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Exhaust emission control with catalytic converters: a review

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ABSTRACT

The rapid growth in automobile usage worldwide has significantly increased the emission of harmful pollutants such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter (PM). These pollutants contribute to environmental problems including global warming, acid rain, photochemical smog, and adverse human health effects. Conventional three-way catalytic converters (TWCs) have been widely adopted in automotive exhaust systems to reduce these emissions effectively. Traditionally, TWCs rely heavily on noble metals such as Platinum (Pt), Palladium (Pd), and Rhodium (Rh) because of their excellent catalytic activity and thermal stability. However, the high cost, limited availability, thermal degradation and susceptibility to catalyst poisoning of noble metals have stimulated growing interest in the development of low-cost non-noble metal catalysts. Recent research has focused on transition metals such as copper (Cu), manganese (Mn), nickel (Ni), cobalt (Co), iron (Fe), chromium (Cr), titanium dioxide (TiO_2), and zinc (Zn) as possible substitutes for precious metals in catalytic converters. These materials are attractive because they are relatively inexpensive, abundant, and environmentally sustainable. Researchers have investigated their catalytic efficiency, durability, geometric configuration, thermal characteristics, and emission reduction performance in various automotive applications. This review examines previous research (1999-2025) on exhaust emission control using catalytic converters.

1.0 Introduction

The rapid growth of the automobile industry has significantly improved transportation and economic development worldwide [1]. However, the increase in vehicle ownership and industrialization has also contributed greatly to environmental pollution through the emission of harmful exhaust gases such as Carbon Monoxide (CO), Hydrocarbons (HC), Nitrogen Oxides (NOx), particulate matter (PM), and Volatile Organic Compounds (VOCs)[2] . These pollutants have been associated with severe environmental and public health problems, including photochemical smog, acid rain, respiratory diseases, and global warming [2].

During the pre-control era before the 1950s, there were no regulations governing automobile emissions [3] . Early automobiles manufactured by companies such as Ford Motor Company operated with simple carbureted engines, releasing untreated exhaust gases directly into the atmosphere [4]. Rapid urbanization and increased vehicle ownership, especially in highly industrialized cities such as Los Angeles, resulted in severe air pollution problems [5]. One of the major environmental concerns identified during this period was photochemical smog, which is primarily formed through the reaction of vehicle emissions with sunlight. By the 1950s and 1960s, scientific understanding of automobile pollution and its effects on human health and the environment had improved considerably. This led to the introduction of the first vehicle emission regulations [6]. The state of California became a pioneer in emission control by introducing the first vehicle emission standards in 1961, targeting hydrocarbons and carbon monoxide emissions. Subsequently, the California Air Resources Board was established in 1967 to regulate and monitor vehicle emissions [7]. Early emission control technologies introduced during this period included the Positive Crankcase Ventilation (PCV) valve, improved carburetor designs, and basic exhaust treatment systems [8].

A major breakthrough in automobile emission control occurred during the 1970s following the enactment of the Clean Air Act in the United States. The Act mandated substantial reductions in vehicle emissions and led to the establishment of the United States Environmental Protection Agency (EPA) in 1970 to enforce emission standards [8]. One of the most significant technological innovations introduced during this era was the catalytic converter in 1975. The catalytic converter became an effective device for converting harmful exhaust gases such as CO, HC, and NOx into less harmful substances including carbon dioxide, nitrogen, and water vapor. The adoption of catalytic converters also resulted in the gradual phase-out of leaded gasoline because lead deposits contaminated platinum-based catalysts used within the converter [9].

Automobile manufacturers such as Honda and Volkswagen became among the early adopters of catalytic converter technology. In 1972, General Motors proposed the elimination of leaded fuels for future vehicle models to support the effective operation of catalytic converters. Between the 1980s and 1990s, emission control systems became more advanced and precise with the introduction of Electronic Fuel Injection (EFI), oxygen (lambda) sensors, and Engine Control

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Units (ECUs) [10]. During this period, global emission regulations also expanded significantly. Europe introduced the Euro Emission Standards beginning with Euro 1 in 1992, while Japan and several other countries established similar regulatory frameworks [11]. These technological and regulatory developments contributed to substantial reductions in vehicle emissions worldwide. The 2000s and 2010s witnessed the introduction of more sophisticated emission reduction technologies, particularly for diesel engines. These technologies included Diesel Particulate Filters (DPF) [12] Exhaust Gas Recirculation (EGR), and Selective Catalytic Reduction (SCR) systems.

Furthermore, stricter environmental policies and global climate agreements such as the Paris Agreement encouraged the development of low-emission and zero-emission vehicles [13]. In recent years, attention has shifted from merely reducing pollutants to completely eliminating vehicle emissions through the development of hybrid and electric vehicles. Hybrid vehicles such as the Toyota Prius and fully electric vehicles manufactured by Tesla represent major advancements in sustainable transportation technology. Modern emission standards such as Euro 6 continue to impose stricter limits on pollutants emitted from internal combustion engines. The development of catalytic converter technology has undergone several stages of improvement since its invention. In 1956, French mechanical engineer Eugene Houdry patented the first catalytic converter design [14]. The technology was further developed in 1973 by Carl D. Keith and John J. Mooney. Early research focused on identifying suitable catalyst materials capable of reducing harmful exhaust gases efficiently. Palladium and platinum were identified as highly effective catalysts, while oxides of iridium, rubidium, and osmium were found to be volatile and unsuitable for long-term application. During the late 1970s and 1980s, researchers faced significant challenges in developing catalysts capable of effectively reducing Nitrogen Oxides (NOx). This led to the introduction of the two-bed catalytic converter system, consisting of a primary reduction bed for NOx treatment and a secondary oxidation bed for treating hydrocarbons and carbon monoxide.

However, ammonia formation within the converter posed operational challenges. Although ruthenium was investigated as a potential catalyst material, it demonstrated poor reducing efficiency and high selectivity toward ammonia formation. Rhodium later emerged as a preferred catalyst for NOx reduction due to its superior reducing properties and lower ammonia selectivity. Research efforts also investigated non-noble metal catalysts as alternatives to expensive Platinum Group Metals (PGMs). Transition metal oxides such as cobalt oxide, nickel oxide, manganese oxide, copper oxide, chromium oxide, cerium dioxide, iron oxide, titanium oxide, and zirconium dioxide were studied because of their lower cost and potential catalytic properties. However, many of these materials exhibited lower durability and reduced emission conversion efficiency compared to platinum-based catalysts.The diagram in figure 1 below shows the picture of catalytic converter in a car Despite the effectiveness of catalytic converters in reducing automobile emissions, the high cost and limited availability of Platinum Group Metals remain major challenges, especially in developing countries [15–19]. Therefore, there is increasing interest in developing alternative catalyst materials using transition metal oxides that are cheaper, environmentally friendly, and locally available. This study therefore focuses on the investigation and development of suitable catalytic converter materials for improved automobile emission control and environmental sustainability

