

Article

Environmental and Economic Impact on Scenario-Based Automotive Part Replacement: Case Study of Constant Velocity (CV) Joint Replacement in Korea

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Abstract: The objective of this study is to comprehensively evaluate the environmental and economic impacts of remanufactured constant velocity (CV) joints using a newly proposed framework for automotive parts replacement. This framework utilizes actual vehicle sales data to accurately estimate the demand for CV joint replacements. Specific parameters are established to calculate this demand, enabling a quantitative assessment of both environmental and economic impacts associated with remanufacturing CV joints and other automotive parts. Additionally, sensitivity analyses are conducted to explore the relationship between environmental benefits and economic outcomes, particularly focusing on the preferences for remanufactured parts and their profitability. The results indicate that increasing the proportion of remanufactured CV joints significantly benefits the environment by reducing CO₂ emissions, raw material usage, and energy consumption. However, this shift also leads to a decrease in total profits within the CV joint replacement market. To address this trade-off, the study suggests that financial incentives, such as subsidies or tax benefits, are necessary to support the remanufacturing industry and facilitate market expansion. These findings provide valuable insights for policymakers aiming to promote sustainable manufacturing practices through effective subsidy policies.



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1. Introduction

Remanufacturing is the process of recovering used products to like-new condition. Recently, great attention has been paid by many countries to the remanufacturing industry as it offers advantages both economically and environmentally [1]. Remanufacturing of automotive parts is one of the main remanufacturing activities, as it is closely connected to environmental issues such as CO₂ emissions. Nearly a ton of CO₂ emissions can be reduced through the remanufacturing of major vehicle parts. Remanufactured products help automakers reduce waste and minimize the use of raw materials needed to make new products [2].

South Korea's relatively short car replacement cycle is driven by improved economic capacity, rapid technological advancements, supportive government policies, and prevailing social and cultural factors. Rising incomes and accessible financial products enable consumers to purchase new vehicles more easily. Technological innovations offer enhanced fuel efficiency, safety, and convenience, making newer models more attractive. Government measures, such as stricter environmental regulations, tax incentives for new cars, and subsidies, discourage the use of older vehicles and promote their replacement. Additionally, owning a new car is seen as a status symbol, and the well-developed automotive infrastructure supports the maintenance of new vehicles. Older cars are regulated through regular inspections, emission standards, and increased taxes, while environmental policies and scrap car programs further encourage consumers to upgrade to newer models. These

combined factors ensure that the car replacement cycle in South Korea remains relatively short, resulting in a steady supply of older vehicles suitable for remanufacturing.

Laws and regulations have also been enacted by governments to support the remanufacturing industry. As awareness of environmental issues increases, pressure from the public and government has prompted car makers to take responsibility for the environmental impacts of their products. For example, the European Union (EU) enacted the End-of-Life Vehicles (ELVs) Directive in 2000, which mandates that the recycling ratio of scrapped vehicles should meet a certain level. The USA has also enacted ELVs, the Restriction of Hazardous Substances (RoHS) Directive, and the Waste Electrical and Electronic Equipment (WEEE) regulations as part of the framework for remanufacturing automotive parts [3–7].

The remanufacturing industry in Korea remains at an early stage compared to those in the USA or EU. Laws and regulations such as the Resource Cyclical Law and the Environmentally Friendly Law were enacted by the Korean government in the late 2000s. These laws have prompted automakers to recycle at least 85% of automotive parts from scrapped vehicles since 2009 [8]. In Korea, the number of registered vehicles reached over 20 million in 2014, and the number of old vehicles aged over seven years among registered vehicles exceeded 10%. This situation provides the remanufacturing industry in Korea with an opportunity to expand its market size. However, the list of remanufacturable automotive parts is very limited in Korea. Only ten types of automotive parts are commonly available for remanufacturing: alternator, starter, CV joints, A/C compressor, injector, brake caliper, shock absorber, lower control arm, turbocharger, and clutch cover. Out of these ten part types, only four (starter, alternator, CV joints, and A/C compressor) have been certified by the government [2,9].

In this paper, a generalized framework is proposed that can be used for any kind of remanufacturable automotive parts. Additionally, the equations for calculating the total demand for automotive part replacements and the environmental and economic impacts are generalized. If all parameters are provided, the environmental and economic impacts of any kind of remanufacturable part can be evaluated. For the case study, the remanufacturing of CV joints in Korea has been considered to evaluate the economic and environmental impacts during the end-of-life operations of a CV joint. Most previous research focuses only on either environmental assessment or economic impact, such as market size or the amount of subsidy [10–22]. However, the objective of this study is to consider both economic and environmental impacts and to find a relationship between the two. Actual vehicle sales data are used to estimate the demand for CV joint replacements each year, which is the most important part of this study. The estimated demand, using the proposed replacement framework with assumptions, can be used to evaluate the environmental impact and economic impact (total profit) as the portion of remanufactured CV joints increases and to suggest the amount of subsidy. Remanufactured products are assumed to be priced lower compared to new ones, meaning that increasing the production of remanufactured products potentially reduces profits for automakers or suppliers while reducing environmental impact.

The calculated demand for CV joint replacements using the proposed framework is used for sensitivity analysis on environmental impact and total profit change according to the increased portion of remanufactured CV joints in the case of replacement. The relationship between economic and environmental impacts as remanufactured CV joints increase has been identified through sensitivity analysis based on different situations, such as preferences or profits on remanufactured CV joints. This relationship can be used as a guide for policymakers to decide how much subsidy should be provided to the remanufacturing industry.

A number of studies have focused on the remanufacturing of automotive parts as more countries are forced to consider the environmental aspects of automotive parts for sustainable design [5,6,13,15,18,23]. The USA and several European countries have been preparing for the remanufacturing industry for sustainable vehicle design by enacting laws

and regulations. Gerrard and Kandlikar studied how the End-of-Life Vehicles Directive affects the remanufacturing industry and how such legislation impacts the environmental footprint of the vehicle industry from the European perspective [13].

In Korea, the remanufacturing industry is in the early stages as the policy “The Act for Recycling of Electrical and Electronic Equipment and Automobiles” has been in effect since 2008. Recently, there has been increasing interest in the remanufacturing industry in Korea. Many researchers in Korea have studied the status of automotive part remanufacturing and strategies for the domestic market to adopt remanufacturing [2–6]. Furthermore, remanufacturing technologies of automotive parts are being studied to extend the life expectancy of vehicles [2].

