Appendix

This appendix includes detailed descriptions of all model equations and input assumptions.

Annual automation budget on a per mile basis

$$\begin{aligned} annual\_automation\_budget &= (fare\_per\_mile \times utilization\_rate) \\ &\quad - (financing + licensing + insurance + maintenance + fuel + labor) \end{aligned} \tag{1}$$

Net Present Value of Automation Budget

Variable Name	Value	Source
av_tech_lifespan	5	Assumption
vehicle_lifespan	5	Nunes and Hernandez (2020); New York City Taxi & Limousine Commission (2014a)
discount rate (i)	5%	Compostella et al. (2020)
mileage_annual	65,000	UITP (2020); New York City Taxi & Limousine Commission (2014b)
fare_per_mile	$5.00	City of Chicago (n.d.); New York City Taxi & Limousine Commission (n.d.b)
utilization_rate	50%	Cramer and Krueger (2016); Nunes and Hernandez (2020)

Year 0: Initial investment = `net_present_automation_budget`

Year 1 to Vehicle Lifespan: Annual automation budget

Year > Vehicle Lifespan: Annual automation budget without vehicle financing

$$net\_present\_automation\_budget = \sum_{k=1}^{n} \frac{annual\_automation\_budget \times mileage\_annual}{(1+i)^k} \tag{2}$$

Financing

Variable Name	Value	Source
vehicle_price	$28,000	Compostella et al. (2020)
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	New York City Taxi & Limousine Commission (n.d.b); UITP (2020); City of Chicago (n.d.)

Equations:

$$monthly\_loan\_payment = \frac{vehicle\_price}{([(1+i)^n - 1] \div [i(1+i)^n]} \tag{3}$$

$$n = payment\_periods\_per\_year \times vehicle\_financing\_lifespan \tag{4}$$

$$i = \frac{annual\_interest\_rate}{months\_per\_year} \tag{5}$$

$$total\_loan\_payment = monthly\_loan\_payment \times months\_per\_year \times vehicle\_financing\_duration \tag{6}$$

$$financing = \frac{total\_loan\_payment}{miles\_per\_year \times vehicle\_lifespan} \tag{7}$$

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:

$$\begin{aligned}annual\_licensing\_taxi = taxi\_licensing\_taxi\_medallion\_license \\ + (taxi\_licensing\_ground\_transportation\_tax + taxi\_licensing\_accessibility\_fund) \times months\_per\_year \\ + taxi\_licensing\_advertising\_fee \quad (8)\end{aligned}$$

$$licensing = \frac{annual\_licensing\_taxi}{miles\_per\_year} \quad (9)$$

TNC Licensing - Chicago

The City of Chicago identified 148,351 unique TNC drivers in a recent study BACP (2023b). 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 (2023b)
miles_per_trip	3.09 miles	City of Chicago (n.d.)

$$\begin{aligned}licensing\_tnc = \frac{tnc\_licensing\_admin\_fee\_tnc\_per\_year}{miles\_per\_year \times fleet\_size} \\ + \frac{tnc\_licensing\_admin\_fee\_tnc\_per\_trip + tnc\_licensing\_ground\_transport\_tnc + access\_fund\_tnc}{miles\_per\_trip} \\ + \frac{tnc\_licensing\_advertising\_fee}{miles\_per\_year} \quad (10)\end{aligned}$$

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	$255,000	New York City Taxi & Limousine Commission (n.d.a)
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:

$$n_d = payment\_periods\_per\_year \times financing\_period\_downpayment \tag{11}$$

$$n_r = payment\_periods\_per\_year \times financing\_period\_remainder \tag{12}$$

$$i = \frac{medallion\_interest\_rate}{months\_per\_year} \tag{13}$$

$$downpayment\_total = downpayment\_percent \times taxi\_licensing\_taxi\_medallion\_price \tag{14}$$

$$downpayment\_upfront = downpayment\_upfront\_percent \times downpayment\_total \tag{15}$$