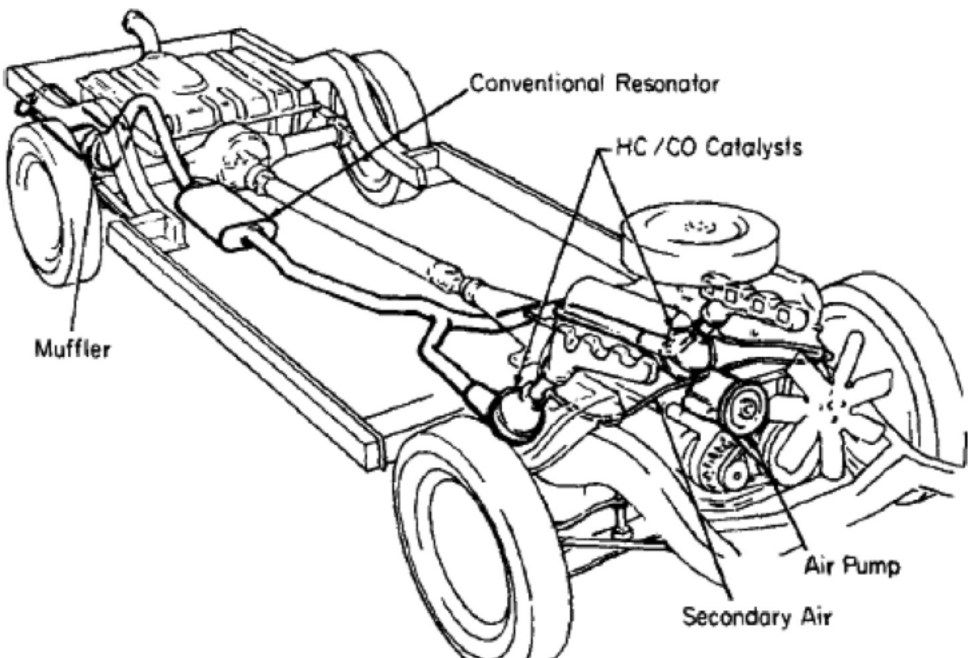

Figure 1: Catalytic Converter in a Car adapted from [50]

2.0 Literature review

Automotive exhaust emissions remain a major contributor to environmental pollution because of the release of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter[1]. To mitigate these emissions, catalytic converters have become an essential component of vehicle exhaust systems. Conventional catalytic converters predominantly employ platinum group metals (PGMs), including platinum (Pt), palladium (Pd), and rhodium (Rh), because of their exceptional catalytic activity and durability across a wide operating temperature range. However, the increasing cost, scarcity, and supply risks associated with PGMs have motivated researchers to investigate alternative catalyst materials, particularly non noble metal catalysts[1]. Platinum group metal catalysts have demonstrated superior catalytic performance in automotive emission reduction systems. PGM-based catalytic converters can achieve conversion efficiencies of approximately 98–99% for CO and above 95% for HC emissions. Similarly, three-way catalytic converters employing PGM catalysts typically achieve pollutant conversion efficiencies ranging from 90—99.9% under normal operating conditions[2]. Despite their high catalytic performance, PGM catalysts face major limitations. One important challenge is their high cost due to limited global reserves and increasing market demand. Catalyst aging also reduces their effectiveness over time. Aged PGM catalysts exhibit reduced conversion efficiencies for CO, HC, and NOx due to metal particle agglomeration and sintering effects[3]. Substantial research has therefore focused on transition metals and metal oxides such as copper (Cu), manganese (Mn), chromium (Cr), nickel (Ni), zinc (Zn), iron (Fe), and cobalt (Co).

These materials are attractive because they are less expensive and more abundant than noble metals. Copper-zinc (Cu-Zn) catalytic materials and reported reductions of approximately 47.71% for CO emissions and 55.34 percent for HC emissions[3]. Chromium-coated copper catalysts reduced CO emissions by approximately 95.35% and HC emissions by 79.28 percent, while manganese-coated copper catalysts achieved reductions of 96.36% and 94.74% for CO and HC respectively. Metal oxide catalysts have also demonstrated favorable results[4]. Albert et al. (2017) reported that MnO-based catalytic converters effectively oxidized CO and reduced NOx emissions. Al_2O_3 and SiO_2 coated catalytic converters reduced NOx emissions by up to 55.22%, CO emissions by approximately 80%, and HC emissions by nearly 88.88%. Recent advances have attempted to eliminate PGMs entirely while maintaining high performance[4]. A Platinum group metal-free three-way catalyst using $MgMn_2O_4$ and $CuCo_2O_4$ in a tandem arrangement was reported.The study reported catalytic performance comparable to Rh-based systems under specific operating conditions [5].

Overall, available literature suggests that non noble metal catalysts have evolved considerably and can achieve substantial reductions in automotive emissions at significantly lower cost than platinum group metals. However, challenges related to catalyst aging, durability, thermal stability, and low-temperature performance remain unresolved. Further research is required to optimize non noble catalyst formulations and designs to achieve performance comparable to platinum group metals while maintaining long-term operational stability. Automotive emissions remain a significant source of environmental pollution because of the release of harmful gases including carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter. To minimize these pollutants, catalytic converters have become essential components of automotive exhaust systems. Conventional catalytic converters primarily employ Platinum group metals (PGMs), mainly Platinum (Pt), Palladium (Pd), and Rhodium (Rh), because of their high catalytic activity, thermal stability, and ability to facilitate oxidation and reduction reactions simultaneously[5]. However, increasing costs, limited availability, and concerns over long-term sustainability have encouraged extensive investigations into non-noble metal catalysts as potential alternatives. PGM-based catalysts have traditionally served as the benchmark for automotive exhaust purification.

Three-way catalytic converters containing Pt, Pd, and Rh exhibit exceptional conversion efficiencies under stoichiometric operating conditions. Previous studies reported that PGM catalysts can achieve approximately 98–99% conversion of CO and greater than 95% conversion of HC emissions under ideal operating conditions. In addition, PGMs catalysts maintain conversion efficiencies ranging between 90—99.9% across wide operating temperatures, making them highly suitable for simultaneous oxidation of CO and HC and reduction of NOx. Although PGMs demonstrate excellent catalytic activity, several challenges limit their continued exclusive use. The major challenge involves their high economic cost resulting from limited global availability. Furthermore, catalyst deactivation and thermal aging significantly reduce long-term performance. Researchers have increasingly explored transition metals and metal oxides as substitute catalyst materials. Transition metals such as copper (Cu), manganese (Mn), cobalt (Co), iron (Fe), zinc (Zn), and chromium (Cr) have attracted substantial attention due to their abundance, lower cost, and favorable redox characteristics. Copper-based catalysts have demonstrated particularly encouraging results[5].

Copper-based catalytic converter systems exhibited lower CO and HC emissions than conventional systems, indicating greater stability and consistency in emission reduction performance [6]. Similarly, Reductions in HC emissions reaching approximately 93.6% with significant reductions in CO emissions. Recent studies demonstrated that modifications of non-noble catalysts can significantly narrow the performance gap between alternative catalysts and PGMs[7]. CO oxidation rates due to synergistic interactions between Cu and noble metals.

