

Decoupling transport & CO₂ emissions for three OECD countries, Mexico, Spain and

The USA: A quotient and time trend analysis

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Abstract

In this paper we develop a methodology to explain the (de)coupling issue among CO₂-emissions, economic-activity, and surface-transport. It presents a comprehensive set of variables that determine how CO₂-emissions decouple at different economic levels and provide direct and useful economic insights for the formulation of goals and policies. A matrix of 17 variables (289 indicators) is built across three data sets: economic (5), transport-volume (9), and environmental damage (5). These indicators predict a) decoupling when using aggregate analysis and b) coupling of transport with the economy at a disaggregate level. The findings are based on 36 key decoupling indicators for three countries (36 each), ranging from the most to the least aggregated. These 36 intensity indicators belong to a decoupling category for 3 countries across 2 distinct geographic zones. The findings reveal a materialization phase in Spain, Mexico, and USA. Also, a decarbonization phase in Spain and USA, and partially in Mexico. Using 36 indicators across four levels provide a detailed analysis of the coupling to decoupling phenomena, highlighting differences between sectors and countries, and unveiling hidden trends when examining various dimensions of the process.

1. Introduction

The growing global concern over climate change has placed the reduction of CO₂ emissions at the heart of international agendas, highlighting surface-transport (rail and road transport, both freight and passenger) as a critical sector due to its significant contribution to the total emissions. The establishment of the United Nations Framework Convention on Climate Change in 1992, followed by initiatives such as the Kyoto Protocol (1997) and the Paris Agreement (2015), reflects the global commitment to mitigating climate change. However, despite international efforts, the decoupling of CO₂ emissions from economic activity in the surface-transport sector remains a formidable challenge.

Two hypotheses are derived directly from this central research problem. First, the growth of transport-volume (total amount of goods and passengers transported measured in ton-

kilometers) disproportionately exceeds economic growth, indicating that the relationship enters a phase of coupling below the threshold offering opportunity for improvement to achieve effective decoupling.¹

Second, the increase in CO₂-Emissions caused by surface-transport grows less than proportional to economic growth, which could signal a phase of decoupling because the transport-economy relationship lies above the threshold, although this relationship requires analysis with more rigorous methodological tools.

In this context, the present research arises from the need to critically evaluate the existing methodologies for measuring the eco-efficiency of surface-transport and its relationship with CO₂-emissions. There is a significant gap in the literature: the lack of accuracy of conventional CO₂ intensity measures to capture the complexity of decoupling in this sector. Therefore, this study aims to contribute to the understanding of this issue by introducing a novel methodology that extends previous work in this field. Our approach is distinguished by two main innovations: first, the detailed analysis of the temporal trajectory of decoupling indicators, of trends, and second, the application of a specific threshold to assess the intensity of decoupling, thus providing a more rigorous and realistic framework for its study.

The motivation behind this research lies in providing a more solid empirical basis for the formulation of public policies and energy transition strategies aimed at the decarbonization of the transport sector. By offering a clearer and more detailed view of decoupling, this study aspires to significantly contribute to global efforts to mitigate CO₂ emissions (the environmental impact) of transport, thus aligning with the long-term sustainability goals set in international climate change agreements.