Manufacturing automotive parts requires significant energy consumption and raw materials, leading to high levels of CO₂ emissions. Therefore, it is necessary to estimate how many automotive parts are environmentally related during the manufacturing or disposal process [15,17,23]. Duval and MacLean conducted a life cycle assessment model for automotive parts [10]. Schmidt also evaluated the life cycle assessment of lightweight vehicles based on end-of-life scenarios but did not consider any economic assessment of automotive parts [18]. Duval and MacLean evaluated both environmental and economic assessments under the situation of recycling automotive parts. Remanufacturing automotive parts should involve both aspects as they are closely connected.

Some studies have considered both the economic and environmental aspects of automotive parts remanufacturing. Kim et al. studied the economic and environmental assessment of the alternator automotive part [12]. They concluded that the market price of a remanufactured component is incorrect and that remanufacturing significantly reduces the environmental burden compared to new production. In other studies, realistic data have been considered to estimate the economic and environmental impact. In developing countries such as Malaysia and China, several researchers have investigated ways to expand the remanufacturing industry [21,24]. They analyzed the effect of government subsidies on the remanufacturing industry to promote remanufacturing activities.

In most cases, the economic and environmental impacts of automotive parts remanufacturing are investigated separately. Laws or regulations related to the remanufacturing industry focus only on the environmental aspect, leading to numerous studies on the environmental assessment of automotive parts. However, the remanufacturing industry has different manufacturing processes and distribution structures, resulting in a different range of prices. As a result, research on the economic assessment of remanufactured automotive parts is also required. Therefore, it is necessary to consider both the environmental and economic aspects of assessment.

2. Methodology

The remanufacturing process consists in the following steps, as depicted in Figure 1, to restore or improve products’ functionality. The parts at the end of their lives (known as core) should be collected at first. All the external parts are cleaned prior to disassembly. After disassembly is completed, the inner parts are also cleaned. All parts are sorted for inspection to determine if they are reusable; otherwise, they are replaced. Parts with severe damage are disposed of. A reconditioning step is performed to restore the condition of the parts to near-new status. Upon completion of all steps, the parts are reassembled, and the functionality of the assembled product is validated in the final stage.

As the remanufacturing industry for automotive parts grows, vehicle owners are presented with options to choose between new or remanufactured parts when replacements are needed. The use of remanufactured automotive parts can reduce CO₂ emissions, raw material usage, and energy consumption. Therefore, both environmental and economic benefits can be obtained by using remanufactured automotive parts.

The framework for automotive parts replacement is proposed in Figure 2. It is noted in the maintenance manual that each part should be regularly inspected [25]. After the inspection is completed, vehicle owners must decide whether to replace the damaged

parts. Replacement does not occur after every inspection; therefore, the replacement probability ($\gamma\%$) for each part must be considered. It is assumed that the replacement probability is equal to the defect rate of parts after inspection. As previously mentioned, vehicle owners have two options when replacing parts. Each option typically depends on the vehicle's age. If the vehicle's age (T) is less than a standard age (T_S), new parts are preferred. This preference is because vehicle owners perceive new parts as more reliable in terms of performance. For older vehicles, however, vehicle owners tend to spend less on maintenance, as the cost of parts replacement becomes more important than performance. Therefore, remanufactured parts are preferred as the vehicle's age increases ($T > T_S$). The preferences for new and remanufactured parts are denoted as α and β , respectively. If the demand for automotive parts replacement can be accurately estimated for this model, the environmental and economic impacts can be quantitatively evaluated. Demand estimation is presented in the following subsection.

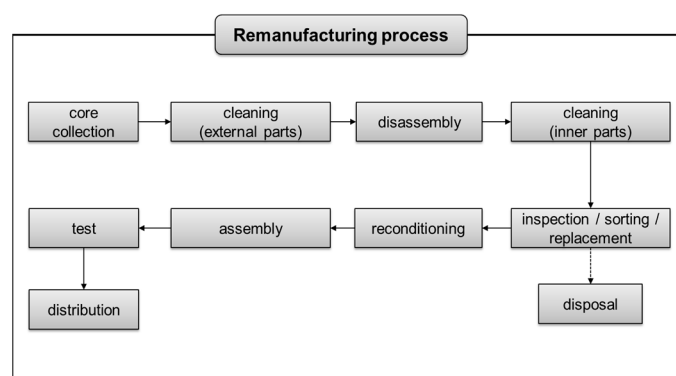


Figure 1. Remanufacturing process of CV joints.

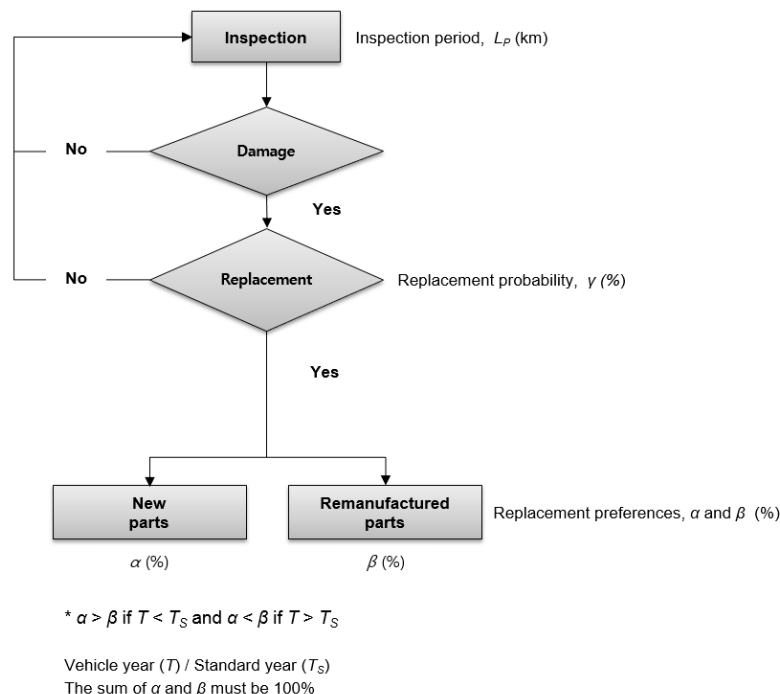


Figure 2. Framework of CV joint replacement.