The incorporation of Cu reduced activation energy and lowered catalyst light-off temperatures. Emerging catalyst systems have also shown favorable durability and efficiency characteristics [8]. Cobalt zeolite catalysts outperformed platinum and palladium in several performance indicators including conversion efficiency, activation energy, reusability, and stability. Despite these promising developments, several limitations continue to prevent complete replacement of PGMs[9]. Challenges including catalyst poisoning, thermal degradation, cold-start inefficiencies, and reduced long-term durability continue to affect non-noble catalyst performance. The reviewed literature demonstrates that non-noble metal catalysts have progressed significantly and are increasingly capable of achieving substantial reductions in automotive emissions at lower economic cost. However, PGM catalysts continue to provide superior overall conversion efficiency and durability[9]. Therefore, further research is required to optimize non-noble catalyst formulations capable of providing comparable catalytic performance under practical automotive operating conditions. Automotive emissions remain one of the major contributors to environmental pollution because of the release of harmful gases such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), volatile organic compounds (VOCs), and particulate matter. Increasing vehicle usage and stricter environmental regulations have necessitated the development of effective emission control systems. Catalytic converters have become the principal technology employed to reduce harmful exhaust emissions through oxidation and reduction reactions[10].

Traditionally, catalytic converters use platinum group metals (PGMs), mainly Platinum (Pt), Palladium (Pd), and Rhodium (Rh), due to their superior catalytic activity and durability. However, their high cost, limited availability, and increasing demand have stimulated extensive research into non-noble metal catalysts as alternative solutions. Platinum group metal catalysts have remained the benchmark in automotive emission control because of their exceptional catalytic performance. Three-way catalytic converters containing Pt, Pd, and Rh exhibit high conversion efficiencies for CO, HC, and NOx under stoichiometric operating conditions. Studies indicate that PGM catalysts achieve conversion efficiencies exceeding 90-–99% for harmful pollutants under optimal conditions. Furthermore, PGM catalysts possess high thermal stability and excellent resistance to catalyst poisoning. The high economic cost associated with platinum group metals remains a significant challenge. Researchers have therefore increasingly investigated transition metals and metal oxides as substitutes. Metal-based catalysts including copper (Cu), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), and zinc (Zn) have received considerable attention because of their low cost, abundance, and favorable redox properties. Among non-noble catalysts, copper-based systems have shown particularly promising performance.

Copper catalyst systems achieved notable reductions in CO and HC emissions, with efficiency increasing as exhaust temperatures increased. Similarly, brass-based catalytic converters demonstrated average reductions of approximately 52% for CO emissions and 29% for HC emission[11]. Chrome-coated copper catalysts have demonstrated substantially improved performance over unmodified systems. Studies reported approximately 95.35% reduction in CO emissions and approximately 79.28% reduction in HC emissions, approaching the performance of conventional PGM catalysts. Metal oxide catalysts have also shown favorable performance characteristics[12]. Transition metal oxides including copper oxide, cobalt oxide, iron chromate, and vanadium oxides possess favorable redox characteristics and oxygen storage capability that support pollutant conversion reactions. Despite these improvements, complete replacement of platinum group metals remains challenging because of durability, catalyst poisoning, thermal stability limitations, and reduced low-temperature performance.

Catalyst geometry and structural design further influence catalytic efficiency. The reviewed literature demonstrates that non-noble metal catalysts have evolved considerably and increasingly exhibit catalytic performance approaching that of platinum group metals. However, platinum group metals continue to provide superior overall performance regarding conversion efficiency, durability, and long-term operational stability. Future research should focus on optimizing catalyst composition, structural design, and catalyst modification techniques to improve the performance of low-cost alternatives[12]. Several studies investigated non noble metal and alternative catalyst systems as substitutes for PGMs. Irawan et al. [20] demonstrated that manganese coated copper catalysts significantly reduced carbon monoxide emissions, with increased catalyst cell density improving performance[12]. ZnO–Cr_2O_3 catalysts showed high thermal and chemical stability, low preparation cost, and effective low temperature CO oxidation. The study further indicated that catalyst activity increased with better particle dispersion and suitable support materials[12]. Gold nanoparticle systems discussed by Zhang et al. (2011) also displayed improved low temperature activity for CO oxidation and NOx reduction, although thermal stability limitations were identified. PGM catalysts still provide superior overall performance because of their broader operating temperature range, higher reaction rates, and established long term durability. Their ability to simultaneously reduce NOx and oxidize CO and HC makes them highly effective in commercial three way catalytic converters. However, non noble catalysts offer several important advantages[13]. Manganese coated copper and $ZnO - Cr_2O_3$ systems demonstrate promising pollutant reduction capability at significantly lower material cost. Non noble catalysts also show potential for reducing dependence on scarce precious metals and improving economic feasibility. Nevertheless, limitations remain, including lower durability, lower conversion efficiency for some pollutants, reduced thermal resistance, and susceptibility to catalyst deactivation. PGM catalysts are widely recognized as the standard for automotive exhaust treatment because of their superior oxidation and reduction properties.

The reviewed literature indicates that PGM-based catalysts exhibit excellent conversion efficiency over a broad temperature range. Conventional PGM-based three way catalytic converters achieve approximately 50% catalytic conversion at light off temperatures around 300°C. Their effectiveness in simultaneously reducing NOx and oxidizing HC and CO makes them highly suitable for commercial applications[14]. However, major drawbacks including rising material costs and dependence on scarce precious metals. In addition, thermal deterioration and catalyst poisoning reduce their long term performance. The literature below presents several non noble metal catalyst systems with encouraging performance characteristics[14].Copper plate catalytic converters achieved reductions of HC by 55.44%, CO by 62.96%, and NOx by 40.41% under full-load conditions.Copper oxide catalysts significantly reduced HC and CO emissions during cold-start conditions when integrated with resistance-heated catalytic converter systems.Manganese-supported copper catalysts effectively reduced carbon monoxide emissions, with performance improving as catalyst cell numbers increased[15]. $La_{0.8}Sr_{0.2}Co_{0.8}Fe_{0.2}O_3$ perovskite catalysts showed acceptable catalytic activity and emission control performance under varying engine conditions, with performance approaching that of commercial converters[16].

Direct comparison between both catalyst categories indicates that PGM catalysts still exhibit superior overall catalytic performance due to higher reaction rates, greater durability, and broader operating temperature windows. Their established commercial reliability allows efficient simultaneous conversion of multiple pollutants. However, non noble catalysts provide several advantages including lower cost, easier availability, recyclability, and reduced dependence on rare materials. Copper-based systems showed substantial pollutant reduction efficiency, while perovskite catalysts demonstrated emission performance approaching commercial catalyst systems[17]. Gold-based catalysts reviewed and also displayed superior low-temperature activity for CO oxidation compared to conventional PGM systems[18]. Despite these benefits, limitations of non noble catalysts remain, including lower thermal stability, potential deactivation, and reduced long-term durability. Properly functioning catalytic converters are essential for reducing hazardous emissions like NOy, PM, CO2, and VOCs, while also highlighting the detrimental impact of catalytic failure on public respiratory health. The review proposes a cost-effective, real-time monitoring paradigm using existing sensor technology to improve catalytic system maintenance and enhance air quality[19].