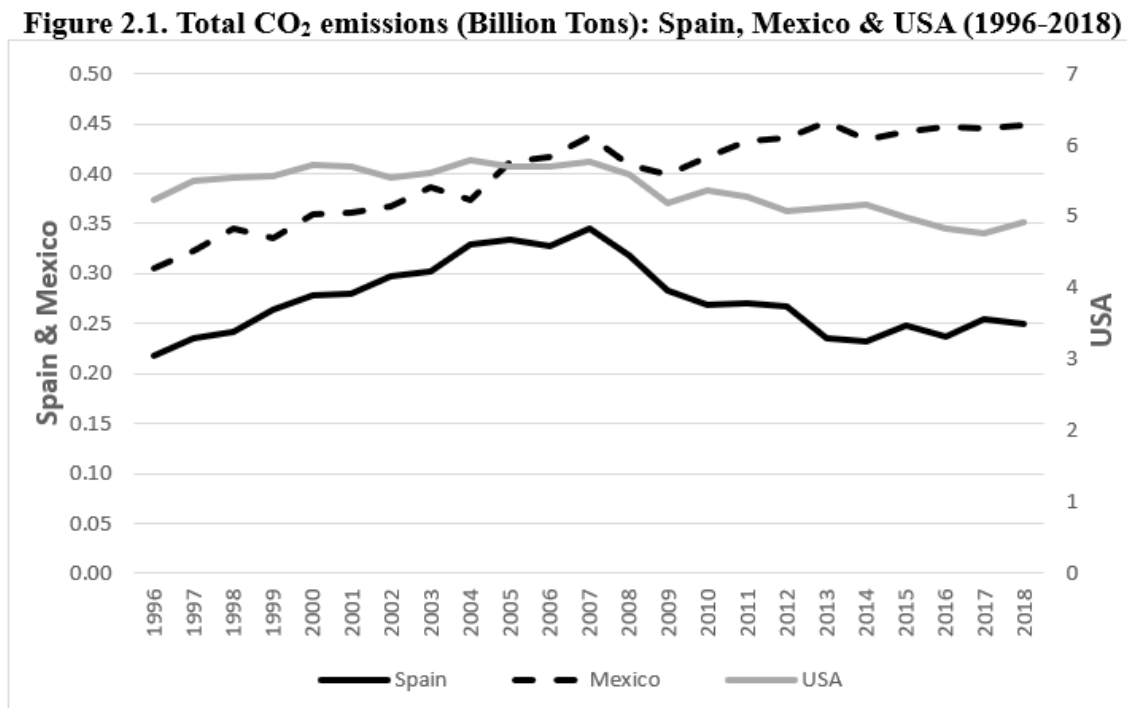
The structure of the article is organized as follows: Section 2 presents the theoretical background and key concepts in the literature on decoupling; Section 3 details the data and proposed methodology; in Section 4, the main findings are discussed; and finally, in Section 5, conclusions and recommendations are made.

¹ **Transport-volumes can be total, by mode of transport, or by transported object (goods or passengers)**

2.1 Background

The selection of Spain and Mexico is due to their geographically strategic locations on international trade routes. Both countries have been integrated into significant free trade blocks (Spain in the European Community and Mexico in North America under the “Northamerican Free Trade Agreement” in 1993, “NAFTA”, now USMCA). This has increased the trade Mexico-USA routes, raising the volume of freight and passenger transport. Additionally, both Mexico and Spain economies are of similar size. The inclusion of the U.S. is due to its impact on Mexico's regional trade and in turn on its transport-volume.

The trend in economy wide CO₂-Emissions continues to grow (Figure 2.1). Over the study period (1996-2018), Mexico experienced an increase of approximately 50%, the United States (USA) a reduction of 5%, although with a rebound in the last two years, and Spain showed an increase of approximately 25%.



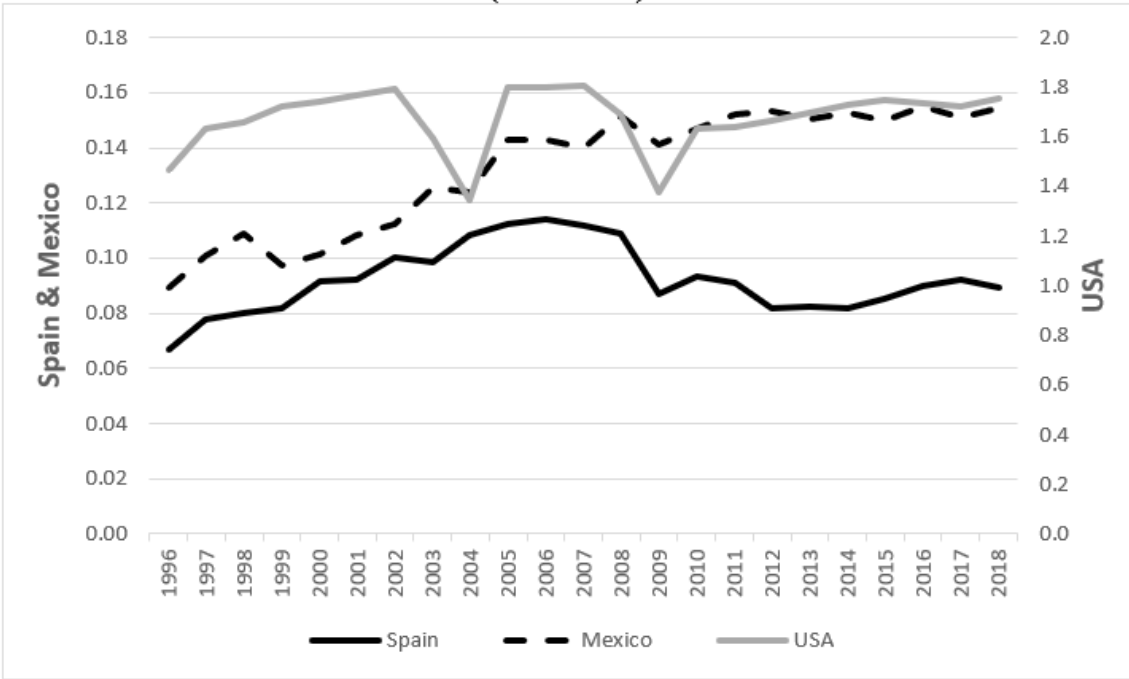
Source: Authors based on IEA (2023)

