Bus Fleet Replacement Optimization:

A case study of key variables affecting optimal bus type, lifecycle, and net cost utilizing King County Metro Transit data

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Introduction

Fleet replacement goal: minimize fleet total net cost

Two main tradeoffs for bus fleet replacement decision:

- Old buses cost more to maintain, but new buses cost to buy
  - ➢ Optimal replacement age
- Competitiveness between bus types/technologies
  - ➢ Optimal bus type

Market uncertainty and bus characteristics/performance variability may affect the two optimality

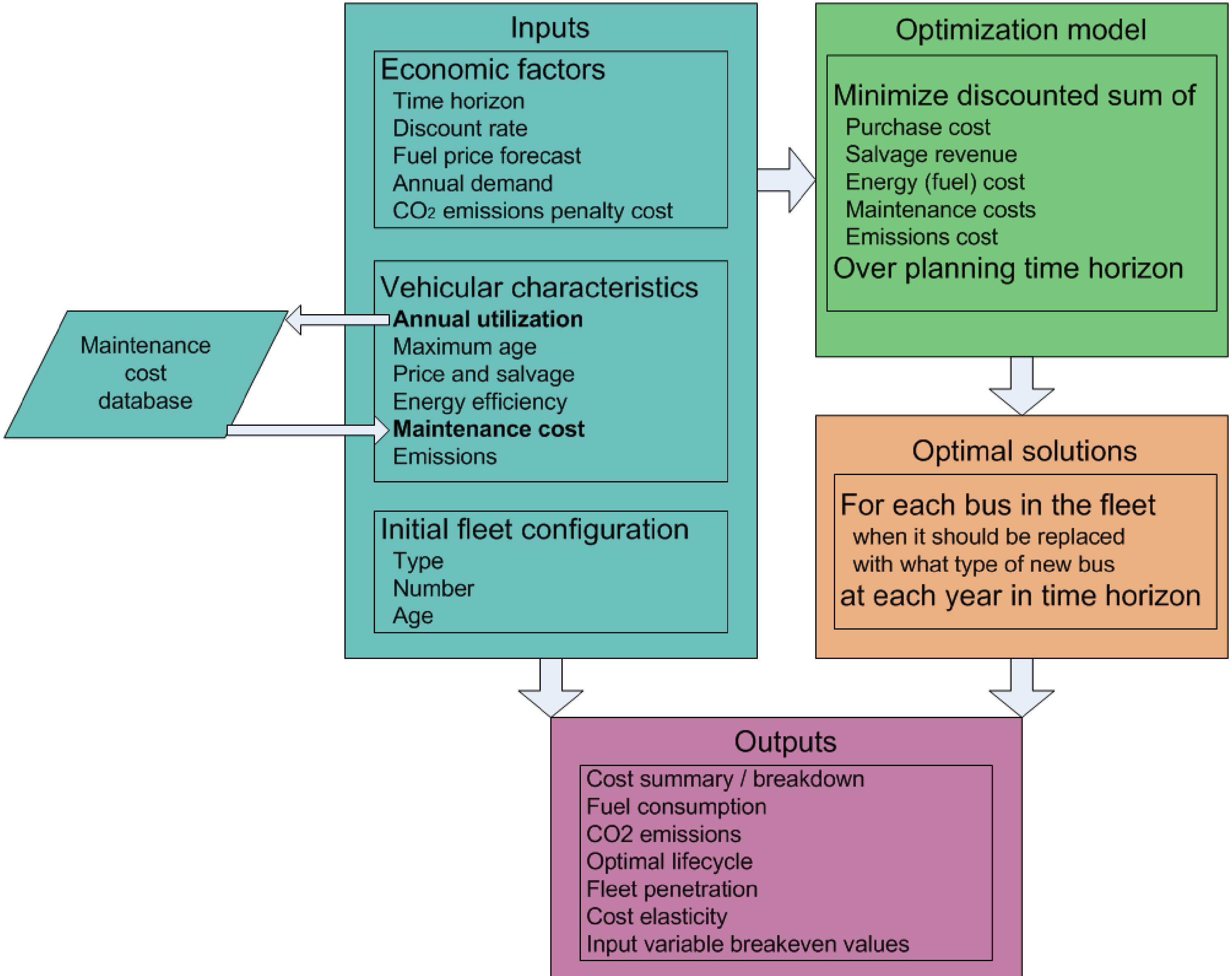
- ➢ Sensitivity analysis

Objectives

1. Develop a bus fleet replacement optimization model and an optimization tool that can help fleet managers minimize fleet total net cost, perform multiple scenarios and sensitivity analysis through interactive interface