Experiments were conducted in three modes: baseline with diesel, with EGR, and with EGR and catalytic converter. The engine with EGR and catalytic converter had the lowest CO (54.37%) and HC (33.33%) emissions compared to the other two cases, but CO2 emissions increased by 7.21%. The brake thermal efficiency was highest for the baseline case and lowest (23.96%) for the EGR with catalytic converter case[20]. The engine with EGR and no catalytic converter had slightly better efficiency than the EGR with catalytic converter case.The design of a platinum group metal (PGM)-free and chromium (Cr)-free automotive three-way catalyst (TWC) using two types of base-metal oxides was presented. MnOx-based binary mixed metal oxides were investigated for hydrocarbon preferential oxidation (HC-PROX) catalysts. Magnesium manganese oxide (MgMnO) showed the best activity among the MnOx-based catalysts, with high propene oxidation activity and low CO oxidation activity.

3.0 Materials and Methods

This review is based on a systematic analysis of peer-reviewed literature obtained from databases including Scopus, ScienceDirect, ResearchGate and Google Scholar. Relevant publications from 1999 to 2025 were selected using keywords such as "catalytic converter," "automotive emissions," "NO_x reduction,", and "alternative catalyst materials." Studies were included based on: Relevance to catalytic converter performance, Experimental or simulation-based validation, Contribution to catalyst material development or emission reduction strategies. The selected literature was critically analyzed to identify trends, limitations, and research gaps.

4.0 Results and Discussion

4.1 Definition of a Catalytic Converter

Catalytic converters as essential emission control devices used in internal combustion engine vehicles to reduce harmful exhaust gases such as carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx). Majority of automobile catalytic converters have a design of a monolithic structure which is coated with alumina wash coat. A monolith structure in a catalytic converter is the internal honey-comb like core or substrate that acts like backbone for the device. Substrate is nothing but a monolith which is coated by noble metals catalysts such as Platinum, Palladium and Rhodium to initiate reactions within. [21–23].

Catalytic converters use metallic catalysts to promote desired reactions at lower temperature. Platinum group solutions (Platinum, Palladium and Rhodium) used to coat the honey-comb structure. Catalytic converters are emission-control devices designed to reduce the release of harmful pollutants from internal combustion engines. They function by using catalysts to transform toxic exhaust gases into less harmful substances before they are discharged into the atmosphere. Typically installed as part of a vehicle's exhaust system between the engine and the muffler, catalytic converters contain a honeycomb-shaped substrate coated with catalytic materials that facilitate chemical reactions [24–26]. As exhaust gases pass through this catalyst-coated structure, a series of oxidation and reduction reactions occur, converting pollutants such as carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NO_x)into less harmful products, primarily nitrogen (N_2), carbon dioxide (CO_2), and water (H_2O). Through these reactions, catalytic converters play a vital role in reducing vehicle emissions and improving air quality. This would allow heterogenous catalysis to take place on the surface of the core allowing for the production of less toxic gases[15,20].

4.2 Reaction Processes in a Catalytic Converter

Inside a three-way catalytic converter, three distinct chemical processes occur simultaneously to neutralize harmful vehicle emissions. The first process focuses on removing toxic, odorless carbon monoxide gas through oxidation. Platinum and Palladium catalysts facilitate this reaction by forcing the carbon monoxide to combine with oxygen molecules in the exhaust stream, transforming it into less harmful carbon dioxide[18,49]. This process follows the specific chemical equation: $2CO + O_2 \rightarrow 2CO_2$ The second process targets unburned hydrocarbons, which are responsible for respiratory illnesses and smog. These volatile organic compounds undergo a similar oxidation reaction on the platinum and palladium surfaces, where they break down into clean water vapor and carbon dioxide. The complex transformation of these varying fuel molecules is represented by the equation: $C_xH_y + \left(x + \frac{y}{4}\right) O_2 \rightarrow xCO_2 + \frac{y}{2} H_2O$ The final process involves a reduction reaction, which behaves inversely to the first two steps to tackle harmful nitrogen oxides. A rhodium catalyst actively strips the oxygen atoms away from the nitrogen compounds, converting the pollutant into harmless, naturally occurring nitrogen and oxygen gases to prevent acid rain. This reduction is written as: $2NO_x \rightarrow xO_2 + N_2$

4.3 Components of a Three-Way Catalytic Converter

Catalyst Core (Substrate): The core consists of an open-channel ceramic monolith designed to host the active catalysts. Cordierite ($2MgO - 2Al_2O_3 - 5SiO_2$) serves as the standard material for this structural foundation. This material features a high surface area, an optimized open frontal area, and low heat capacity. It provides exceptional structural integrity and mechanical strength under harsh automotive operating conditions [3,27–29,29]. The internal geometry consists of thousands of parallel micro-channels to maximize exhaust gas contact. A comprehensive view of a catalytic converter is detailed in the labeled diagram in figure 2, figure 3 and a diagram showing four old catalytic converters in figure 4.

Wash Coat: A porous layer of supported catalysts covers the smooth surface of the honeycomb ceramic structure. Alumina is the primary material used to create this internal coating. This layer increases the effective surface area of the substrate by a factor of several thousand. The rough texture provides a high density of microscopic sites to trap active metal particles. Thermal stabilizers like ceria or zirconia are often added to prevent the coat from degrading [20,30].

Catalyst Solution: A precise solution containing active noble metal nitrates coats the prepared alumina layer. This catalytic formulation utilizes specific combinations of dissolved palladium, platinum, and rhodium. These elements belong to the Platinum Group Metals family, which exhibits elite catalytic efficiency. They offer superior resistance against aggressive chemical degradation and high-temperature oxidation. This solution layer actively reduces activation energy barriers to accelerate the exhaust cleaning reactions [31].

Metal Casing: A thin-walled metallic housing encloses the internal ceramic monolith to protect it from road debris. This thin profile enhances heat dissipation to the surrounding environment to avoid thermal runaway. Proper thermal management keeps the internal core from exceeding its structural limit of 1000°C. Designers must carefully calculate the thermal expansion differentials and material yield strengths. Adjusting the chemistry of the stainless-steel alloy helps minimize catastrophic gap expansion. Utilizing ferritic steel shells like SS409 reduces thermal expansion by 50 percent compared to austenitic SS310 [32,33].

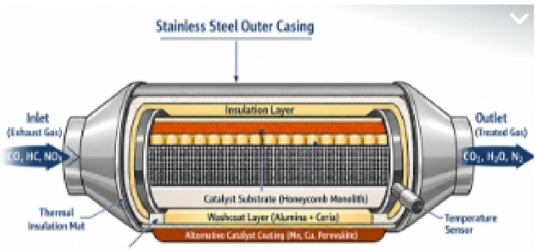

Figure 2: Well labelled diagram of a three-way catalytic converter

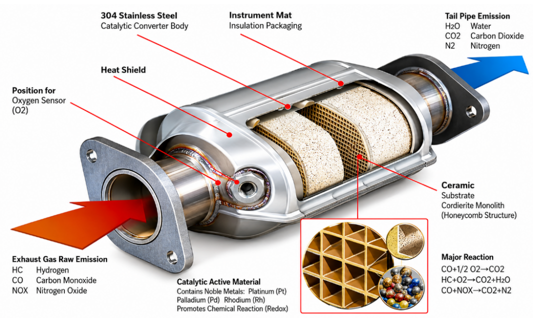

Figure 3: Three-way catalytic converter adapted from adapted from [27]