For developed countries such as Spain and USA, it is observed that CO₂-Emissions related to the surface-transport either remain stable or continue to increase. The same applies to

developing countries. During the period (1996-2018), Mexico increased CO₂-Emissions from transport by 73%, Spain by about 33% and USA by 20% (Figure 2.2). The growth in transport CO₂-Emissions supersedes that of economy wide CO₂-Emissions over the same period.

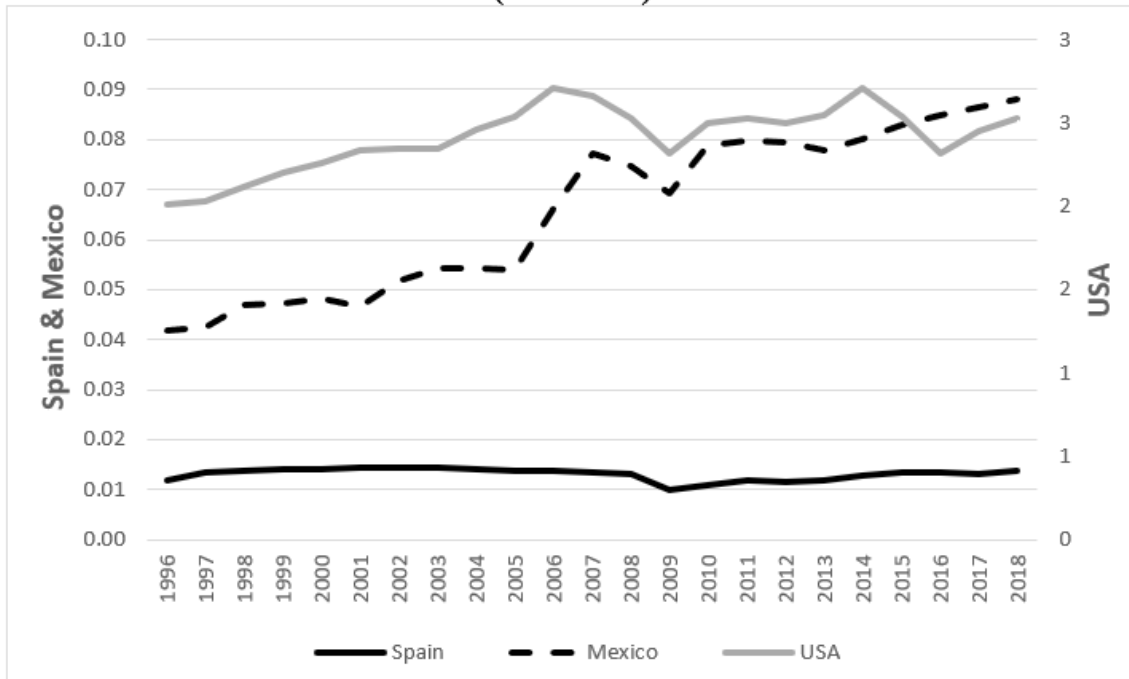
Trends in road and rail transport modes (t-km) show recovery periods for both passenger (Fig. 2.4 & 2.6) and freight movement, for the three countries (Figures 2.3 and 2.5). Mexico increased rail transport-volume by 110% and road freight transport-volume by 47%. Spain increased rail freight transport-volume by 15% and road freight transport-volume by 120%. Meanwhile, USA saw a 70% increase in road freight transport-volume and a 25% increase in rail freight transport-volume. Both the rail and road modes (passenger) for Mexico registered a similar recovery and an increase of 37% respectively, Spain saw an increase of 75 and 53% respectively, and the USA 45 y 44% respectively (Figure 2.4 and 2.6).

