_licensing\_taxi\_medallion\_price$$

$$downpayment\_upfront = downpayment\_upfront\_percent \times downpayment\_total$$

$$downpayment\_remainder = downpayment\_total - downpayment\_upfront$$

$$downpayment\_monthly\_loan\_payment = \frac{downpayment\_remainder}{([(1+i)_d^n - 1] \div [i(1+i)_d^n]}$$

$$loan\_remainder = taxi\_licensing\_taxi\_medallion\_price - downpayment\_total$$

$remainder\_monthly\_loan\_payment = \frac{loan\_remainder}{([(1+i)_r^n - 1] \div [i(1+i)_r^n]}$

$$\begin{aligned} total\_medallion\_payment &= downpayment\_upfront \\ &+ (downpayment\_monthly\_loan\_payment \times n_d) \\ &+ (remainder\_monthly\_loan\_payment \times n_r) \end{aligned}$$

$licensing = \frac{total\_medallion\_payment}{miles\_per\_year \times medallion\_lifespan}$

Insurance For the *AV Baseline* model, the `av_operations_factor` is 1. The listed `av_operations_factor` is used in the *AV Advanced Technology* scenario.

Variable Name	Value	Source
vehicle_operations_insurance	$682/month	Bodine and Walker (2023); "Taxi Insurance" (2023)
av_operations_factor_insurance	0.5	Fagnant and Kockelman (2016)

Equation:

$$insurance = \frac{vehicle\_operations\_insurance \times months\_per\_year}{miles\_per\_year} \times av\_operations\_factor\_insurance$$

Maintenance We assume maintenance costs are $0.06/mi. For the *AV Baseline* model, the `av_operations_maintenance` factor is 1. The listed `av_operations_maintenance` factor is used in the *AV Advanced Technology* scenario.

Variable Name	Value	Source
vehicle_operations_maintenance	$0.06/mi	Parrott and Reich (2018); Reich and Parrott (2020)
av_operations_factor_maintenance	0.9	Fagnant and Kockelman (2016)

Equation:

$$maintenance = vehicle\_operations\_maintenance \times av\_operations\_factor\_maintenance$$

Cleaning We assume that taxi drivers clean the interiors of their vehicles every other day using $6 do-it-yourself cleaning supplies and clean the exterior of their vehicles using a $10 automatic car wash once per week. Given the sensitive nature of their sensors, robotaxi vehicles must be cleaned by hand by field support agents. We thus account for the robotaxi cleaning costs as part of the field support agent labor cost, assuming that the cost of the worker is greater than the marginal cost of the cleaning supplies required to perform the cleaning task.

Variable Name	Value	Source
exterior_cleaning_price	$6 per cleaning	Rainstorm Car Wash (2023)
interior_cleaning_price	$10 per cleaning	Rainstorm Car Wash (2023)
mileage_annual	65,000	Schaller Consulting (2006)

Equation:

$$cleaning = \frac{(weeks\_per\_year \times exterior\_cleaning\_price) + (\frac{days\_per\_year}{2} \times interior\_cleaning\_price)}{mileage\_annual}$$

Fuel For the *AV Baseline* scenario, the `av_operations_fuel` factor is 1. The listed `av_operations_fuel` factor is used in the *AV Advanced Technology* scenario.

Variable Name	Value	Source
fuel_cost_per_gal	$3.829/gallon	AAA (2023)
fuel_efficiency	45 miles per gallon	EPA (2021)
av_operations_factor_fuel	0.8	Stephens et al. (2016); Bösch et al. (2018)

Equations:

$$annual\_fuel\_cost = \frac{miles\_per\_year}{fuel\_efficiency} \times fuel\_cost\_per\_gal$$

$$fuel = \frac{annual\_fuel\_cost}{miles\_per\_year} \times av\_operations\_factor\_fuel$$

Labor

Traditional Taxis Overall equation:

$$labor = dispatcher + driver$$

Dispatcher

Variable Name	Value	Source
shift_days_per_year_dispatcher	365 days/year	Assumption
shift_length_dispatcher	8 hours	Assumption
wage_dispatcher	$17.05/hr	BLS (2022)
workers_per_shift_dispatcher	1 per shift per cluster	Assumption
vehicles_per_cluster	20	Nunes and Hernandez (2020)
overhead_rate	1.59	Nunes and Hernandez (2020)

Equations:

$$dispatcher\_per\_day = workers\_per\_shift\_dispatcher \times \frac{hours\_per\_day}{shift\_length\_dispatcher}$$

$$\begin{aligned} cluster\_cost\_dispatcher = (&shift\_days\_per\_year\_dispatcher \times shift\_length\_dispatcher \\ &\times wage\_dispatcher \times overhead\_rate \times 1) \\ +(&shift\_days\_per\_year\_dispatcher \times shift\_length\_dispatcher \times wage\_dispatcher \\ &\times (dispatcher\_per\_day - 1)) \end{aligned}$$

$$miles\_per\_cluster = vehicle\_annual\_miles \times vehicles\_per\_cluster$$

$$dispatcher = \frac{cluster\_cost\_dispatcher}{miles\_per\_cluster}$$

Driver

Variable Name	Value	Source
shift_days_per_year_driver	365 days/year	Assumption
shift_length_driver	12 hours	Assumption
wage_driver	$15.82/hr	Bureau of Labor Statistics (2022)
workers_per_shift_driver	1 per shift per cluster	Assumption
vehicles_per_cluster	1	Assumption

Equations:

$$driver\_per\_day = workers\_per\_shift\_driver \times \frac{hours\_per\_day}{shift\_length\_driver}$$

$$cluster\_cost\_driver = (shift\_days\_per\_year\_driver \times shift\_length\_driver \times wage\_driver \times driver\_per\_day)$$

$$miles\_per\_cluster = vehicle\_annual\_miles \times vehicles\_per\_cluster$$

$$driver = \frac{cluster\_cost\_driver}{miles\_per\_cluster}$$

Robotaxis Overall equation:

$$labor = customersupport + fieldsupport + monitor + coordinator$$

Field Support We assume that it takes a field support agent 20 minutes to clean and prepare a vehicle. Given that assumption, 24 vehicles could be cleaned by one person during an 8 hour shift. Additional field support agents are required in the deployment area to respond to incidents. We assume 4 field support agents are required to support 24 vehicles, yielding a worker to vehicle ratio of ratio of 1:6.