Figure 4: Four Old Catalytic Converters adapted from [27]

4.4 Cold Start Emission

At cold start, the catalytic converter is at the same temperature as its surroundings and the catalyst conversion efficiency is zero at this point. There is a time interval that is required for the temperature of the catalytic converter to increase from ambient temperature to its optimum temperature. During this period, Cold start emissions are present [34,35]. Cold start emission is the emission produced by an engine during the initial warm up period after a long period of non-use before the engine, catalytic converter or any other emission reduction systems would reach their optimum operating conditions. Vehicle emissions from internal combustion engines during cold starts are exceptionally high because the catalytic converter has not yet reached its optimal operating temperature. When an engine is cold, the fuel does not vaporize efficiently, which requires a fuel-rich mixture that generates a massive amount of pollutants. At the same time, the catalytic converter requires high temperatures to trigger the chemical reactions that neutralize toxic gases, leaving the environment entirely unprotected during the initial minutes of driving.Figure 3 below shows the diagram of a catalytic converter from the inventor of catalytic converter Eugene J Houndry in 1956, he secured a patent for it.

During this vulnerable phase, the engine releases several major pollutants into the atmosphere. Incomplete fuel combustion creates dangerous carbon monoxide, while high engine pressures generate harmful nitrogen oxides. Furthermore, unburnt fuel molecules enter the exhaust system as hydrocarbons, which are accompanied by tiny airborne solid particles known as particulate matter. Because the converter remains inactive during these suboptimal temperatures, this combination of incomplete combustion and an untreated exhaust flow lead to a sharp spike in toxic environmental pollution. Automobile engine usually begins from a cold start, meaning the catalytic converter starts at the surrounding ambient temperature of fifteen to twenty-five degrees Celsius [36–38]. At this initial stage, the catalyst conversion efficiency is effectively zero because the device has not yet reached its specified optimum operating temperature of four hundred to eight hundred degrees Celsius. Operating above this optimal range is dangerous because it accelerates the thermal aging process, causing the noble metals and carrier to sinter and shrink the active surface area. Therefore, a specific time interval is required for the converter to warm up from ambient conditions to its peak operating state. During this crucial warm-up period, the vehicle produces what are known as cold-start emissions [39–41].

These are defined as the pollutants released after a long period of non-use before the engine, converter, or other emission reduction systems reach their optimum conditions. Within this transition, the catalyst must first pass its light-off temperature, which is a threshold of around two hundred and fifty to three hundred degrees Celsius. This light-off temperature represents the critical point at which the catalyst finally becomes more than fifty percent effective at converting harmful emissions.

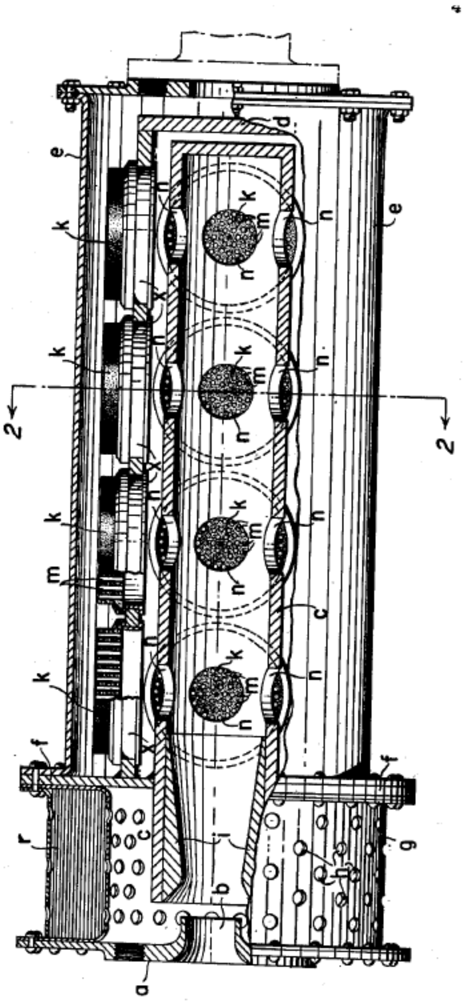

Figure 5: Catalytic converter adapted from Eugene J. Houndry(1956)

Figure 6: A refurbished catalytic converter adapted from [27]

4.5 Catalyst Efficiency

Catalyst conversion efficiency is a measure of how effectively a catalytic converter neutralizes harmful engine emissions before they exit the vehicle tailpipe. It evaluates the percentage of untreated "feed gases" (like carbon monoxide, unburned hydrocarbons, and nitrogen oxides) that are successfully transformed into harmless gases like carbon dioxide, water, and nitrogen [42, 43]. The diagram below in figure 6 shows a refurbished catalytic converter.

4.5.1 Conversion Efficiency Formula

The basic conversion efficiency (η) for any given pollutant is calculated by comparing its concentration at the converter's inlet (from the engine) to its concentration at the outlet (exiting the tailpipe). The primary mathematical equation is: $\eta = \left(\frac{C_{in} - C_{out}}{C_{in}}\right) \times 100\%$
Where:

$\eta =$ Catalyst conversion efficiency (expressed as a percentage)

. $C_{in}=$ Inlet concentration of the pollutant entering the converter.
$C_{out}=$ Outlet concentration of the pollutant exiting the converter.

4.5.2 Key Factors Dictating Efficiency

A three-way catalytic converter's conversion efficiency fluctuates dynamically based on two critical operational boundaries.

1. Operating Temperature (The "Warm-Up" Phase) When you first start a car, the catalytic converter does not work at all because it is too cold. The chemical reactions require intense heat to begin according . The converter must reach a specific trigger temperature—between 250°C and 300°C—called the "light-off" point. Think of this like striking a match; once it hits this temperature, the chemical reactions suddenly ignite and efficiency spikes rapidly [44–46]. The converter reaches its absolute best performance, cleaning 90% to 95% of all pollutants, only when it gets blisteringly hot—specifically between 400°C and 800°C. This is why short driving trips create more tailpipe pollution than long highway drives.
2. Air-Fuel Ratio (The "Goldilocks" Balance): For a catalytic converter to clean all three major pollutants at the exact same time, the engine must burn fuel at a perfect ratio 14.7 pounds of air for every 1 pound of gasoline. This sweet spot is called the stoichiometric region. When the engine runs "Lean" (Too Much Air / Too Little Fuel), there is plenty of leftover oxygen, so the converter easily burns off Carbon Monoxide (CO) and Hydrocarbons (HC), cleaning them up to 99%. Because there is too much oxygen, the chemistry fails to break down Nitrogen Oxides , The NOx cleaning efficiency drops to nearly zero. When the engine runs "Rich" (Too Much Fuel / Too Little Air),the lack of oxygen makes it very easy for the converter to strip apart and destroy Nitrogen Oxides. When the engine used up all the oxygen to burn the excess fuel, there is no oxygen left inside the converter to burn off the toxic CO and HC gases [47–49].

4.6 Catalytic Converter Design Optimization

Catalytic converter optimization balances two conflicting goals: maximizing emissions reduction and minimizing engine power loss.Adjusting physical geometry directly by controlling gas flow, reaction time, and thermal behavior [46, 50].