Figure 2.2. CO₂ Emissions from Transport (Billion Tons): Spain, Mexico & USA (1996-2018)



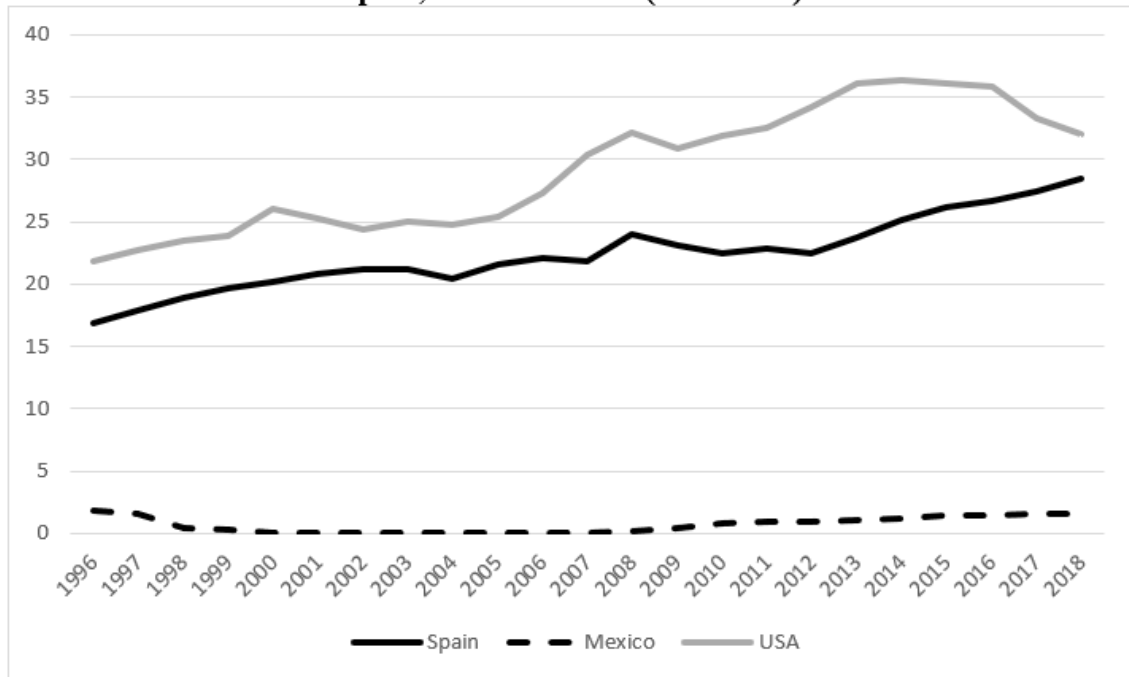
Source: Authors based on IEA (2023).

Figure 2.3. Rail Freight Transport (Trillion Ton-Km): Spain, Mexico & USA (1996-2018)



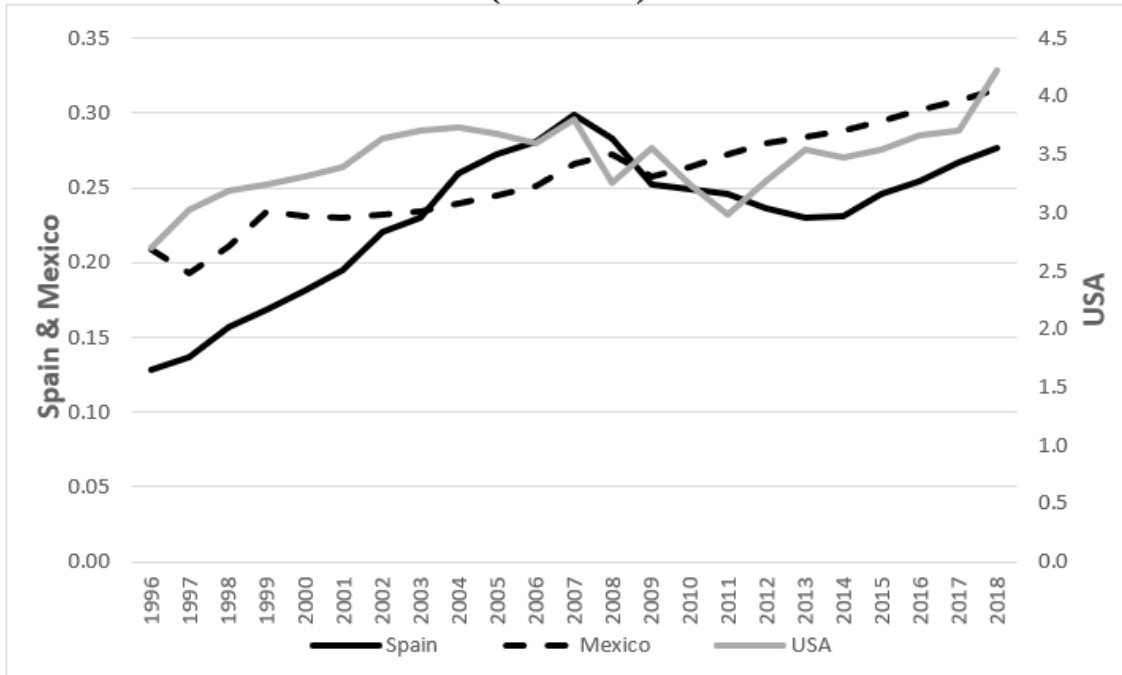
Source: Authors based on data of OECD (2023)