3. Estimating the Demand for Automotive Parts Replacement

The factors considered in the framework for parts replacement are listed in Table 1. The replacement probability ($\gamma\%$) is assumed to be identical for both new and remanufactured parts. It is expected that replacement demand will increase as the replacement probability

increases. Replacement preferences (α , β) between new and remanufactured parts are dependent on the vehicle's age. When the vehicle's age is less than the standard age (T_S), the preferences for new and remanufactured parts are denoted as α_1 and β_1 , respectively. Conversely, when the vehicle's age exceeds the standard age, the preferences are denoted as α_2 and β_2 . The life expectancy of a vehicle (T_L) is also utilized to define the range of vehicle sales data. It is assumed that no demand for parts replacement will exist when the vehicle's age exceeds its life expectancy.

Table 1. Parameters to calculate the demand of automotive parts replacement.

Description	Parameters		Unit
Replacement probability	γ		%
Standard age	T_S		Year
Vehicle age	T		Year
Life expectancy of the vehicles	T_L		Year
Inspection period	L_P		km
Avg. mileage per year	M		km/year
Replacement probability	γ		%
Standard age	T_S		Year
Vehicle age	T		Year
Replacement preference ($T < T_S$ years)	α_1 (new)	β_1 (remanufactured)	%
Replacement preference ($T > T_S$ years)	α_2 (new)	β_2 (remanufactured)	%

Due to the varying preferences for CV joint replacement based on vehicle age, Equation (1) is employed to calculate the parts replacement demand each year, specifically the demand for new parts (D_{new}) and remanufactured parts (D_{reman}). The number of vehicles sold each year is represented as N_i , and the average mileage per year is represented as M .

$$D = (M/L_P)\gamma \left(\alpha_1 \beta_1 \sum_{i=1}^{T_S} N_i + \alpha_2 \beta_2 \sum_{i=T_S+1}^{T_L} N_i \right) \left\{ \begin{array}{l} \beta_1 \text{ and } \beta_2 \text{ are 1 for new parts, } D_{new} \\ \alpha_1 \text{ and } \alpha_2 \text{ are 1 for remanufactured parts, } D_{reman} \end{array} \right\} \quad (1)$$

The detailed parameters for calculating the demand for automotive parts are described in Table 1. The total demand for new or remanufactured automotive parts depends on each parameter. The replacement probability and inspection period vary for each part. Once the type of automotive part is determined, the total demand can be calculated by adjusting the parameters accordingly.

4. Calculation of Environmental Impact and Economic Effect

4.1. Environmental Impact of Automotive Parts Replacement

Remanufactured automotive parts consume less energy, use fewer raw materials, and emit less CO₂, despite requiring additional steps such as machining, cleaning, and conditioning during the remanufacturing process. However, most components are reused as their life cycles have not yet ended. Therefore, less energy is required for remanufactured parts compared to new ones. This indicates that environmental impacts, such as CO₂ emissions, can be reduced by increasing the proportion of remanufactured automotive parts in replacement scenarios.

The detailed remanufacturing process for each automotive part must be considered to conduct a life cycle assessment (LCA). Each process is related to the amount of energy used, material consumption, transportation, and labor. Additionally, the bill of materials (BOM) for each part should be examined. As previously noted, only a few components are replaced to restore the functionality of automotive parts. LCA requires information on which components are replaced and the amount of energy consumed. The environmental impact of remanufactured parts can be evaluated by considering the number of replaced components throughout their life cycles.

ReCiPe [26] is a recent and harmonized indicator metric available for life cycle impact assessment. Unlike other approaches (such as Eco-indicator 99, the EPS method, LIME, and Impact 2002+), ReCiPe does not include potential impacts from future resource extraction in the impact assessment. ReCiPe has been used to evaluate the environmental impact of both new and remanufactured automotive parts. Three impact categories are calculated: ecosystem quality, human health, and resource use.

4.2. Economic Effect of CV Joint Replacements

Remanufacturing typically requires less energy, labor, and raw materials. Consequently, the cost of remanufactured automotive parts is relatively lower than that of new ones. Due to the differences in retail prices and production costs between new and remanufactured parts, profit calculations are performed to evaluate the economic effects of increasing the proportion of remanufactured parts. The profits for new and remanufactured parts are calculated using Equations (2) and (3).

$$\pi_N = P_N - C_N \text{ for a new CV joint} \quad (2)$$

$$\pi_R = P_R - C_R \text{ for a remanufactured CV joint} \quad (3)$$

where π_N and π_R are the profit of new and remanufactured parts, respectively, P_N and P_R are the retail price of new and remanufactured parts, respectively, and C_N and C_R are the estimated total cost of new and remanufactured parts, respectively.

Although the retail prices of automotive parts (both new and remanufactured) are well known, estimating their production costs is challenging. Therefore, certain assumptions have been made to calculate the profit of remanufactured automotive parts. Obtaining the exact manufacturing cost of automotive parts is almost impossible, as it is treated as proprietary information. Consequently, the cost is estimated using the company's operating profit-to-sales ratio in the automotive parts industry.

The detailed parameters used to calculate the profit from automotive parts replacement are presented in Table 2. New and remanufactured automotive parts have different retail prices, production costs, and profits. The total profit can also vary depending on the standard vehicle age and consumer preferences. Sensitivity analysis can be conducted by varying the preference ratios, retail prices, and production costs.

Table 2. Parameters to calculate the profit of automotive parts replacement.