4.6.1 Fluid Dynamics and Flow Uniformity

Exhaust gas must spread evenly across the catalyst brick to work efficiently.

1. **Pipe and Diffuser:** Sharp angles cause flow separation and turbulence. Widening the diffuser gently ensures the exhaust gas hits the entire front face of the substrate [39].
2. **Uniformity Index (FUI):** This metric measures how evenly gas distributes across the monolith channels. A higher FUI prevents local "hot spots" and stops premature catalyst degradation [51].
3. **Nozzle Design:** The exit nozzle must transition smoothly back to the tailpipe. Poor design creates backpressure, which forces the engine to work harder and consume more fuel [31].

4.6.2 Monolith and Substrate Engineering

The monolith structure dictates the physical surface area available for chemical reactions.

1. **Density (CPSI):** Increasing cells per square inch multiplies the surface area. This change speeds up toxic gas conversion but increases resistance to the gas flow [16].
2. **Thickness:** Thinner channel walls reduce the thermal mass of the brick. Lower thermal mass allows the catalyst to heat up faster during cold starts [44].
3. **Multi-Region Permeability:** Modern designs vary channel sizes across the brick. Larger channels in the center and smaller channels on the edges equalize flow velocity. [52].

4.6.3 Thermal Management and Pressure Drop

Two critical performance metrics define a successful catalyst design.

1. **Light-Off Temperature:** This is the temperature where the catalyst reaches 50% conversion efficiency. High surface area and low thermal mass help reach this state within seconds of starting the vehicle.Figure 7 below shows the carbon dioxide oxidation under light-off temperature [25].
2. **Pressure Drop Minimization:** High resistance in the monolith creates backpressure. Engineers use computational fluid dynamics (CFD) to find the geometric sweet spot that lowers emissions without suffocating engine exhaust flow [53].

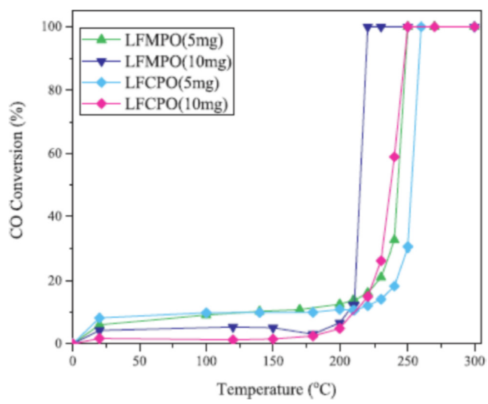

Figure 7: Carbon dioxide oxidation under light off temperature adapted from [50]

4.7 Platinum Group Metals (PGMs)

The Platinum Group Metals (PGMs) baseline catalyst system is primarily composed of Platinum, Rhodium, and Palladium, which are widely recognized for their excellent catalytic activity and superior emission reduction capabilities [38]. These noble metals effectively facilitate the oxidation of carbon monoxide and hydrocarbons, as well as the reduction of nitrogen oxides, making them the standard materials used in modern catalytic converters. However, despite their high performance, PGM-based catalysts are associated with significant drawbacks, particularly their high and often volatile market prices, which increase manufacturing costs and create economic challenges for large-scale automotive applications [51]. Traditional market systems rely heavily on Palladium, Platinum, and Rhodium .These noble metals are noted for being highly expensive catalyst options. The primary Platinum Group Metals (PGMs) used in automotive catalytic converters are Platinum (Pt), Palladium (Pd), and Rhodium (Rh) [54].

These noble metals serve as highly effective catalysts that facilitate the conversion of harmful engine exhaust pollutants, including carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides, into less harmful substances such as carbon dioxide, water vapor, and nitrogen. Platinum is predominantly utilized in diesel engine catalytic converters because of its excellent ability to oxidize carbon monoxide and hydrocarbons [55]. Palladium is more commonly employed in gasoline engine applications and has increasingly replaced platinum in many systems due to its effectiveness in promoting the oxidation of hydrocarbons and carbon monoxide. Rhodium plays a critical role in three-way catalytic converters, where it is primarily responsible for reducing nitrogen oxides into harmless nitrogen gas. The combined use of these PGMs enables catalytic converters to achieve high emission-conversion efficiencies and comply with stringent environmental regulations [52, 56].

4.8 Prospective Alternative Catalyst

The use of brass-based catalytic converter substrates significantly improved exhaust emission reduction performance. Their findings showed that a raw brass substrate reduced average carbon monoxide (CO) emissions by 52 percent and hydrocarbon (HC) emissions by 29 percent. Further enhancement was achieved through chrome-plated brass catalyst, which decreased CO emissions by 88.41 percent and reduced total hydrocarbon emissions by 39.84 percent. In addition, manganese-coated copper (Cu+Mn) demonstrated remarkable effectiveness in lowering carbon dioxide (CO) emissions, achieving a reduction of 91.03 percent. The study also highlighted the catalytic potential of copper oxide (CuO), which was found to accelerate carbon monoxide oxidation reactions at temperatures as low as 30°C, indicating its suitability for improving catalytic activity under low-temperature operating conditions, [1, 57, 58].

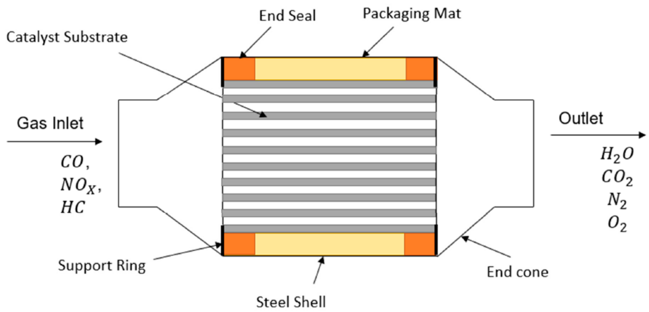

Figure 8: Automobile catalytic converter adapted from [2]

The findings indicate that brass- and copper-based alternative catalysts can serve as highly effective and cost-efficient substitutes for expensive Platinum Group Metals (PGMs) in catalytic converters. These alternative catalyst materials demonstrated significant emission-control capabilities, achieving an average reduction of 52% in carbon monoxide (CO) emissions while offering a more economical solution for exhaust gas treatment. Their effectiveness highlights the potential of non-noble metal catalysts to reduce reliance on scarce and costly PGMs without substantially compromising catalytic performance [59–61].

Conventional catalytic converters composed of highly expensive noble metals demonstrated exceptional emission-control performance, achieving reductions in raw exhaust emissions of up to 98 percent. The study reported average carbon monoxide (CO) emissions of 2.14% Volume and average hydrocarbon (HC) emissions of 238 ppmVol after catalytic treatment. These findings highlight the effectiveness of noble-metal-based catalysts in minimizing harmful vehicular emissions, while also emphasizing the challenge posed by their high material costs. Ariyanto et al. [1] reported that copper-based alternative catalysts (MCC Cu) demonstrated excellent emission-control performance and, in some cases, outperformed conventional Original Equipment Manufacturer (OEM) catalytic converter systems in reducing raw exhaust pollutant concentrations [62–64].

