Engineering Economic Valuation of Ready-Made Design for Transportation Vehicles

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Abstract

Nowadays, transportation vehicles are upfront equipped with fuel saving devices such as winglets in airplanes so as to reduce fuel consumption. By ready-made design, we mean this approaching of equipping upfront on transportation vehicles. In this article, under the reasonable assumption that the fuel cost is volatile and follows a geometric Brownian motion (GBM) process, we use the theory of stochastic optimal control (1) to determine the threshold of fuel cost to decommission such a transportation vehicle, and (2) to determine the engineering economic valuation of such a design. For the threshold and the valuation, we proceed to obtain the analytical solutions to our approach, followed by sensitivity analyses as well as the derivation of the total expected operation lifetime until decommissioning. Finally, for the managerial insights and economic implications, we present an extensive numerical example with numerous empirical data sets from publicly available sources. For instance, as the fuel cost becomes more uncertain, economically rational decision makers will defer the decommissioning of a vehicle.

Keywords: Ready-Made Design, Fuel Saving Devices, Volatile Fuel Cost, Engineering Valuation, Transportation Vehicles

Introduction

Given that fuel saving devices reduce the fuel consumption of transportation vehicles, manufacturers tend to install fuel saving devices in the design of transportation vehicles. In this article, a vehicle equipped with fuel saving devices at the initial manufacturing stage is referred as "ready-made" design. For aging vehicles with such designs, the end-of-life (EOL) decisions are often made under uncertainties with economic consequences. Furthermore, an optimal EOL decision under given uncertainty can lead to the maximization of EOL value of the transportation vehicle. In practice, facing the increasing fuel cost in the long term with fluctuation over time, the decision makers can opt to decommission an aging transportation vehicle at certain time, and that invites us to view its decommissioning problem from a real options perspective. In this article, we aim to determine the optimal threshold of fuel cost to decommission such a transportation vehicle as well as to determine the engineering economic valuation of such a design.

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The rest of the article is organized as follows. A brief review of related literature on ready-made design of transportation vehicles and real option analysis is introduced in the next section. We then provide the definitions and assumptions, as well as the formulation and analyses of the mathematical model for the decommissioning decision. Sequentially, we conduct a numerical study on airplanes that is equipped with winglets to further illustrate the insights of the analytical results and sensitivity analysis. Finally, conclusions and future research are presented.

Literature Review

Ready-Made Design of Transportation Vehicles

Fuel saving devices have been commonly implemented in the design of transportation vehicles on the land, under the water, and in the air because of the reduction in fuel consumption.

For vehicles that travel on the ground, MirrorEye Camera Monitor System (CMS) reduces fuel consumption from aerodynamic design by removing traditional mirrors during fleet trials and replacing with integrated external digital cameras and internal digital monitors (Stoneridg, 2018). A roughly two to three percent per year of fuel cost savings has been demonstrated in European trucks.

In terms of ships, various advanced technologies have been invented and applied to reduce the fuel consumption as well. For instance, Air Lubrication System - also known as the “Bubble technology” – significantly saves the fuel consumption by reducing the resistance between the ship’s hull and seawater using air bubbles (MI News Network, 2019). This technology can be added to new ship or retrofitted to an existing ship within just 14 days. In practice, it has been successfully installed on the vessel of Norwegian Cruise Line.

As for airplanes, the Aviation Partners Boeing (APB)’s Blended Winglet reduces drag and takes advantage of the energy from wingtip vortices, generating additional forward thrust (NASA Spinoff, 2010). Its employment has been proved to reduce fuel consumption by 3 percent, or about 100,000 U.S. gallons of fuel a year, per Boeing 737 airplane (Freitag & Schulze, 2009).

Real Options Approach

Real option approach is useful to decision making in capturing and valuing the flexibility inherent in many operating decisions that decision makers encounter (Trigeorgis & Tsekrekos, 2018). It has been widely applied in the content of investment under uncertainty, production and manufacturing, innovation and technology, supply chain and logistics, energy, natural resources and environment, valuation models and others, etc.