Figure 2.4. Rail Passenger Transport (Billion Passenger-Km): Spain, Mexico & USA (1996-2018)



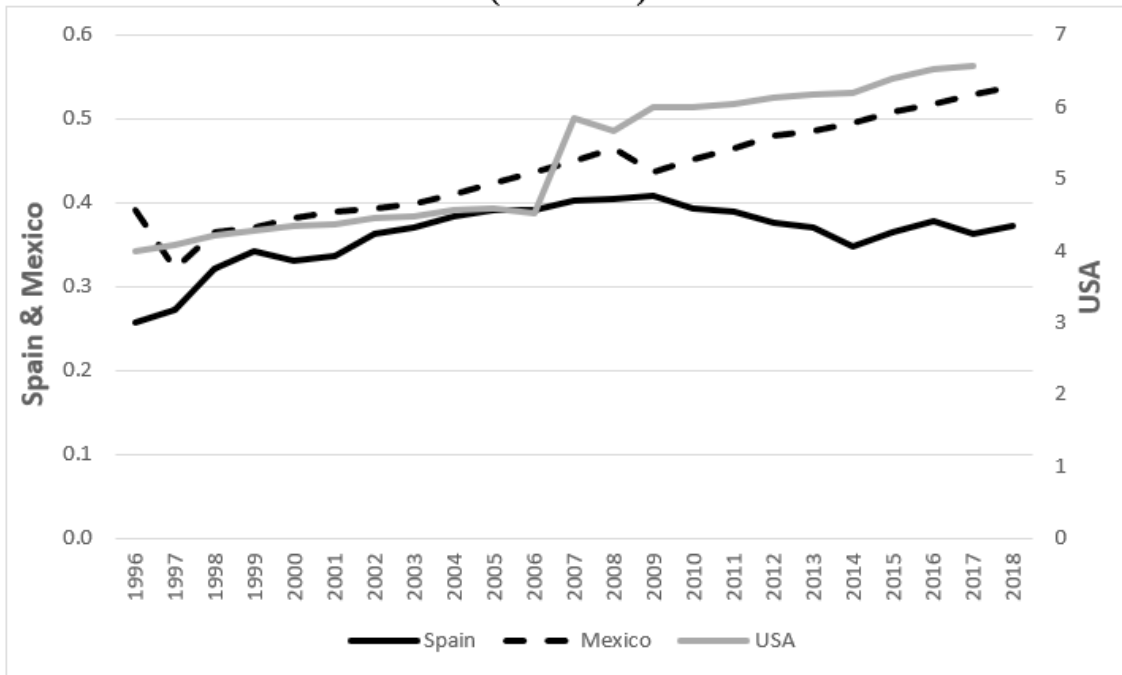
Source: Authors based on data of OECD (2023)

Figure 2.5. Road Freight Transport (Trillion Ton-Km): Spain, México & USA (1996-2018)



Source: Authors based on data of OECD (2023)

Figure 2.6. Road Passenger Transport (Trillion Passenger-Km): Spain, Mexico & USA (1996-2018)