Copper-based catalyst lowered average carbon monoxide (CO) emissions to 2.13 percent Vol and reduced average hydrocarbon (HC) emissions to 198 ppmVol. In addition to achieving lower emission levels, the catalyst exhibited superior performance consistency and structural stability, as evidenced by the lowest recorded emission standard deviations for both CO (1.68) and HC (95). The authors further noted that alternative brass-based catalyst configurations have been shown to reduce carbon monoxide emissions by as much as 52 percent, highlighting the significant potential of copper- and brass-based materials as cost-effective and efficient alternatives to conventional noble-metal catalysts. SengoleRayan et al. [59] reported that silicon dioxide [SiO] and aluminum oxide (AlO) coatings represent promising low-cost alternatives to Platinum Group Metal (PGM) catalysts due to their high thermal stability, excellent durability, and significantly lower cost.

The study found that the SiO-coated catalyst was particularly effective in reducing nitrogen oxide (NO) and carbon monoxide (CO) emissions, achieving NO reductions of 20.38 percent at maximum engine load and 55.22 percent at minimum load. In contrast, the AlO-coated catalyst demonstrated superior performance in controlling carbon monoxide and hydrocarbon (HC) emissions, reducing total hydrocarbons by 88.88 percent at maximum load and 80 percent at minimum load. Furthermore, both non-noble metal catalyst systems exhibited substantial carbon monoxide reduction capabilities, lowering CO emissions by 75 percent under maximum load conditions and by 80 percent under minimum load conditions. These findings suggest that SiO and AlO coatings can provide effective emission control while offering a more economical and thermally stable alternative to conventional PGM-based catalytic converters.

Patel et al. [52] reported that several non-noble metal catalysts demonstrated considerable potential for carbon monoxide (CO) oxidation and emission control. The study found that a perovskite catalyst achieved 50% CO conversion at 420°C, while a modified perovskite composition, $La_{0.8}Sr_{0.2}Co_{0.8}Cu_{0.2}O_3$, exhibited enhanced catalytic performance by attaining 80% CO conversion at a lower temperature of 355°C. Among the catalysts evaluated, hopcalite (CuMnO) was identified as one of the most effective materials for low-temperature CO oxidation, making it particularly suitable for addressing cold-start emission challenges. The researchers also reported that a TiO_2–CoO wire mesh catalyst reduced carbon monoxide emissions by 41 percent more than baseline equipment, demonstrating its superior oxidation efficiency. Furthermore, zinc and chromium oxide-based catalysts were highlighted as promising alternatives due to their low cost, good thermal stability, and strong catalytic activity, offering a viable pathway toward reducing dependence on expensive Platinum group metals in catalytic converter applications. Platinum Group Metals (PGMs), including platinum, palladium, and rhodium, exhibit significantly higher catalytic activity than base metal catalysts, enabling effective emission conversion even when used in relatively small quantities.

This superior catalytic performance has made PGMs the preferred materials for conventional catalytic converters. However, the study also highlighted the potential of alternative non-noble metal catalyst systems, particularly electroplated nickel oxide (NiO) coatings on metallic substrates. The researchers reported that these NiO-based catalysts were capable of reducing carbon monoxide (CO) emissions to below 7 ppm, demonstrating that non-noble metal catalysts can provide effective emission control while offering a more economical alternative to expensive PGM-based systems. These findings suggest that properly engineered base metal catalysts could contribute to reducing reliance on scarce and costly noble metals in future catalytic converter technologies. Gold (Au) nanoparticles have demonstrated exceptional catalytic activity for the oxidation of carbon monoxide (CO) at very low temperatures, making them particularly attractive for improving cold-start performance. In some cases, nano-sized gold catalysts have been reported to outperform platinum under low-temperature operating conditions.

However, their practical application is limited by poor thermal stability at the high temperatures commonly encountered in vehicle exhaust systems. Another promising class of materials is perovskites, which are oxide compounds typically containing elements such as lanthanum, strontium, cobalt, or other transition metals. These materials can mimic the oxidation and reduction functions of precious metals while offering a significantly lower-cost alternative. Additionally, metal oxides such as cerium oxide (CeO) play an important role in catalytic converter technology due to their oxygen storage and release capabilities. By supplying or absorbing oxygen as operating conditions change, cerium oxide enhances redox reactions and supports the efficient conversion of pollutants, thereby complementing or partially replacing the functions traditionally performed by PGMs.

Together, these alternative materials represent promising pathways toward developing more affordable and sustainable emission-control technologies. Magnesium manganese oxide (MgMnO)showed the best activity among the MnOx-based catalysts, with high propene oxidation activity and low CO oxidation activity. less expensive catalyst materials such as perovskites, spinels, monels, and hopcalites that can potentially substitute noble metals. Figure 8 below shows a well labelled cross-sectional diagram of an automobile catalytic converter. Studies have shown that perovskite-based catalysts like SrCoO3 and LaCoO3 can achieve good CO oxidation performance. Doping perovskites with palladium can also improve thermal-chemical stability and reduce catalyst costs [53, 65].

4.9 Methods to Shorten Warm Period to Reduce Cold Start Emission

Several strategies have been developed to reduce cold-start emissions and improve the performance of catalytic converters. One of the most effective approaches is the close-coupled placement of the catalytic converter, where the converter is installed very close to the engine exhaust manifold. This arrangement minimizes heat loss between the engine and the catalyst, enabling the catalyst to reach its light-off temperature more quickly. Another method involves the use of electrically heated catalysts (EHC), which incorporate electric heating elements to preheat the catalyst before or immediately after engine startup, thereby reducing reliance on exhaust heat alone. Exhaust gas thermal management techniques are also widely employed, whereby engine control strategies such as retarding ignition timing, increasing idle speed, modifying the air–fuel ratio, and post-injection of fuel are used to raise exhaust gas temperatures and accelerate catalyst activation [62–64].

Further improvements can be achieved through the use of advanced catalyst materials with lower light-off temperatures, allowing catalytic reactions to begin earlier. Current research focuses on developing low-cost and highly efficient catalyst formulations based on copper, manganese, iron, cobalt, and mixed oxides. Thermal insulation of exhaust manifolds and pipes is another effective strategy, as it reduces heat loss and helps retain thermal energy within the exhaust system, enabling the catalyst to heat up more rapidly. In addition, catalyst substrate optimization through the use of thin-wall ceramic or metallic substrates and low thermal mass materials allows the catalyst to warm up faster than conventional substrate designs.

Secondary air injection systems also contribute significantly to reducing cold-start emissions by introducing fresh air into the exhaust stream during startup. The additional oxygen promotes the oxidation of unburned hydrocarbons and carbon monoxide, generating extra heat that rapidly increases catalyst temperature. Exhaust heat recovery systems provide another solution by capturing and reusing waste heat from previous engine operation or redirecting heat to critical components to facilitate faster catalyst warm-up. Similarly, phase-change thermal storage materials can store heat after engine shutdown and release it during subsequent engine starts, thereby reducing catalyst cooling between trips. Finally, hybrid vehicle technologies and start-stop strategies help minimize the frequency and impact of cold starts by optimizing engine operation, resulting in lower cold-start emissions and improved overall catalytic converter efficiency.