Description	New Parts	Remanufactured Parts	Unit
Retail price	P_N	P_R	USD
Cost	C_N	C_R	USD
Profit	π_N	π_R	USD
Replacement preference ($T < T_S$)	$\alpha_1 = 100 - \beta_1$	β_1	%
Replacement preference ($T > T_S$)	$\alpha_2 = 100 - \beta_1$	β_2	%
Replacement probability		γ	%

5. Case Study: CV Joint Replacement in Korean Automotive Market

5.1. Estimating the Demand of CV Joint Replacement

The case study of CV joint replacement in Korea is presented to evaluate the environmental and economic impact. A CV joint is one of the remanufacturable automotive parts, and the remanufacturing industry for CV joints is relatively well established in Korea. Although it has a long life cycle and replacements occur infrequently, it is still valuable to evaluate the environmental and economic impacts of CV joint remanufacturing due to their significance. The results can be used to determine how much financial support should be provided to expand the remanufacturing industry in Korea. For this case study, it is assumed that the exact annual sales data for a D-segment vehicle (Sonata) from 1992 to

2013 is provided [27]. The D-segment is popular in Korea, making its sales data a suitable reference for estimating the demand for CV joint replacement. The following assumptions are introduced to estimate CV joint replacements for each year.

According to the maintenance manual, CV joints are recommended to be inspected every 10,000 km [25]. This inspection period aligns with that for engine oil changes. Visual inspections can be performed when vehicles are lifted, and this is usually the only opportunity to check for damage to the underside of the vehicle. Therefore, the inspection period (LP) for CV joints is assumed to be 10,000 km in this study. Since CV joints are not replaced after every inspection, the replacement probability (γ) must be considered. It is assumed that the replacement probability is 3%, as damage to CV joints is uncommon except for vehicles that are driven on rough or dirt roads.

Surveys [28,29] indicate that vehicle owners have different preferences when replacing CV joints. Most owners of older vehicles tend to spend less on maintenance, preferring remanufactured CV joints. The preference for new CV joints is denoted as alpha (α), and the preference for remanufactured CV joints is denoted as beta (β). The sum of these preferences must equal 100%.

The standard age distinguishing new from old vehicles is assumed to be seven years, as noted in [30]. According to this source, 90% of owners with newer vehicles prefer new CV joints due to their perceived reliability, despite the higher cost, while 10% prefer remanufactured ones. Conversely, 90% of owners with older vehicles prefer remanufactured CV joints, as the cost of parts becomes more important than reliability for older vehicles. The estimated annual demand for CV joint replacement is shown in Figure 3, which illustrates that while demand fluctuates, the changes are less significant than the fluctuations in vehicle sales.

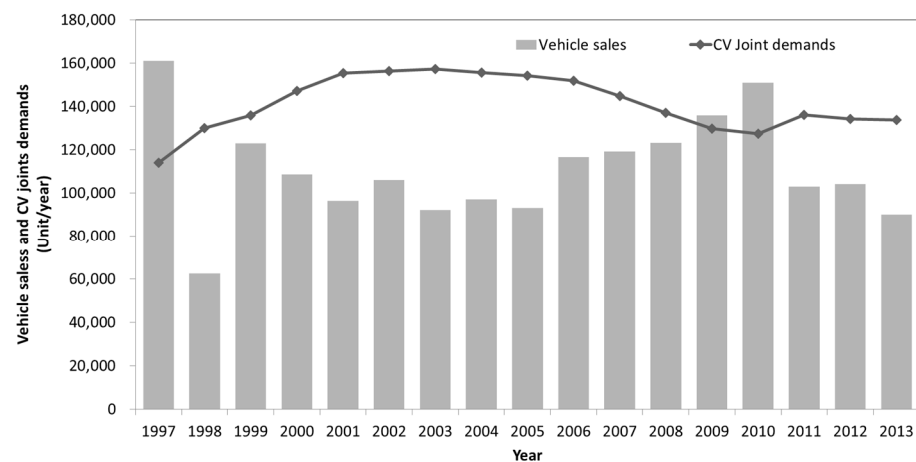


Figure 3. The demand for CV joint replacements with respect to vehicle sales.

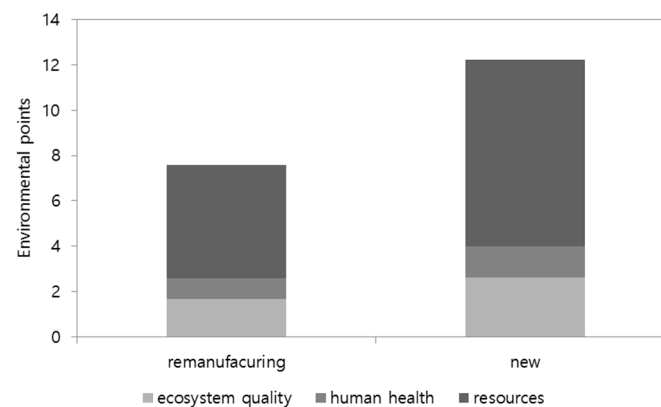
5.2. Environmental Impact of CV Joint Replacements

A CV joint mainly consists of three parts: the inboard joint, outboard joint, and shaft [31]. The bill of materials for each part is described in Table 3. The shaft is typically reused unless cracks or severe damage are observed. Most components of the inboard and outboard joints are also reused, but certain components, such as the boot, clamp, retaining ring, retainer, and grease, must be replaced with new ones during the remanufacturing process. The environmental impact of remanufactured parts can be evaluated by considering these components throughout their life cycle.

The ReCiPe method has been used to assess the environmental impact of both new and remanufactured CV joints, with the results shown in Figure 4. Three impact categories such as ecosystem quality, human health, and resource were calculated. The calculated points for ecosystem quality, human health, and resources for a new CV joint are 2.63, 1.35, and 8.22, respectively, whereas the points for remanufactured CV joints are 1.67, 0.92, and 5.00, respectively.

Table 3. Bill of materials (BOM) for CV joints (D-segment vehicle in Korea).

Type	Components	Material	Mass (g)	Unit
Shaft	Shaft	SM 53C	3916	1
Inboard Joint	Housing	SAE 4121-H	1690	1
	Boot	Rubber	153	1
	Clamp	SS304	32	2
	Retaining ring	SAE 1070/1074	4	1
	Spider	SAE 4118-H	201	1
	Roller	SAE 52100	90	3
	Retainer	SAE 1070/1074	2	1
	Grease		150	1
Outboard Joint	Housing	SAE-4121-H	1988	1
	Boot	Rubber	104	1
	Clamp	SS304	38	2
	Retaining ring	SAE1070/1074	2	1
	Race	SAE 52100	275	1
	Cage	SAE 52100	157	1
	Ball	SAE 52100	188	6
	Grease		100	1

**Figure 4.** Environmental impact point of CV joints based on ReCiPe method.

The “human health” impact includes factors such as the number and duration of diseases and life years lost due to premature death caused by environmental factors. “Ecosystem quality” measures the effects on species diversity, particularly in vascular plants and lower organisms. Additionally, the “resources” category indicates the surplus energy required in the future to extract lower-quality mineral and fossil resources. The total environmental impact points for each CV joint are 12.20 for a new CV joint and 7.59 for a remanufactured CV joint. The results show that remanufactured CV joints have a lower environmental impact, approximately 62% of that of new ones.