The examples of literature on transportation vehicles using a real options approach are as follows. Given the fuel flexibility (choice between electricity and gasoline), Lemoine (2010) evaluated the battery capacity of plug-in hybrid electric vehicles (PHEVs) under a real options framework. In 2018, Kang, Bayrak, & Papalambros presented an optimization framework for redesigning or investing in future vehicles using real options to address the uncertainty in gas price and regulatory standards. Agaton, Guno, Villanueva, & Villanueva (2019) studied the decision making on investment between modernized diesel jeepney and the e-jeepney fleet. They evaluated the option values and investigated the optimal investment strategies under multiple uncertainties (i.e., uncertainties in diesel prices, jeepney base fare price, electricity prices, and government subsidy) using real options approach.

Model and Analyses

Definitions and Assumptions

In this section, we determine the threshold of fuel cost at which level it is optimal to decommission a transportation vehicle with read-made design, as well as the corresponding total operation lifetime until decommissioning.

The timeline of a vehicle starts from the time point at which a vehicle is manufactured to the time point at which the vehicle is decommissioned, and its revenue-generating operation is in progress at the same time. Based on these simplifying assumptions, the timeline for ready-made design is shown in Figure 1, where t=0 is both the time point a vehicle is manufactured and the start of revenue-generating operation (i.e., when it is ready for operation, it will be used to generate revenue instantaneously), and $t=\tau_D$ is the time point to decommission.

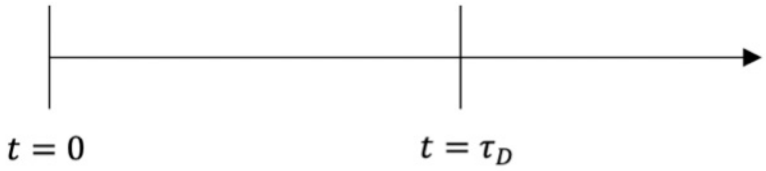

Figure 1. The timeline for vehicle under ready-made design

For vehicle under ready-made design, we assume that the fuel cost is characterized by a geometric Brownian motion (GBM) process as follows:

$$dC_t = \alpha C_t dt + \sigma C_t dz \qquad (1)$$

where C_t is the fuel cost at a time of day t (unit: $ per seat-mile). α is the instantaneous growth rate of the fuel cost (unit: %), and it is assumed to be positive. σ is the instantaneous volatility of the fuel cost (unit: %). Finally, dt is the increment of time while dz is the increment of a standard Wiener process z(t). That is, $dz=\varepsilon_t \sqrt{dt}$ where $\varepsilon_t \sim N(0,1)$.

The rest notations are given as follows.

ρ: the discount rate for money (unit: %).

P: the revenue per seat-mile net of non-fuel costs such as labor costs (unit: $ per seat-mile). For simplicity, we assume it is unrelated to the changing fuel cost.

K: the total seat miles of operation per day (unit: seat-mile), which is assumed to remain unchanged over time.

W: the salvage cost associated with decommissioning (unit: $). It is defined as the dismantling cost net of the salvage value, and assumed to be a constant.

C_0: the initial fuel cost (unit: $ per seat-mile).

Model Formulation

During the operating process, the value of this project V obeys a Bellman optimality principle equation as follows:

$$\rho V dt = (P - C_t)K dt + E[dV] \qquad (2)$$

Equation (2) indicates that the total return for this project consists of the net revenue that is currently generated from the operation plus the expected future appreciation in the value of the project. By applying Ito's Lemma on dV, equation (2) yields a second order differential equation as follows:

$$\frac{1}{2}\frac{\partial^2 V}{\partial {C_t}^2}\sigma^2 {C_t}^2 + \frac{\partial V}{\partial C_t}\alpha C_t - \rho V + (P - C_t)K = 0 \qquad (3)$$

which is subject to the following two boundary conditions:

$V(C^*) = -W$ (4)

$V'(C^*) = 0$ (5)

where C* denotes the optimal threshold of the fuel cost at which point a vehicle with ready-made design is decommissioned. Boundary condition (4) is the value matching condition, implying that the value of the project at the time of decommissioning is equal to the negative value of the decommissioning cost. Boundary condition (5) is the smooth pasting condition, requiring that the slope of the left-hand side and the right-hand side of equation (4) be equal at the optimal point C*.

To solve the differential equation (3), we first note that a particular solution to equation (3) can be verified to be:

$$V(C_t) = \frac{-C_t K}{\rho-\alpha} + \frac{PK}{\rho} \qquad (6)$$

with a technical condition of $\rho-\alpha>0$ (Dixit and Pindyck, 1994).