$$downpayment\_remainder = downpayment\_total - downpayment\_upfront \tag{16}$$

$$downpayment\_monthly\_loan\_payment = \frac{downpayment\_remainder}{([(1+i)_d^n - 1] \div [i(1+i)_d^n]} \tag{17}$$

$$loan\_remainder = taxi\_licensing\_taxi\_medallion\_price - downpayment\_total \tag{18}$$

$$remainder\_monthly\_loan\_payment = \frac{loan\_remainder}{([(1+i)_r^n - 1] \div [i(1+i)_r^n]} \tag{19}$$

$$\begin{aligned} total\_medallion\_payment = {} & downpayment\_upfront \\ & +(downpayment\_monthly\_loan\_payment \times n_d) \\ & +(remainder\_monthly\_loan\_payment \times n_r) \end{aligned} \tag{20}$$

$$licensing = \frac{total\_medallion\_payment}{miles\_per\_year \times medallion\_lifespan} \tag{21}$$

Insurance

For the base model, the `av_operations_factor` is 1. The listed `av_operations_factor` is used in the Advanced AV Tech 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:

$$insurance = \frac{vehicle\_operations\_insurance \times months\_per\_year}{miles\_per\_year} \times av\_operations\_factor\_insurance \quad (22)$$

Maintenance

We assume maintenance costs are \$0.06/mi. For the base model, the `av_operations_maintenance` factor is 1. The listed `av_operations_maintenance` factor is used in the Advanced AV Tech 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:

$$maintenance = vehicle\_operations\_maintenance \times av\_operations\_factor\_maintenance \tag{23}$$

Fuel

For the base model, the `av_operations_fuel` factor is 1. The listed `av_operations_fuel` factor is used in the Advanced AV Tech 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:

$$annual\_fuel\_cost = \frac{miles\_per\_year}{fuel\_efficiency} \times fuel\_cost\_per\_gal \tag{24}$$

$$fuel = \frac{annual\_fuel\_cost}{miles\_per\_year} \times av\_operations\_factor\_fuel \tag{25}$$

Labor

Overall equation:

$$labor = cleaning + customersupport + fieldsupport + monitor \tag{26}$$

Cleaning We assume the vehicles receive a basic cleaning daily, and a deep cleaning 3 times per week. We assume that one cleaner can perform a basic cleaning for 50 vehicles in one hour, and that one cleaner can perform a deep cleaning for 10 vehicles in 3 hours. In the City of Chicago, minimum wage is $15.80 per hour.

Variable Name	Value	Source
shift_days_per_year_cleaner_basic	365 days/year	Assumption
shift_days_per_year_cleaner_deep	156 days/year	Assumption
shift_length_cleaner_basic	1 hour	Assumption
shift_length_cleaner_deep	3 hours	Assumption
vehicles_per_cluster_cleaner_basic	12	Assumption
vehicles_per_cluster_cleaner_deep	10	Assumption
wage_cleaner	$15.80	BACP (2023a)

Equations:

$$\begin{aligned} cluster\_cost\_cleaner\_basic = shift\_length\_cleaner\_basic \times shift\_days\_per\_year\_cleaner\_basic \\ \times workers\_per\_shift\_cleaner\_basic \times wage\_cleaner \end{aligned} \tag{27}$$

$$\begin{aligned} cluster\_cost\_cleaner\_deep = shift\_length\_cleaner\_deep \times shift\_days\_per\_year\_cleaner\_deep \\ \times workers\_per\_shift\_cleaner\_deep \times wage\_cleaner \end{aligned} \tag{28}$$

$$cost\_per\_cluster\_cleaner = cluster\_cost\_cleaner\_basic + cluster\_cost\_cleaner\_deep \tag{29}$$

$$cleaning = \frac{cost\_per\_cluster\_cleaner}{vehicles\_per\_cluster \times miles\_per\_year} \tag{30}$$