5.0 Current Challenges and Limitations

Catalytic converters possess several limitations that affect their overall performance and long-term durability. One major drawback is their inability to effectively control nitrogen oxide emissions, necessitating the use of additional emission-control technologies. Their performance is also highly dependent on temperature, as they generally require temperatures above 150°C to achieve optimal catalytic activity. Consequently, catalytic converters exhibit poor efficiency during cold-start conditions when engine and exhaust temperatures are still low. Another challenge is the reliance on scarce and expensive Platinum Group Metals (PGMs), which significantly increases manufacturing costs and makes catalytic converters attractive targets for theft due to their high precious-metal content. Furthermore, exposure to sulfur-containing compounds in diesel fuel can result in sulfur poisoning, where sulfur deposits accumulate on the catalyst surface and block active reaction sites, reducing catalyst effectiveness. At elevated operating temperatures, platinum nanoparticles may undergo thermal sintering, causing the particles to agglomerate into larger clusters.

This process leads to a permanent loss of active surface area, thereby reducing catalytic efficiency and shortening the operational lifespan of the catalyst. Several challenges continue to influence the development and application of catalytic converter technologies. The rising cost of platinum group metals (PGMs) has made conventional catalyst systems increasingly expensive and, in some cases, economically unsustainable. In addition, incomplete fuel combustion in spark-ignition engines results in the continuous emission of harmful carbon monoxide (CO), creating a persistent need for highly efficient emission-control systems. The development of non-noble metal catalysts presents another significant challenge, as designing alternatives that can match the performance, durability, and stability of noble-metal-based catalysts remains technically demanding. For example, pure copper catalysts used without appropriate supports or modifications often exhibit lower catalytic efficiency, limiting their practical application. Furthermore, increasing environmental regulations place considerable pressure on vehicle manufacturers, as unmodified exhaust and muffler systems are generally unable to meet modern government emission standards without the incorporation of effective catalytic emission-control technologies. Several challenges continue to influence the development and application of catalytic converter technologies.

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Furthermore, the study emphasized several mechanical challenges, such as engine power losses resulting from exhaust backpressure, the risk of catalyst plugging due to deposit accumulation, and structural deformation caused by prolonged exposure to thermal stress. Collectively, these issues can adversely affect catalyst durability, efficiency, and overall vehicle performance [38, 46, 53, 62–65, 65].

6.0 Recommendation

Future research and development efforts in catalytic converter technology should focus on exploring non-precious metal substitutes such as iron, cobalt, and nickel as alternatives to platinum group metals (PGMs) in order to address resource scarcity and reduce manufacturing costs. Advances in nanotechnology should also be leveraged through the synthesis of nanostructured catalysts and composite materials that provide greater surface area, increased active site density, and enhanced catalytic reactivity. Additionally, researchers should concentrate on developing catalyst materials and structures capable of maintaining high activity across a broader temperature range, ensuring effective performance during low-temperature cold starts while remaining stable under extreme operating temperatures. The integration of real-time smart monitoring systems, including adaptive sensor networks and efficiency monitoring technologies, can further optimize catalytic conversion processes and enable early detection of catalyst degradation. Furthermore, closed-loop diagnostic capabilities should be enhanced by pairing three-way catalytic converters with highly responsive nitrogen oxide and oxygen sensors to meet increasingly stringent On-Board Diagnostics (OBD-II) requirements. The implementation and standardization of advanced recycling protocols should be prioritized to improve the recovery of platinum group metals from spent catalytic converters, thereby reducing dependence on newly mined raw materials and promoting greater sustainability within the automotive industry [3-7].

Future advancements in catalytic converter technology should focus on the development of base metal catalysts by investigating non-precious alternatives such as iron, cobalt, and nickel to reduce dependence on expensive platinum group metals. The deployment of nanotechnology is also essential for producing advanced catalysts with greater surface area, enhanced reactivity, and improved catalytic efficiency. Additionally, the integration of adaptive sensors and real-time monitoring systems can enable dynamic control strategies that optimize converter performance under varying operating conditions. Efforts should also be directed toward optimizing structural materials through the use of modified nanostructures that enhance catalyst stability and durability[11-13]. Expanding the effective temperature range of catalysts by engineering active coatings capable of functioning efficiently during cold starts remains another important area of research. Furthermore, maximizing component recycling through advanced post-consumer recovery and purification processes can improve the reclamation of embedded precious metals, reducing the demand for newly mined resources. Finally, catalytic converters should be integrated with complementary emission-control technologies such as Exhaust Gas Recirculation (EGR) and Selective Catalytic Reduction (SCR) systems to achieve more effective management of nitrogen oxide emissions and ensure compliance with increasingly stringent environmental regulations.

Future research should focus on improving catalyst durability, reducing cold-start emissions, optimizing catalyst geometry, and developing hybrid catalyst systems with enhanced thermal stability and resistance to poisoning. The continued development of low-cost non-noble metal catalysts will contribute significantly toward sustainable, affordable, and environmentally friendly automotive emission control technologies. Furthermore, the review highlights the growing importance of sustainable and locally available catalyst materials, particularly for developing countries where the high cost of noble metals remains a major limitation. Advances in catalyst engineering, nanotechnology, AI-assisted emission control, and PGM-free catalytic systems indicate promising future directions for automotive emission reduction technologies.

7.0 Conclusion

In conclusion, the reviewed literature demonstrates that catalytic converters remain one of the most effective technologies to control harmful automotive exhaust emissions such as carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NOx). Although conventional platinum group metal (PGM) catalysts provide excellent conversion efficiencies, their high cost, scarcity, and susceptibility to degradation have intensified the search for affordable and sustainable alternatives. Numerous studies reviewed in this work have shown that low-cost non-noble metal catalysts based on transition metals such as copper, manganese, cobalt, nickel, brass, and mixed metal oxides possess significant potential for reducing vehicle emissions effectively. The literature further reveals that catalyst performance can be enhanced through improved substrate materials, optimized wash-coat formulations, better thermal management systems, and advanced catalytic converter geometries. Several researchers reported considerable reductions in CO and HC emissions using non-noble metal catalysts, with some emerging catalyst systems demonstrating performances that are comparable to those of conventional PGM-based converters.

However, challenges such as lower NOx conversion efficiency, catalyst aging, thermal instability, poisoning, and poor low-temperature activity still limit the widespread adoption of these alternative catalysts. The reviewed literature demonstrates that low-cost non-noble metal catalysts possess significant potential for automotive exhaust emission reduction. Transition metals such as copper, manganese, nickel, cobalt, iron, and zinc have shown promising catalytic activity in reducing CO, HC, and NOx emissions. Among these materials, manganese-coated copper catalysts and mixed metal oxide systems have demonstrated particularly high conversion efficiencies comparable to those of noble metal catalysts [33-37]. Therefore, this study concludes that low-cost non-noble metal catalysts represent a viable and environmentally sustainable alternative for automotive exhaust emission control. Nevertheless, further experimental investigations are required to improve their durability, thermal resistance, and overall catalytic efficiency, especially under real engine operating conditions. Continued research in this area will contribute significantly to the development of affordable, efficient, and eco-friendly catalytic converter technologies for future transportation systems.

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