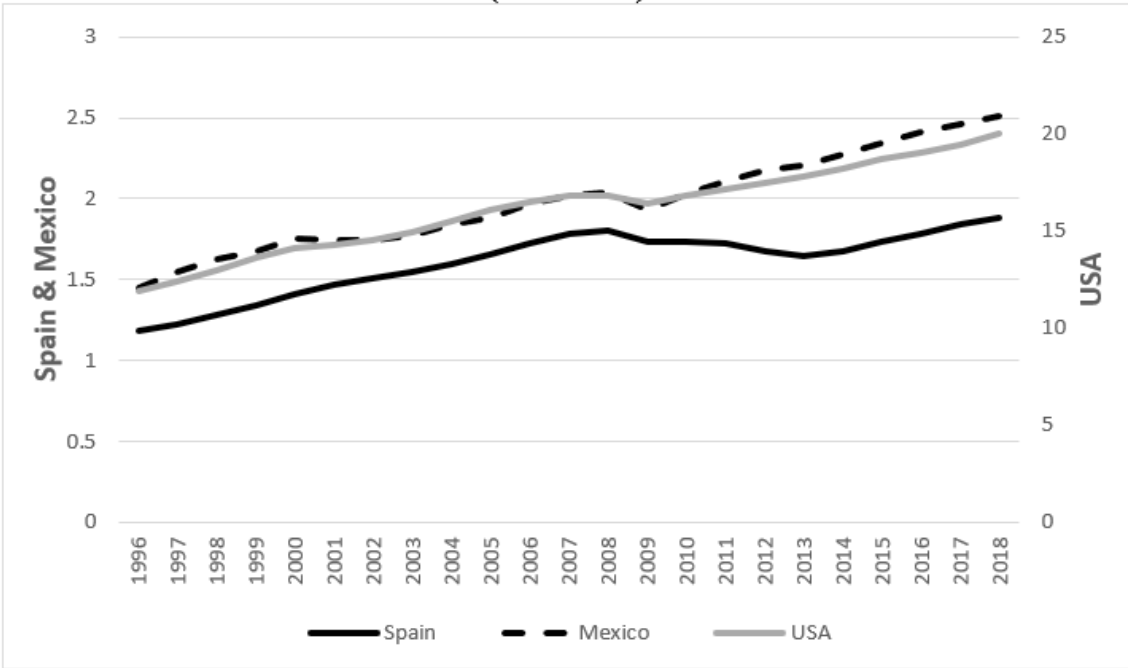


Source: Authors base on data OECD (2023)

In addition, both the national GDP and the GDP of the transport sector show a slight upward trend that does not justify the negative externality and the transport-volume. From 1996-2018, it can be seen that the increase in GDP in Purchasing Power Parity (World Bank, 2023) of Spain, Mexico and USA is approximately 59, 73 and 69%, respectively (Figure 2.7).²

The GDP of the Transport Sector increased 41.6, 115 and 57% for Spain, Mexico and USA respectively (Figure 2.8). Therefore, it is plausible to consider coupling between the surface-transport sector variables and the Economic-Activity variables. Furthermore, it is observed that both the transport-volume (see definition above) grow more than proportionally to the Economic-Activity for the three countries studied. This is evident in both the transport of goods and passengers by surface-transport.

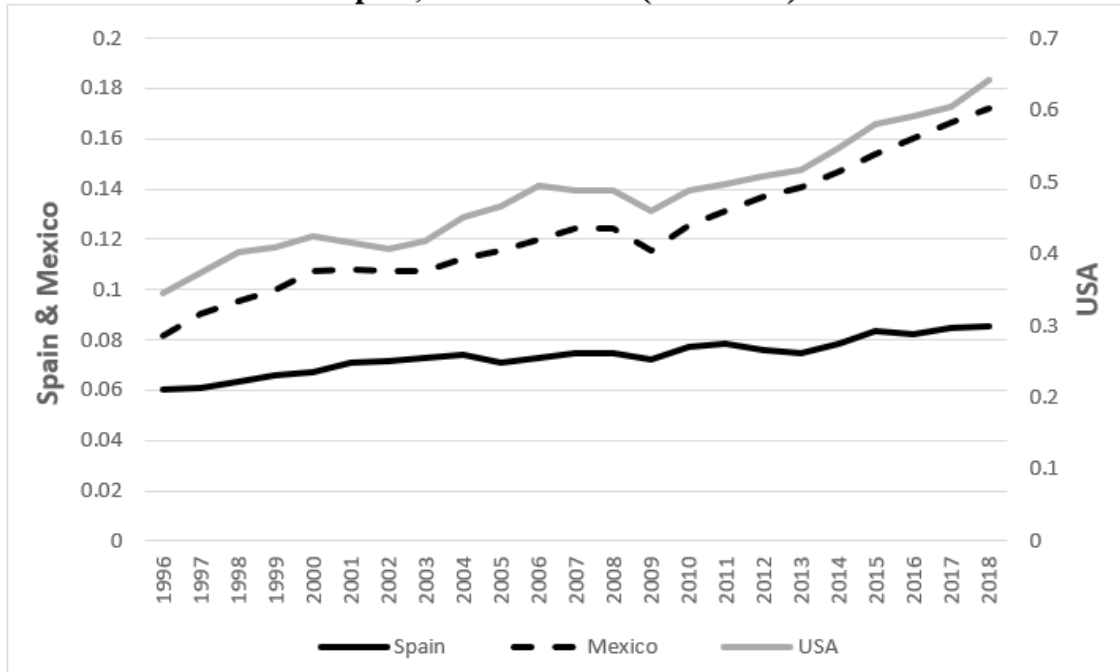
Figure 2.7. GDP Purchasing power parity (Trillion USD (2017)), Spain, México & USA (1996-2018)



Source: The authors based on World Bank (2023).