Next, a homogeneous solution to equation (3) can be verified to be:

$$V(C_t) = A_1 {C_t}^{\beta_1} \qquad (7)$$

with a technical condition of $\alpha - \frac{\sigma^2}{2} > 0$ (Dixit and Pindyck, 1994).

The fundamental quadratic equation is an equation of β:

$$\mathbb{Q}(\beta) = \frac{1}{2}\sigma^2\beta^2 + \left(\alpha - \frac{1}{2}\sigma^2\right)\beta - \rho = 0 \qquad (8)$$

The two roots of the $\mathbb{Q}(\beta)$ are given by $\beta_{1,2} = \frac{-\left(\alpha-\frac{1}{2}\sigma^2\right)\pm\sqrt{\left(\alpha-\frac{1}{2}\sigma^2\right)^2+2\sigma^2\rho}}{\sigma^2}$. According to Dixit & Pindyck (1994), the coefficient of β^2 in $\mathbb{Q}(\beta)$ is positive so the graph of $\mathbb{Q}(\beta)$ goes to ∞ as β goes to $\pm\infty$. Also, $\mathbb{Q}(1) = \alpha - \rho < 0$ and $\mathbb{Q}(0) = -\rho < 0$. Therefore, the graph of $\mathbb{Q}(\beta)$ crosses the horizontal axis at one point to the right of 1 and another point to the left of 0, i.e., $\beta_2 < 0$ and $\beta_1 > 1$.

From the particular and homogeneous solutions, the general solution to equation (3) is given by:

$$V(C_t) = A_1 {C_t}^{\beta_1} - \frac{C_t K}{\rho-\alpha} + \frac{PK}{\rho} \qquad (9)$$

To analytically solve for A_1 and C*, we should utilize the two boundary conditions as follows. First, using the smooth pasting condition equation (5), by differentiating both sides of equation (9) with respect to C_t, at C*, we have

$$A_1 = \frac{K}{(\rho-\alpha)\beta(C^*)^{\beta_1-1}} \qquad (10)$$

Next, using the value matching condition equation (4) and the expression of A_1 given in equation (10), we can solve for C* such that:

$$C^* = \frac{\left(\frac{PK}{\rho}+W\right)(\rho-\alpha)\beta_1}{(\beta_1-1)K} \qquad (11)$$

It can be verified that for C_t given by equation (1) $dC_t=\alpha C_t dt+\sigma C_t dz$, $F(C_t)=\ln C_t$ is the following simple Brownian motion with drift (Dixit & Pindyck, 1994).

$$dF = \left(\alpha - \frac{1}{2}\sigma^2\right) dt + \sigma dz \qquad (12)$$

Over finite time interval t, the change in the logarithm of C_t is normally distributed with mean $\left(\alpha - \frac{1}{2}\sigma^2\right) t$ and variance of $\sigma^2 t$. Hence, the total expected operation lifetime until decommissioning T^*, i.e., the expected time for fuel cost C_t to evolve from the initial fuel cost C_0 to the optimal decommissioning threshold C^*, can be calculated as:

$$T^* = \frac{F(C^*)-F(C_0)}{\mu} = \frac{\ln C^* - \ln C_0}{\alpha - \frac{1}{2}\sigma^2} \qquad (13)$$

Analytical Sensitivity Analysis

In this section, we conduct the analytical sensitivity analysis for the decommissioning threshold C^* and the total expected operation lifetime until decommissioning T^* by differencing them with respect to the decommissioning cost W, the revenue net of non-fuel costs P, and the total seat-miles of operation K, respectively. As for the discount rate for money ρ, the growth rate α and the volatility σ of fuel cost, the results are not amenable to straightforward analyses, the corresponding numerical sensitivity analysis will be given in the numerical study section instead.

Proposition 1. *Given* $\rho > \alpha > \frac{1}{2}\sigma^2$, $\frac{\partial C^*}{\partial W} = \frac{(\rho-\alpha)\beta_1}{(\beta_1-1)K} > 0$ *and* $\frac{\partial T^*}{\partial W} = \frac{1}{(\alpha-\frac{1}{2}\sigma^2)\left(\frac{PK}{\rho}+W\right)} > 0$

When the decommissioning cost increases, the decision maker is inclined to stay within the project and not to decommission the vehicle as it requires a larger payment for the exiting fee. The value of decommissioning cost W can be either positive or negative depending on the definition. In this paper, W is justified as the dismantling cost net of the salvage value of the vehicle. Specifically, a positive decommissioning cost implies that the decision maker loses money in the vehicle decommissioning. An increase in such positive W corresponds to more money lost in the decommissioning, which discourages the decision maker to decommission vehicles. On the other hand, a negative decommissioning cost suggests that the decision maker makes money from the vehicle decommissioning. An increase in such negative W brings less profit from the decommissioning, so the economically rational decision is to postpone the decommissioning of vehicle.