5.3. Economic Effect of CV Joint Replacement

The retail price of new CV joints installed in D-segment vehicles in Korea is \$170, while the price of remanufactured CV joints is approximately \$70. Although the retail prices of CV joints (both new and remanufactured) are well known, estimating their production costs remains challenging. Consequently, certain assumptions must be made when calculating the profit of CV joints. Obtaining the exact manufacturing cost of automotive parts is nearly impossible, as this information is treated as proprietary. Therefore, the cost is estimated using the company’s operating profit-to-sales ratio, which is typically below 10% in the automotive parts industry. The average profit margin for the automotive parts industry ranges between 8% and 10%, with the maximum percentage of 10% being considered to estimate the profit of both new and remanufactured CV joints.

Profits were calculated, and the results for each CV joint type are presented in Figure 5. The profit from a new CV joint is approximately 62.5% higher than that of a remanufactured CV joint, despite the lower production cost of the remanufactured version. The reduction in profit due to the increased preference for remanufactured CV joints can be offset by considering the preservation of the loss rate, which can be determined by government policy.

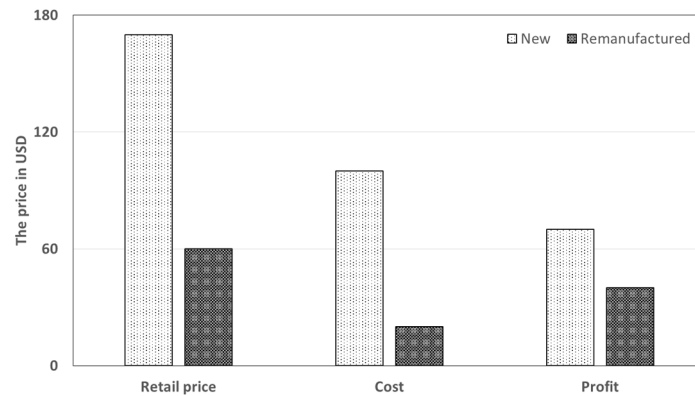


Figure 5. The price, cost, and profit of new and remanufactured CV joints.

5.4. Sensitivity Analysis on Preference Change

The environmental and economic impacts were evaluated in the previous section, respectively. As some parts are reused in the remanufacturing process, reductions in energy consumption, raw material usage, and CO₂ emissions can be achieved. As a result, the environmental impact of remanufactured CV joints can be reduced if the proportion of remanufactured CV joints in replacements increases. However, profit could fall to almost 40% when a CV joint is replaced with a remanufactured one due to the relatively low price of remanufactured CV joints.

The proportion of remanufactured CV joints in replacement scenarios affects both environmental and economic impacts. Thus, a sensitivity analysis was conducted to evaluate the changes in environmental and economic impacts by increasing the proportion of remanufactured parts. In the baseline study, it was assumed that the preference for CV joint replacement when the vehicle age exceeds seven years is fixed at 10% (new CV joint) and 90% (remanufactured CV joint). The proportion of remanufactured CV joints (β_1) was considered as a variable and was increased from 0% to 100%.

The sensitivity analysis results, according to the change in the proportion of remanufactured CV joints, are shown in Figure 6. It can be seen from the figure that the total environmental impact (new and remanufactured together) gradually decreases as the proportion of remanufactured CV joints increases. Additionally, the environmental impact attributed solely to remanufactured CV joints increases as anticipated. These results indicate that replacing damaged CV joints with remanufactured CV joints can minimize environmental impact.

The total profit, representing economic impact, also decreases as the proportion of remanufactured CV joints increases. The results show that while the market size of the remanufacturing industry is expanded, the total market profit is simultaneously reduced. Thus, increasing the proportion of remanufactured CV joints offers advantages in terms of environmental impact but disadvantages in terms of industry profit.

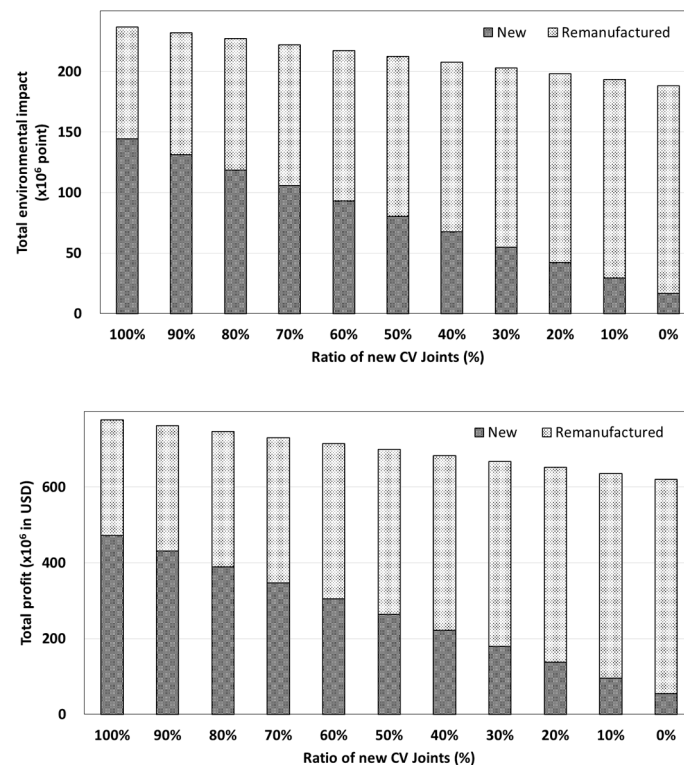


Figure 6. Total environmental impact point and total profit with the ratio of new CV joints (100~0%).