Variable Name	Value	Source
shift_days_per_year_fieldsupport	365 days/year	Assumption
shift_length_fieldsupport	8 hours	Assumption
wage_fieldsupport	$21/hr	Adecco (2023)
workers_per_shift_fieldsupport	1 per shift per cluster	Assumption
vehicles_per_cluster	6	Assumption
overhead_rate	1.59	Nunes and Hernandez (2020)

Equations:

$$fieldsupport\_per\_day = workers\_per\_shift\_fieldsupport \times \frac{hours\_per\_day}{shift\_length\_fieldsupport}$$

$$\begin{aligned} cluster\_cost\_fieldsupport = (&shift\_days\_per\_year\_fieldsupport \times shift\_length\_fieldsupport \\ &\times wage\_fieldsupport \times overhead\_rate \times 1) \\ +(&shift\_days\_per\_year\_fieldsupport \times shift\_length\_fieldsupport \times wage\_fieldsupport \\ &\times (fieldsupport\_per\_day - 1)) \end{aligned}$$

$$miles\_per\_cluster = vehicle\_annual\_miles \times vehicles\_per\_cluster$$

$$fieldsupport = \frac{cluster\_cost\_fieldsupport}{miles\_per\_cluster}$$

Remote Monitor

Variable Name	Value	Source
shift_days_per_year_monitor	365 days/year	Assumption
shift_length_monitor	8 hours	Pawlowski (2011)
wage_monitor	$19/hr	ICONMA (2023)
workers_per_shift_monitor	1 per shift per cluster	Assumption
vehicles_per_cluster	16	Kolodny (2023)
overhead_rate	1.59	Nunes and Hernandez (2020)

Equations:

$$monitor\_per\_day = workers\_per\_shift\_monitor \times \frac{hours\_per\_day}{shift\_length\_monitor}$$

$$\begin{aligned} cluster\_cost\_monitor = (&shift\_days\_per\_year\_monitor \times shift\_length\_monitor \\ &\times wage\_monitor \times overhead\_rate \times 1) \\ +(&shift\_days\_per\_year\_monitor \times shift\_length\_monitor \times wage\_monitor \\ &\times (monitor\_per\_day - 1)) \end{aligned}$$

$$miles\_per\_cluster = vehicle\_annual\_miles \times vehicles\_per\_cluster$$

$$monitor = \frac{cluster\_cost\_monitor}{miles\_per\_cluster}$$

Customer Support

Variable Name	Value	Source
shift_days_per_year_customersupport	365 days/year	Assumption
shift_length_customersupport	8 hours	Pawlowski (2011)
wage_customersupport	$19/hr	Indeed (2023); ICONMA (2023)
workers_per_shift_customersupport	1 per shift per cluster	Assumption
vehicles_per_cluster	16	Assumption
overhead_rate	1.59	Nunes and Hernandez (2020)

Equations:

$$customersupport\_per\_day = workers\_per\_shift\_customersupport \times \frac{hours\_per\_day}{shift\_length\_customersupport}$$

$$\begin{aligned} cluster\_cost\_customersupport = (&shift\_days\_per\_year\_customersupport \times shift\_length\_customersupport \\ &\times wage\_customersupport * overhead\_rate * 1) \\ +(&shift\_days\_per\_year\_customersupport \times shift\_length\_customersupport \\ &\times wage\_customersupport \times (customersupport\_per\_day - 1)) \end{aligned}$$

$$miles\_per\_cluster = vehicle\_annual\_miles \times vehicles\_per\_cluster$$

$$customersupport = \frac{cluster\_cost\_customersupport}{miles\_per\_cluster}$$

Coordinator

Variable Name	Value	Source
shift_days_per_year_coordinator	365 days/year	Assumption
shift_length_coordinator	8 hours	Assumption
wage_coordinator	$29/hr	Salary.com (2022)
workers_per_shift_coordinator	1 per shift per cluster	Assumption
vehicles_per_cluster	80	Assumption
overhead_rate	1.59	Nunes and Hernandez (2020)

Equations:

$$coordinator\_per\_day = workers\_per\_shift\_coordinator \times \frac{hours\_per\_day}{shift\_length\_coordinator}$$

$$\begin{aligned} cluster\_cost\_coordinator = (&shift\_days\_per\_year\_coordinator \times shift\_length\_coordinator \\ &\times wage\_coordinator * overhead\_rate * 1) \\ &+ (shift\_days\_per\_year\_coordinator \times shift\_length\_coordinator \\ &\times wage\_coordinator \times (coordinator\_per\_day - 1)) \end{aligned}$$

$$miles\_per\_cluster = vehicle\_annual\_miles \times vehicles\_per\_cluster$$

$$coordinator = \frac{cluster\_cost\_coordinator}{miles\_per\_cluster}$$

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