2. Analyze the impacts of key variables on optimal replacement plan and total net cost

Optimization framework



Mathematical model

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Objective Function, minimize

$$\sum_{j=0}^{T-1}\sum_{k=1}^{K}[v_k \cdot P_{jk} + \sum_{i=0}^{A_k-1}(\frac{fc_j}{f_{ik}} + m_{ik} + e_{ik}) \cdot u_{ik} \cdot X_{ijk}] \cdot (1+\delta)^{-j} + \sum_{j=0}^{T}\sum_{k=1}^{K}\sum_{i=1}^{A_k} s_{ik} \cdot Y_{ijk}\,(1+\delta)^{-j}$$

Constraints:

$$\sum_{k=1}^{K} v_{jk} \cdot P_{jk} \leq b_j, \forall j \in \{0,1,2,\dots,T-1\}$$

$$X_{iTk} = 0, \forall i \in \{0,1,2,\dots,A_k-1\}, \forall k \in \mathbf{K}$$

$$\sum_{i=0}^{A_k-1}\sum_{k=1}^{K} X_{ijk} \cdot u_{ik} \geq d_j, \forall j \in \{0,1,2,\dots,T-1\}$$

$$X_{A_k jk} = 0, \forall j \in \{0,1,2,\dots,T\}, \forall k \in \mathbf{K}$$

$$P_{jk} = X_{0jk}, \forall j \in \{1,2,\dots,T-1\}, \forall k \in \mathbf{K}$$

$$Y_{0jk} = 0, \forall j \in \{0,1,2,\dots,T\}, \forall k \in \mathbf{K}$$

$$P_{0k} + h_{0k} = X_{00k}, \forall k \in \mathbf{K}$$

$$P_{jk}, X_{ijk}, Y_{ijk} \in \mathbf{I} = \{0,1,2,\dots\}$$

$$X_{i0k} + Y_{i0k} = h_{ik} \forall i \in \{1,2,\dots,A_k\}, \forall k \in \mathbf{K}$$

$$X_{(i-1)(j-1)k} = X_{ijk} + Y_{ijk}, \forall i \in \{1,2,\dots,A_k\}, \forall j \in \{1,2,\dots,T\}, \forall k \in \mathbf{K}$$

Data and assumptions

- **Economic factors:**

  100 years planning time horizon,
  $3.48/gal fuel price with 2.6% annual increase,
  9.55% discount rate,
  33045 miles/year/bus,
  $30/ton CO_2 emissions penalty cost

- **Vehicular factors:**

Vehicle type	Max age	Purchase Cost	MPG	Maintenance cost ($/mile)	CO2 emissions rate (kg/gal)
60ft Hybrid	20	$958,000	3.65	0.530+0.0867*age	2.504
60ft Diesel	20	$737,000	2.5	0.372+0.0673*age	3.407

- **Existing fleet configuration:**

  no existing bus, results will be based on a per bus basis

- **Two scenarios:** purchase cost subsidy (0% and 80%)