5.5. Sensitivity Analysis on Profit Change

Additional sensitivity analysis was conducted to evaluate the change in profit according to variations in the retail price of remanufactured CV joints. Profit could be increased by either reducing production costs or raising the retail price. In this study, only the retail price was considered, as estimating the exact production costs of both new and remanufactured CV joints is challenging. The retail price of remanufactured CV joints was set as a variable, changing from \$75 to \$90 in \$5 increments. When the retail price of remanufactured CV joints reached \$80, profits from new and remanufactured CV joints became identical. As previously mentioned, the maximum profit was assumed to be 10%, equating to \$20 for a new CV joint. The replacement preference for vehicles over seven years old was fixed at 10% for new CV joints and 90% for remanufactured CV joints, respectively. Additionally, the replacement probability was fixed at 3%.

Profit changes for various replacement preference values were simulated, and the results are shown in Figure 7. The figure indicates that different slopes can be observed according to the profit gap between new and remanufactured CV joints (0%, 8%, 15%, and 25%). As the proportion of remanufactured CV joints increases, the slope becomes steeper with a higher profit gap. The slope of total profit becomes zero when the profit of a remanufactured CV joint equals that of a new CV joint, which can be used as a baseline. A higher profit gap indicates that the market for remanufactured CV joints is relatively small compared to that for new CV joints. The profit gap can be reduced by minimizing production costs or raising the retail price. However, minimizing the production cost of remanufactured CV joints is very difficult, as the retail price and production cost are already low. Therefore, the retail price of remanufactured CV joints should be increased to reduce the profit gap. The issue with raising the retail price is that the preference for remanufactured CV joints would decrease as their retail price approaches that of new ones. Since the quality and reliability of remanufactured CV joints are generally lower than those of new ones, it may be necessary to provide subsidies to manufacturers instead of raising retail prices. Consequently, this would lead to an increase in the preference for remanufactured CV joints in replacements, as customers can still purchase remanufactured

CV joints at a lower price. The relationship between profit and environmental impact according to the proportion change of remanufactured CV joints is analyzed in the following section.

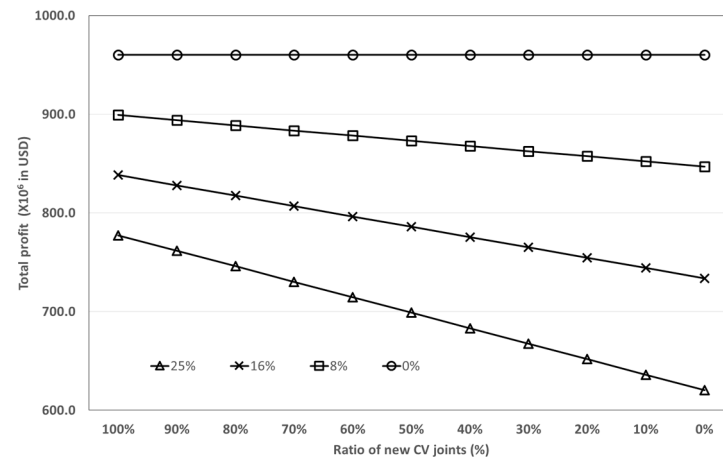


Figure 7. Total profit analysis according to profit difference between new and remanufactured products (profit gap: 0, 8, 16, and 25%).

5.6. Relationship between Environmental and Economic Impact

The increased proportion of remanufactured CV joints consistently has a positive effect on reducing environmental impact. However, it has been identified that companies within the remanufacturing industry incur a loss in profit, as described in Figure 8 (profit vs. environmental impact). In Figure 8, the X-axis represents environmental impact, while the Y-axis represents total profit change.

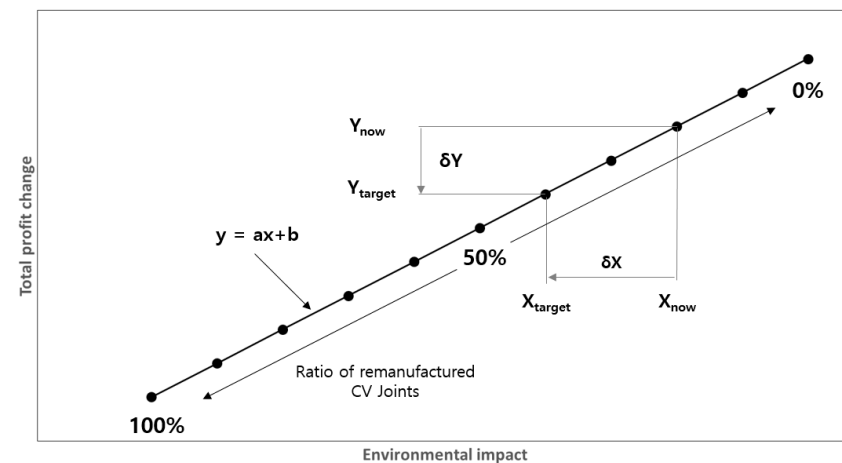


Figure 8. Relation between economic and environmental impact.

Figure 7 was generated by calculating environmental impact and profit reduction based on the assumptions explained in the previous subsections. The replacement preferences for vehicles older than seven years were fixed at 10% for new CV joints and 90% for remanufactured CV joints, respectively. The replacement preference for remanufactured CV joints was varied from 0% to 100%. The calculations were based on accumulated vehicle sales data, resulting in a linear-like relationship between environmental impact and profit. The slope of this relationship depends on the retail price, production cost, and replacement preferences.

The figure indicates that environmental impact is inversely proportional to profit change. It is necessary to reduce environmental impact by increasing the proportion of remanufactured CV joints during replacements. This reduction in environmental impact

results in a profit loss for companies manufacturing new CV joints. Therefore, accurately determining the slope in Figure 8 is crucial for calculating the profit loss associated with environmental impact savings, and vice versa.