² The variable GDP PPP per capita holds important information. However, the analysis, being based on the accumulation of the negative externality (CO₂) as a function (Y-axis), requires GDP as the domain (X-axis) to provide a better analysis of the slope of the function (intensity).

Figure 2.8. GDP Purchasing power parity of Transport sector (Trillion USD (2017)), Spain, México & USA (1996-2018)



Source: The authors based on World Bank (2023), INE (2023), INEGI (2023) & FRED (2023). Spain: includes warehousing. Mexico: includes mail and warehousing. USA: includes warehousing.

2.2 Review of literature

Major problems associated with the transport sector include road accidents, traffic congestion, greenhouse gas CO₂-Emissions, and dependence on oil (Loo et al., 2020; Nasreen et al., 2020; Nelson and Warren, 2020; Zhu et al., 2020). Reducing CO₂-Emissions implies reducing energy consumption, which is an essential input for production and can potentially decrease economic growth (Abam et al., 2021; Acheampong et al., 2022). While economic growth is desirable, the same cannot be said for the growth of carbon-based transport. This negative externality of economic activity has become an important transport policy issue: decoupling economic growth from energy and CO₂-Emissions (Loo and Banister, 2016; Nelson and Warren, 2020; Szaruga and Zaloga, 2022). The increase in demand increases CO₂-Emissions in the short term. Therefore, mitigation policies, such as energy efficiency and technological innovation, are targeted at the transport sector to reduce the externalities and increase efficiency (Du et al., 2019).

It is equally important to decouple the transport sector from CO₂-Emissions. The main objective is continuous economic growth with low contributions from the transport sector (decoupling effect). But the growth of the transport sector, both passengers and freight, usually goes hand in hand with economic growth (coupling effect) (Tapio, 2005 & 2007). The phenomenon of decoupling is the general concept and is defined as the breakdown of environmental "bads" and economic "goods" (OECD, 2000). Terms such as immaterialization, dematerialization and decarbonization are derived from this concept (Tapio, 2005).

2.2.1 Decoupling Categories

Achieving economic growth with low CO₂ contributions through transport occurs under the decoupling effect. This decoupling-process is crucial for sustainable transport, especially in the passenger and freight sectors (Tapio et al., 2007). The concept of dematerialization refers to achieving as many service units as possible with the least amount of material (Hinterberger and Schmidt-Bleek, 1988). Dematerialization is defined as the decoupling of specific environmental damage from material production (Loo and Banister, 2016).

In this context, the separation of the transport-volume of road (or rail) from CO₂-Emissions and the "Kuznets U" curve represent an example of dematerialization (Tapio; 2002 & 2005).

Decarbonization is believed to contribute to dematerialization because energy is an important factor in production and a major source of CO₂-Emissions associated with human activity (Nakicenovic, 1996). In fact, this phenomenon is a specific case of dematerialization measured in CO₂-Emissions. Furthermore, one way to measure this phenomenon is through the carbon intensity of the economy (CO₂/GDP) or changes in the carbon intensity of a sector such as transport (CO₂T/GDP) (Loo and Banister, 2016).

On the other hand, the immaterialization-process describes the decoupling of both material production and consumption from Economic-Activity (Heinonen et al., 2005; Loo and Banister, 2016). One way to measure this phenomenon is through energy intensity indicators that reflect the unit of energy consumed per unit of economic production (TEPS/

GDP). Alternatively, transport intensity indicators that illustrate the separation of GDP and road (and rail) transport-volume exemplify immaterialization (Tapio, 2002; Banister and Loo, 2016).

2.2.2. Decoupling Indicators.

An important contribution was to unify the units of measurement for the transport of goods and passengers, respectively, as tonnes per kilometer (t-km) and passenger per kilometer (p-km), on the same basis. This was achieved by considering that an average passenger with their luggage is equivalent to a certain weight, X kilograms. Thus, $1000\text{kg}/X\text{kg}$ equals the proportion q of passengers needed to weigh 1 ton ($1000=qX$). Therefore, if the total number of passengers is Q , then Q/qX equals the total number of passengers measured in tonnes, which is the unit of measurement for transporting goods. This approach allows for expressing passenger and goods movement in the same unit (Peak, 1994; Banister and Stead, 2002). A similar process is possible to convert the total weight of goods transported into the number of passengers transported by multiplying the total tonnage, Z , by the proportion q of passengers (Zq).