Proposition 2. Given $\rho > \alpha > \frac{1}{2}\sigma^2$, $\frac{\partial C^*}{\partial P} = \frac{(\rho-\alpha)\beta_1}{\rho(\beta_1-1)} > 0$ and $\frac{\partial T^*}{\partial P} = \frac{K}{(\alpha-\frac{1}{2}\sigma^2)\left(\frac{PK}{\rho}+W\right)\rho} > 0.$

As the revenue net of non-fuel costs increases, the decision maker tends to keep the vehicle operating to collect more revenue and not to pull it out of operation. Hence, as P increases, the optimal decommissioning threshold of fuel cost C^* increases, and the total expected operation lifetime T^* is extended.

Proposition 3. Given $\rho > \alpha > \frac{1}{2}\sigma^2$, $\frac{\partial C^*}{\partial K} = -\frac{(\rho-\alpha)\beta_1 W}{(\beta_1-1)K^2} < 0$ and

$\frac{\partial T^*}{\partial K} = -\frac{W}{\left(\alpha-\frac{1}{2}\sigma^2\right)\left(\frac{PK}{\rho}+W\right)K} < 0.$

In terms of the decommissioning, it is comprehensible that a vehicle with higher daily total seat-miles of operation is apt to exit the operation earlier. As a result, as K increases, the optimal decommissioning threshold of fuel cost C^* decreases, and the total expected operation lifetime T^* is shortened.

Numerical Study

In this section, a numerical study on airplanes with winglets is introduced to demonstrate the results and findings from previous sections.

Parameters Values and Numerical Results

The parameter values used in the numerical example are summarized in Table 1. The sources of parameter values are justified as follows.

The growth rate and volatility of fuel cost α and σ are adopted from the GBM parameters estimation of oil price (Croghan, Jackman, & Min, 2017). This is because, typically, higher oil prices result in higher jet fuel prices (JPMorgan, 2018). Also, the correlation coefficient between the price rate of jet fuel and crude oil is up to 0.959857 (IndexMundi, 2019). The Weighted Average Cost of Capital (WACC) as of October 25, 2019 (5.59%) for American Airlines Group is used as the value of discounted rate of money ρ (GuruFocus, 2019).

The revenue per seat-mile net of non-fuel costs such as labor costs P is calculated by subtracting system total labor and related expense per available seat mile and system management and other expense per available seat mile from system passenger revenue per available seat mile of total all sectors in 2018 (Swelbar & Belobaba, 2018a, 2018b, 2018c), i.e., P=11.70-4.7-0.69=6.31 cents per available seat mile=0.0631 $ per available seat mile. Note that we assume the value of seat mile and available seat mile are the same for simplicity.

The initial fuel cost C_0 is estimated from the fuel expense per available seat mile as of total all sectors in 2018, 0.030 $ per available seat mile (Swelbar & Belobaba, 2018d). The unit transformation of fuel cost from $ per gallon to $ per available seat mile can be obtained using

$$\frac{fuel\ cost\ \mathbb{C}_t\ \left(\$/_{gallon}\right) * fuel\ consumption\ of\ a\ day\ (gallon)}{available\ seat\ miles\ of\ a\ day\ (available\ seat\ miles)} = fuel\ cost\ C_t\ \left(\$/_{available\ seat\ mile}\right).$$

Since Southwest Airlines has almost exclusively operated Boeing 737 aircrafts after it was founded (Wikipedia, 2019), we estimate the total available seat-miles of operation per day K by dividing the total system available seat miles of Southwest Airlines as of 2018 (Swelbar & Belobaba, 2018e) (159,920 million) by the number of operating fleets as of 2018 (Swelbar & Belobaba, 2018f) (722) and 365 days in a year, i.e.,

$$K = \frac{159{,}920\times10^6 /_{722}}{365} = 606{,}838\ available\ seat\ miles.$$

The decommissioning cost W is evaluated by subtracting the salvage value of the recycled products and the reused products from the cost of aircraft dismantling service (Bouzarour-Amokrane, Tchangani, & Peres, 2012). The sixth alternative was selected and the value of W has been transformed from Euro to US Dollars using 1 Euro=1.11 USD. The negative value ($-211,129) implies that the airline company makes money in the airplane decommissioning.