The environmental impact savings ($EI_{saving} = \delta X$) and profit drop ($P_{drop} = \delta Y$) are defined in Equations (4) and (5).

$$EI_{saving} = X_{now} - X_{target} \quad (4)$$

$$P_{drop} = Y_{now} - Y_{target} \quad (5)$$

Since the profit drop is proportional to the environmental impact savings, the slope of this relationship can be easily determined. The amount of profit drop per remanufactured CV joint can be calculated using Equation (6). The coefficient of the slope is determined by the retail price of a remanufactured CV joint. The slope is defined by dividing the profit drop by the environmental impact savings. Therefore, the total profit drop can be obtained by multiplying the slope coefficient by the environmental impact savings. Additionally, the unit profit drop is calculated by dividing the profit drop by the total number of increased remanufactured CV joints (D_{gap}).

$$P_{drop/unit} = \frac{a \times EI_{saving}}{D_{gap}} \quad (\text{per a remanufactured CV joint}) \quad (6)$$

Once the unit profit drop is estimated, the amount of subsidy for a remanufactured CV joint replacement can be calculated by considering the preservation of the loss rate (θ) using Equation (7). The profit drop caused by the increased proportion of remanufactured CV joints can be compensated by governments through tax benefits or direct financial aid for each remanufactured CV joint. If the preservation of the loss rate exceeds 100%, the preference for remanufactured CV joints can be increased by the industry or consumers. The compensated benefit is defined as $P_{sub/unit}$. This allows governments to use the obtained subsidy as a guideline for determining the amount of subsidy to provide to the remanufacturing industry or vehicle owners to expand the market size.

$$P_{sub/unit} = P_{drop/unit} \times \theta \quad (\text{per a remanufactured CV joint}) \quad (7)$$

Table 4 describes the amount of subsidy (P_{sub}) per increased number of remanufactured CV joints according to the retail price of remanufactured CV joints. First, all parameters in Tables 2 and 3 must be determined based on the scenario. Except for replacement preference, the parameters are generally fixed. Replacement preference is considered a major factor in calculating the demand for CV joints. It is assumed that the current proportion of remanufactured CV joints for vehicles older than seven years is 40%, which will be increased to 60%. The number of increased remanufactured CV joints can be calculated by subtracting the demand for remanufactured CV joints at 40% preference D_{reman} (β_2 is 40%) from the demand at 60% preference D_{reman} (β_2 is 60%), denoted as D_{gap} . The environmental impact savings are assumed to remain constant as the increased proportion of remanufactured CV joints is fixed from 40% to 60%. Therefore, the relationship between environmental impact and total profit can be determined by changing the retail price of remanufactured CV joints. From this relationship, the slope (a) can be obtained by using the profit drop and environmental impact savings. The calculated environmental impact savings are 457,776, and the total profit drop can be calculated by multiplying the slope coefficient, 4.170, by the environmental impact savings, resulting in 455,765. The profit drop per remanufactured CV joint is obtained from Equation (6), which is \$4.170. The amount of subsidy per increased number of remanufactured CV joints is calculated as \$4.170, assuming that the preservation of the loss rate is 100%.

The results in Table 4 indicate that a subsidy of \$4.17 is required for each remanufactured CV joint when the retail price is set at \$90, which corresponds to the maximum

profit gap (25%) between new and remanufactured CV joints. At this retail price, the profit gap between new and remanufactured CV joints is \$20. This gap could be compensated by the proposed subsidy as the proportion of remanufactured CV joints increases. A larger subsidy is required as the profit gap between new and remanufactured CV joints increases, and the amount of subsidy can be controlled by the government to preserve the loss rate. If full preservation of the loss rate for subsidies is considered, the market size of the remanufacturing industry could be rapidly expanded.

Table 4. The amount of subsidy depends on the retail price of remanufactured CV joints (with the preservation of loss rate at 100%).

The Retail Price of Remanufactured CV Joint	The Retail Price of New CV Joint	The Coefficient of the Slope (a)	The Number of Increased Remanufactured CV Joints (D_{gap})	Preservation of Loss Rate (θ)	Unit Subsidy
\$90 (USD)	\$170 (USD)	0.000	376,421	100%	\$0.000 (USD)
\$85 (USD)		1.083			\$1.390 (USD)
\$80 (USD)		2.166			\$2.166 (USD)
\$75 (USD)		3.249			\$4.170 (USD)

6. Conclusions

This study evaluates both the environmental and economic impacts of remanufactured CV joints. While existing research predominantly examines the environmental benefits of replacing automotive parts with remanufactured alternatives and some explores necessary government subsidies to promote remanufacturing, few studies employ realistic data to assess both impacts comprehensively. Utilizing actual vehicle sales data, this research introduces a framework to accurately estimate the demand for CV joint replacements, despite the inherent challenges in determining exact replacement numbers. This estimation facilitates a quantitative assessment of the associated environmental and economic impacts.

A sensitivity analysis was conducted to investigate the effects of increasing the proportion of remanufactured CV joints. The results indicate that a higher share of remanufactured parts significantly benefits the environment by reducing CO₂ emissions, raw material usage, and energy consumption. However, this shift also leads to a decrease in total profits within the CV joint replacement market. To address this trade-off, further analysis explored the relationship between economic impacts and the proportion of remanufactured parts by varying the profitability of remanufactured CV joints.

The findings suggest that financial incentives, such as tax benefits or direct funding from the government, are essential to mitigate the profit losses faced by manufacturers as the market share of remanufactured parts increases. Substantial subsidies are required to bridge the profit gap between new and remanufactured CV joints, thereby facilitating the expansion of the remanufacturing industry. With adequate financial support, the remanufacturing sector could experience rapid market growth.

Future research should apply the proposed framework to other automotive parts with similar replacement scenarios, further validating its applicability and effectiveness in promoting sustainable manufacturing practices.