Scenario results

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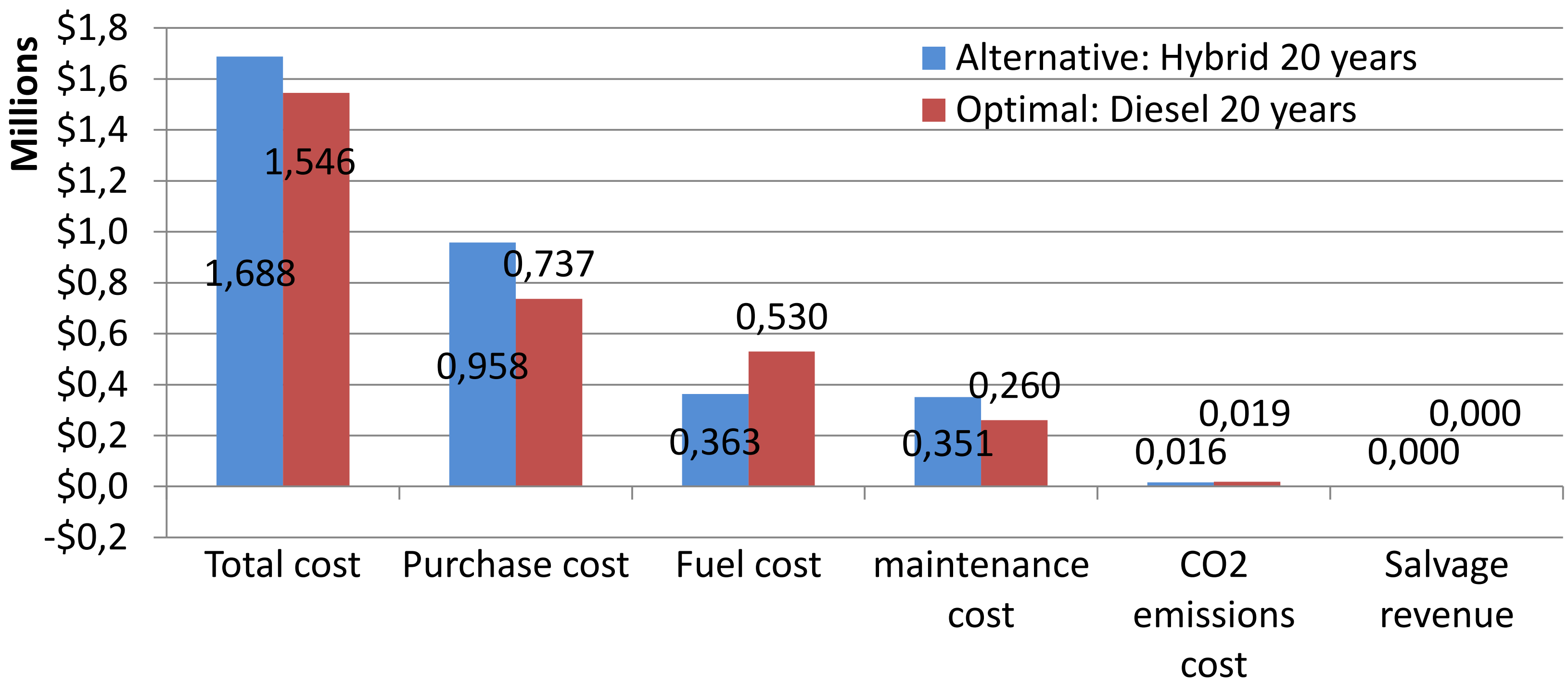
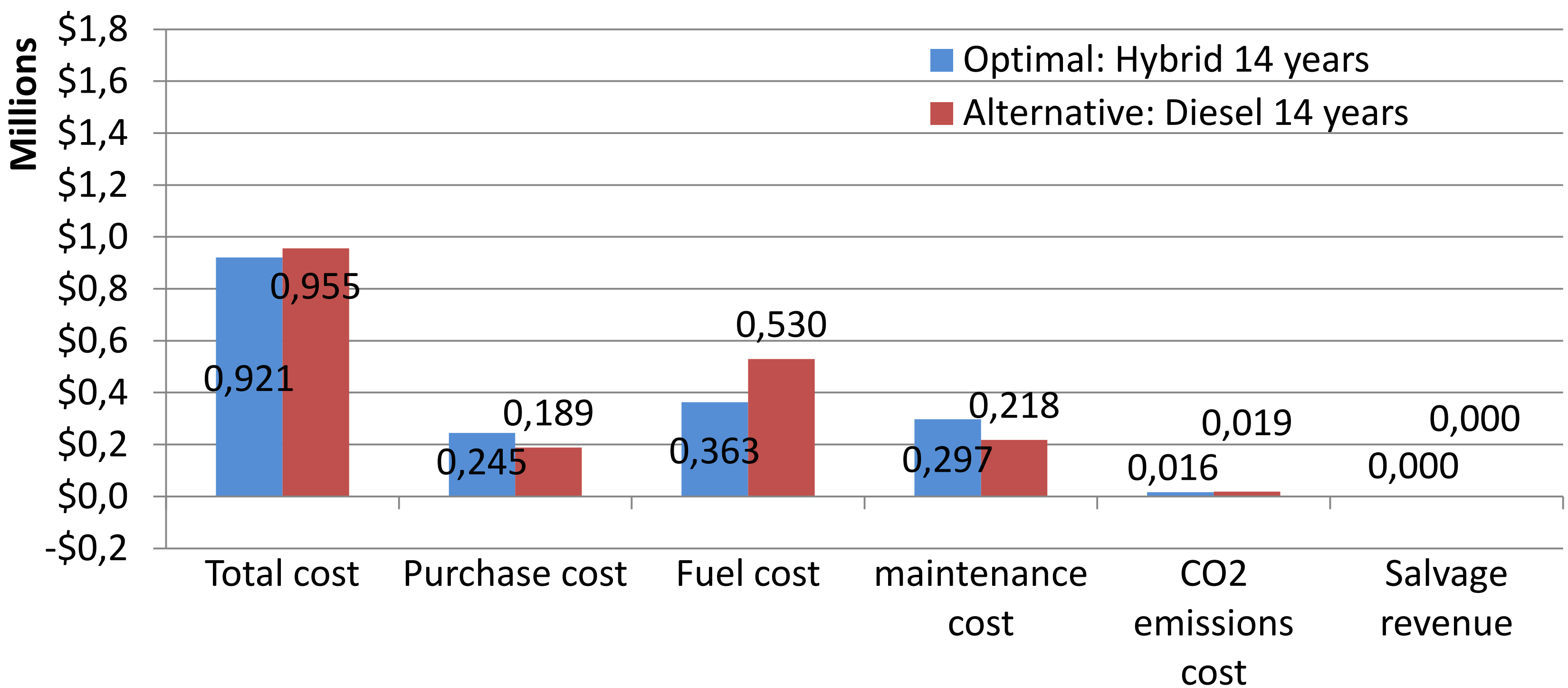
No purchase cost subsidy