Table 1

Parameter values

Symbol	Parameter	Unit	Value
a	Growth rate of fuel cost	%	0.05
s	Volatility of fuel cost	%	0.15
r	Discount rate for money	%	0.0559
P	Revenue per seat-mile net of non-fuel costs	$ per seat-mile	0.0631
K	Total seat-miles of operation per day	seat-mile	606,838
W	Decommissioning cost	$	-211,129
C_0	Initial fuel cost	$ per seat-mile	0.030

Applying the above parameter values, the coefficient values are calculated as β_1=1.0947 and A_1=1.2403×10^8. The solutions for C* and T* can be obtained by implementing the analytical results presented in the previous section, as are shown in Table 2.

Table 2

Numerical results

Notation	Decision variable	Unit	Solution
C^*	Optimal threshold of fuel cost to decommissioning	\$ per seat-mile	0.0533
T^*	Total expected operation lifetime until decommissioning	Day	14.8166

Numerical Sensitivity Analysis

The influence of growth rate and volatility of fuel cost, α and s, as well as the discount rate of money r on the optimal time to decommission an airplane is investigated through the numerical sensitivity analysis.

Growth rate of fuel cost α. As is shown in Figure 2, as the growth rate of fuel cost increases, the airline company spends more money on the fuel expenses. Therefore, the airline company is recommended to decommission an end-of-life airplane earlier from an economic perspective.

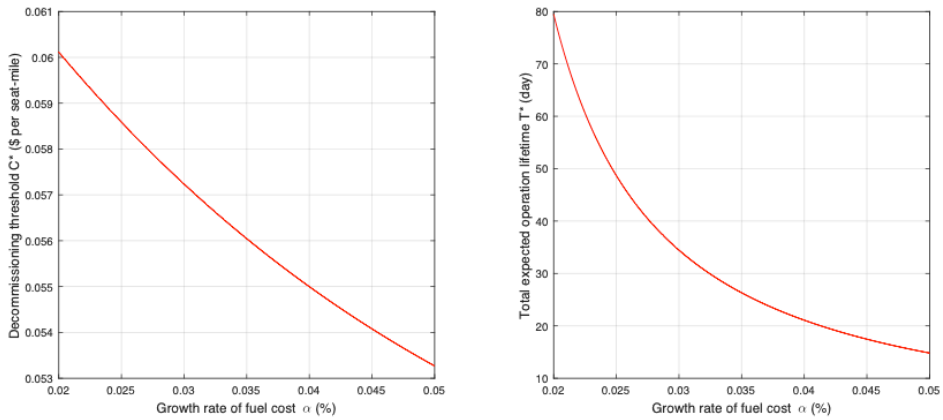

Figure 2. Variation in C and T* with* α

Volatility of fuel cost s**.** From Figure 3, a significant implication that can be derived is the airline company should wait longer before exercising the option to decommission an aging airplane when the fuel cost is uncertain. The implication is straightforward because the high volatility contributes to an unpredictable fuel cost in the future, so the airline company would prefer to operate the airplane longer before decommissioning it.