Field Support

Variable Name	Value	Source
shift_days_per_year_fieldsupport	365 days/year	Kaplan, Szajnfarber, and Helveston (2023)
shift_length_fieldsupport	8 hours	Kaplan, Szajnfarber, and Helveston (2023)
wage_fieldsupport	$23/hr	Adecco (2023)
workers_per_shift_fieldsupport	1 per shift per cluster	Assumption
vehicles_per_cluster	20	Assumption
overhead_rate	1.59	Nunes and Hernandez (2020)

Equations:

$$fieldsupport\_per\_day = workers\_per\_shift\_fieldsupport \times \frac{hours\_per\_day}{shift\_length\_fieldsupport} \tag{31}$$

$$\begin{aligned} cluster\_cost\_fieldsupport = (&shift\_days\_per\_year\_fieldsupport \times shift\_length\_fieldsupport \\ &\times wage\_fieldsupport \times overhead\_rate \times 1) \\ +(&shift\_days\_per\_year\_fieldsupport \times shift\_length\_fieldsupport \times wage\_fieldsupport \\ &\times (fieldsupport\_per\_day - 1)) \end{aligned} \tag{32}$$

$$miles\_per\_cluster = vehicle\_annual\_miles \times vehicles\_per\_cluster \tag{33}$$

$$fieldsupport = \frac{cluster\_cost\_fieldsupport}{miles\_per\_cluster} \tag{34}$$

Remote Monitor

Variable Name	Value	Source
shift_days_per_year_monitor	365 days/year	Kaplan, Szajnfarber, and Helveston (2023)
shift_length_monitor	8 hours	Pawlowski (2011)
wage_monitor	\$21/hr	ICONMA (2023)
workers_per_shift_monitor	1 per shift per cluster	Assumption
vehicles_per_cluster	10	Assumption
overhead_rate	1.59	Nunes and Hernandez (2020)

Equations:

$$monitor\_per\_day = workers\_per\_shift\_monitor \times \frac{hours\_per\_day}{shift\_length\_monitor} \tag{35}$$

$$\begin{aligned} cluster\_cost\_monitor = (&shift\_days\_per\_year\_monitor \times shift\_length\_monitor \\ &\times wage\_monitor \times overhead\_rate \times 1) \\ +(&shift\_days\_per\_year\_monitor \times shift\_length\_monitor \times wage\_monitor \\ &\times (monitor\_per\_day - 1)) \end{aligned} \tag{36}$$

$$miles\_per\_cluster = vehicle\_annual\_miles \times vehicles\_per\_cluster \tag{37}$$

$$monitor = \frac{cluster\_cost\_monitor}{miles\_per\_cluster} \tag{38}$$

Customer Support

Variable Name	Value	Source
shift_days_per_year_customersupport	365 days/year	Kaplan, Szajnfarber, and Helveston (2023)
shift_length_customersupport	8 hours	Pawlowski (2011)
wage_customersupport	$21/hr	Indeed (2023); ICONMA (2023)
workers_per_shift_customersupport	1 per shift per cluster	Assumption
vehicles_per_cluster	50	Assumption
overhead_rate	1.59	Nunes and Hernandez (2020)

Equations:

$$customersupport\_per\_day = workers\_per\_shift\_customersupport \times \frac{hours\_per\_day}{shift\_length\_customersupport} \tag{39}$$

$$\begin{aligned} cluster\_cost\_customersupport = (&shift\_days\_per\_year\_customersupport \times shift\_length\_customersupport \\ &\times wage\_customersupport * overhead\_rate * 1) \\ +(&shift\_days\_per\_year\_customersupport \times shift\_length\_customersupport \\ &\times wage\_customersupport \times (customersupport\_per\_day - 1)) \end{aligned} \tag{40}$$

$$miles\_per\_cluster = vehicle\_annual\_miles \times vehicles\_per\_cluster \tag{41}$$

$$customersupport = \frac{cluster\_cost\_customersupport}{miles\_per\_cluster} \tag{42}$$

Description of Monte Carlo simulation inputs

Please see the `inputs_monte_carlo.xlsx` file.

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