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References

1. Kwak, M.; Kim, H. Design for life-cycle profit with simultaneous consideration of initial manufacturing and end-of-life remanufacturing. *Eng. Optim.* **2015**, *47*, 18–35. [CrossRef]
2. Kang, H.; Kim, Y. Current status and trend of Korea's remanufacturing R&D in the field of automotive parts. *Trans. Korean Soc. Automot. Eng.* **2013**, *35*, 20–24.
3. Mok, H.; Jeon, C.; Han, C.; Park, S.; Sagong, H.; Seliger, G. Remanufacturing industry for automobile parts of European. *Trans. Korean Soc. Automot. Eng.* **2011**, *19*, 38–44.
4. Mok, H.; Chang, S.; Han, C.H.; Skerlos, S.J.; Kim, H.J.; Lee, K.C. Remanufacturing Industry for Automobile Parts in USA. *J. Korean Soc. Precis. Eng.* **2010**, *27*, 58–65.
5. Blume, T.; Walther, M. The End-of-life Vehicle Ordinance in the German automotive industry—Corporate sense making illustrated. *J. Clean. Prod.* **2013**, *56*, 29–38. [CrossRef]
6. Xiang, W.; Ming, C. Implementing extended producer responsibility: Vehicle remanufacturing in China. *J. Clean. Prod.* **2011**, *19*, 680–686. [CrossRef]
7. Zhang, T.; Chu, J.; Wang, X.; Liu, X.; Cui, P. Development pattern and enhancing system of automotive components remanufacturing industry in China. *Resour. Conserv. Recycl.* **2011**, *55*, 613–622. [CrossRef]
8. Mok, H.; Jeon, C.; Han, C.; Song, M.; Park, B.; Kwak, H.; Park, S. A study on remanufacturing industry for automobile parts. *Trans. Korean Soc. Automot. Eng.* **2008**, *19*, 184–191.
9. Jung, D. The activation method of remanufacturing automotive parts for implementation of resource recycling society. *Trans. Korean Soc. Automot. Eng.* **2014**, *36*, 28–34.
10. Duval, D.; MacLean, H.L. The role of product information in automotive plastics recycling: A financial and life cycle assessment. *J. Clean. Prod.* **2007**, *15*, 1158–1168. [CrossRef]
11. Ferrer, G. The economics of tire remanufacturing. *Resour. Conserv. Recycl.* **1997**, *19*, 221–255. [CrossRef]
12. Kim, H.; Raichur, V.; Skerlos, S.J. Economic and environmental assessment of automotive remanufacturing: Alternator case study. In Proceedings of the International Manufacturing Science and Engineering Conference, Evanston, IL, USA, 7–10 October 2008; pp. 33–40.
13. Gerrard, J.; Kandlikar, M. Is European end-of-life vehicle legislation living up to expectations? Assessing the impact of the ELV Directive on 'green' innovation and vehicle recovery. *J. Clean. Prod.* **2007**, *15*, 17–27. [CrossRef]
14. Mitra, S.; Webster, S. Competition in remanufacturing and the effects of government subsidies. *Int. J. Prod. Econ.* **2008**, *111*, 287–298. [CrossRef]
15. Prateek, P.; Paul, C.; Victor, P. Life cycle assessment of Australian automotive door skins. *Int. J. Life Cycle Assess.* **2009**, *14*, 420–428. [CrossRef]
16. Rebitzer, G.; Ekvall, T.; Frischknecht, R.; Hunkeler, D.; Norris, G.; Rydberg, T.; Schmidt, W.-P.; Suh, S.; Weidema, B.P.; Pennington, D.W. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environ. Int.* **2004**, *30*, 701–720. [CrossRef]
17. Saavedra, Y.M.B.; Barquet, A.P.B.; Rozenfeld, H.; Forcellini, F.A.; Ometto, A.R. Remanufacturing in Brazil: Case studies on the automotive sector. *J. Clean. Prod.* **2013**, *53*, 267–276. [CrossRef]
18. Schmidt, W.; Dahlqvist, E.; Finkbeiner, M.; Krinke, S.; Lazzari, S.; Oschmann, D.; Pichon, S.; Thiel, C. Life cycle assessment of lightweight and end-of-life scenarios for generic compact class passenger. *Int. J. Life Cycle Assess.* **2004**, *9*, 405–416. [CrossRef]
19. Subramoniam, R.; Huisingh, D.; Chinnam, R.B. Remanufacturing for the automotive aftermarket-strategic factors: Literature review and future research needs. *J. Clean. Prod.* **2009**, *17*, 1163–1174. [CrossRef]
20. Sundin, E.; Bras, B. Making functional sales environmentally and economically beneficial through product remanufacturing. *J. Clean. Prod.* **2005**, *13*, 913–925. [CrossRef]
21. Wang, L.; Chen, M. Policies and perspective on end-of-life vehicles in China. *J. Clean. Prod.* **2013**, *44*, 168–176. [CrossRef]
22. Wang, Y.; Chang, X.; Chen, Z.; Zhong, Y.; Fan, T. Impact of subsidy policies on recycling and remanufacturing using system dynamics methodology: A case of auto parts in China. *J. Clean. Prod.* **2014**, *74*, 161–171. [CrossRef]
23. Östlin, J.; Sundin, E.; Björkman, M. Product life-cycle implications for remanufacturing strategies. *J. Clean. Prod.* **2009**, *17*, 999–1009. [CrossRef]
24. Amelia, L.; Wahab, D.A.; Che Haron, C.H.; Muhamad, N.; Azhari, C.H. Initiating automotive component reuse in Malaysia. *J. Clean. Prod.* **2009**, *17*, 1572–1579. [CrossRef]
25. Available online: <http://justgivemethedamnmanual.com/hyundai/hyundai-sonata-owners-manual/> (accessed on 11 July 2024).
26. Available online: <http://www.pre-sustainability.com/recipe> (accessed on 11 July 2024).
27. Available online: https://www.autoview.co.kr/news/articleList.html?sc_section_code=S1N1&sc_sub_section_code=S2N5&view_type=sm (accessed on 10 July 2024).
28. Jung, D. Development strategy through standardization of the remanufacturing part of automobiles. *Trans. Korean Soc. Automot. Eng.* **2013**, *35*, 37–45.

29. Lee, J.; Choi, K. A study on the activation of remanufacturing industry according to the korean automobile cultures—Focusing on the automobile parts industry in Korea. *Korea Sci. Art Forum* **2013**, *12*, 229–236. [[CrossRef](#)]
30. Yoo, T.W.; Baek, J.H.; Hong, S.W.; Jung, K.R. Status of Automotive Parts Remanufacturing Industry and Strategies for Activating Its Domestic Market. *J. Korean Soc. Automot. Eng.* **2012**, *34*, 45–54.
31. Lee, C.-H.; Polycarpou, A.A. A phenomenological friction model of tripod constant velocity (CV) joints. *Tribol. Int.* **2010**, *43*, 844–858. [[CrossRef](#)]

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