Total net cost difference between optimal and alternative solution:
9.18% or $0.142 million

Scenario results

80% purchase cost subsidy



Total net cost difference between optimal and alternative solution:
3.69% or $0.034 million

Scenario results

Purchase cost subsidy has significant impact on optimal solutions and total net cost.

	Optimal bus type	Replacement cycle	NPV in next 20 years
0% subsidy	Diesel	20 years	$1,545,537
80% subsidy	Hybrid	14 years	$ 920,914

40% reduction

Breakeven subsidy that can make hybrid buses more cost effective than diesel buses is 63%.

Breakeven values

Factors	Scenarios / Baseline solution / Baseline values	0% subsidy / Diesel bus 20 years / Breakeven value for hybrid bus		80% subsidy / Hybrid bus 14 years / Breakeven value for diesel bus	
Vehicular factors					
Diesel bus mpg	2.50	≤	1.98	≥	2.67
Hybrid bus mpg	3.65	≥	5.92	≤	3.34
Diesel bus purchase cost ($)	737,000	≥	875,934	≤	613,242
Hybrid bus purchase cost ($)	958,000	≤	819,066	≥	1,093,217
General factors					
Annual utilization (miles/bus)	33,045	≥	128,716	≤	13,760
Fuel price ($/gal)	3.48	≥	6.38	≤	2.79
Fuel inflation rate	2.6%	≥	10.2%	≤	inf.
CO2 emissions penalty cost ($/ton)	30	≥	506	≤	inf.
Nominal annual discount rate	9.55%	≤	inf.	≥	25.09%

Cost elasticity

Factors	0% subsidy	80% subsidy
Vehicular Factors		
Diesel bus mpg (2.2 – 2.8)	-0.34	-0.09
Hybrid bus mpg (3.35 – 3.95)	0.00	-0.39
Diesel bus price ($589,600 – $737,000)	0.45	0.05
Hybrid bus price ($766,400 – $958,000)	0.15	0.27
General Factors		
Annual utilization (28,379 miles/year – 39,679 miles/year)	0.63	0.85
CO_2 emissions penalty cost ($0/ton – $100/ton)	0.01	0.01
Fuel price ($2.64/gallon – $4.46/gallon)	0.34	0.41
Fuel inflation rate (0% – 5%)	0.06	0.07
Nominal annual discount rate (5% – 15%)	-0.37	-0.54
Purchase cost subsidy (0% – 80%)	-0.25	

Conclusions

- A bus fleet replacement optimization model and an optimization tool are developed and can be easily used by fleet managers through interactive interface to perform scenarios and sensitivity analysis.

- Government purchase cost subsidy has significant impact on optimal replacement decision and total net cost

- Bus purchase cost and relative fuel economy can affect the optimal bus type choice within realistic ranges in 0% and 80% subsidy scenarios.

- Annual utilization, discount rate, and fuel price have the most significant impact on total net cost.

Future work

- Compare more bus technologies as challengers, such as electric trolley bus and compressed natural gas buses
- Include facility and construction cost into optimization model.
- More advanced optimization models that address market uncertainty and bus performance variability.

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Thank you!

Questions?

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