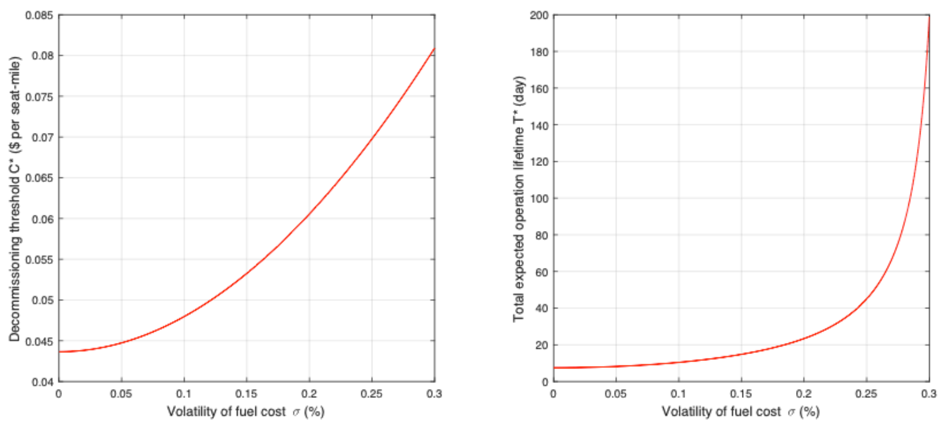

Figure 3. Variation in C and T* with* σ

Discount rate for money r. Figure 4 demonstrates the influence of discount rate for money on the decommissioning decision. In this case, since the airline company makes money from the airplane decommissioning, when the discount rate of money increases, the airline company makes less money in the airplane decommissioning. Stated otherwise, decommissioning the airplane at a lower level discount rate of money is proposed. On the other hand, if the airline company loses money in the airplane decommissioning, operating the airplane longer before decommissioning would be more economically rational when the discount rate of money increases.

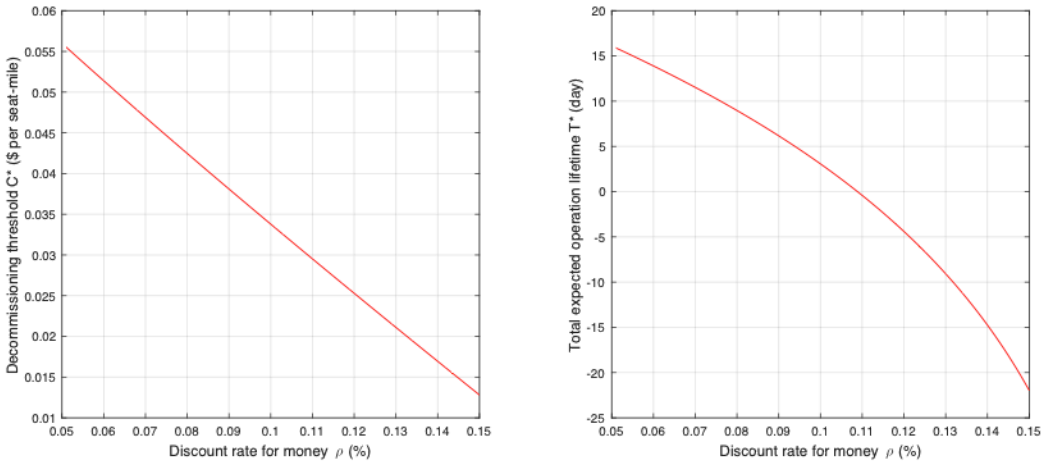

Figure 4. Variation in C and T* with* ρ

Conclusion

In summary, this paper presents a comprehensive framework for decision makers regarding the optimal timing to implement the end-of-life decision (i.e., decommissioning) of transportation vehicles under the fuel cost uncertainty. By assuming the fuel cost follows a GBM process, we solve for the optimal fuel cost threshold to decommission a transportation vehicle and the total expected operation lifetime using the theory of stochastic optimal control. The analytical analysis and numerical study illustrate critical economic implications and managerial insights. For instance, as the fuel cost becomes more volatile, the decision maker has a higher tolerance towards the fuel cost before decommissioning.

What makes this study advantageous is that we incorporate economic uncertainties (i.e., uncertainty in fuel cost) whereas many of the current valuation approaches simply assume deterministic frameworks. Another strength of our study is that our approach is not dependent on an accurate prediction of fuel cost. Instead, considering such quantities are unpredictable, we provide economic threshold to optimally take actions that one typically would not regret. In addition, decision makers can take economically rational reactions towards the decommissioning of vehicle when a change in any of the parameters (e.g., fuel cost becomes volatile, discount rate for money increases) is observed by referring to our findings derived in previous sections.

Our research can be employed as a basis for future research in quantitative valuation of the properties of transportation vehicle design such as flexibility and reliability under economic uncertainties. Specifically, one can study the fuel saving efficiency by incorporating a fuel saving coefficient, and how that will influence the decision of vehicle decommissioning. Furthermore, the choice for the design of a new transportation vehicle among various designs can be extensively studied as it might be affected by the fuel cost uncertainty as well.

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