Additionally, this equivalence introduces the concepts of gross mass movement and net mass movement (MMN). In the first case, it captures all transport movement in the economy, while in the second case, it captures movement per activity (Peak, 1994). Based on these concepts, indicators of Gross Transport Intensity and Net Transport Intensity can be created. For instance, if each of these indicators is divided by GDP, indicators of transport efficiency and the utility of transport activity can be obtained.

In this way, efficiency variables are included in the analysis of transport intensity to obtain implications for the transport and environmental impacts of policy adoption by evaluating CO_2 -Emissions and resource use (Peak, 1994; Banister and Stead, 2002). Some of the proposed indicators (Table 2.1) rely on variables: energy consumption in transport (CET), gross domestic product (GDP), passengers or goods per kilometer (p-km), (t-km) and net mass movement (Banister and Stead, 2002):

Table 2.1. Indicators for transport Intensity

Energy Efficiency of transport			Economic efficiency of transport		
CET/p-km	CET/t-km	CET/MMN	GDP/p-km	GDP/t-km	GDP/MMN

The authors based on Stead (2001) & Banister, Stead (2002). MMN is net mass movemet.

There are two types of transport intensity measures: the first is the transport energy efficiency measure, which relates energy consumption and the movement of passengers or goods, or both. The second is economic efficiency that relates Economic-Activity and the movements of passengers, cargo or both. In this way, an improvement in the intensity of transport means that less energy is used per unit transported (**economic activity**). And the opposite in case of worsening intensity (More energy per unit **in the numerator**).

Subsequently the quotients of these variables were considered intensities. Those associated with the negative externalities of transport are the environmental intensity of transport (Narayan and Narayan, 2010; Juanky, 2011). Those referring to the amount of transport generated per unit of income or Economic-Activity are transport intensity in volume, and those associated with the amount of energy used per unit of production or Economic-Activity are energy intensity (Loo and Banister, 2016). There are also studies on the intensity of road freight transport that use different measures of Economic-Activity at the sectoral level (Agnolucci and Bonilla, 2009).

The decoupling between variables can also be analyzed through elasticities, e , which is the quotient of percentage variations (Table 2.2). Different types of coupling or decoupling emerge, which depend on the variations in the specified variables (Loo and Banister, 2016) or on the interval in which the result of the quotient falls (Tapio 2005 and 2007). These different types of coupling and decoupling trends can be summarized as follows:

1. Relative Coupling: Both variables change in a positive direction, but the externality increases at a faster rate or Economic-Activity remains the same, resulting in a higher or equal intensity (Loo and Banister, 2016).
2. Absolute Coupling: Changes in the variables are in opposite directions, but the intensity increases. For example, Economic-Activity decreases (in a negative

direction), but the externality increases (in a positive direction) (Bellingal et al, 2003).

In all of these situations, variations in Economic-Activity characterize whether it is an expansive (Economic-Activity increase), stable (same Economic-Activity level), or recessive (Economic-Activity reduction) decoupling or coupling (Loo and Banister, 2016).

Table 2.2. General system for decoupling

$e = \frac{\Delta NE}{\Delta Y}$		Negative Externality		
		∇	Δ	
Y	Δ	$\uparrow C$	-----	Expansive relative coupling
		$\downarrow C$	Absolute expansive Decoupling:	Expansive relative Decoupling
	=	$\uparrow C$	-----	Stationary absolute coupling
		$\downarrow C$	Absolute stationary decoupling	-----
	∇	$\uparrow C$	Relative recessive Coupling	Recessive absolute coupling
		$\downarrow C$	Relative recessive decoupling	-----

Source: The authors based on Loo & Banister (2016). “Y” is economic activity; Δ represents increase; ∇ represents decrease. Negative Externality is CO2 emissions or traffic accidents. C is the intensity as defined above.

Most of the literature cited above is non-econometric but there is work based on different econometric methodologies to explain the decoupling process (Tian et al., 2018; Xiaoyu et al., 2018; Engo, 2018 & 2019) and intensities (Namahoro et al., 2021; Ozkan et al., 2023). Others indirectly present results that can be interpreted by the decoupling literature (Wang and Zhang, 2021 and Alali et al., 2022).

2.2.3. Contributions

Previous analyses are conducted in fixed time intervals, 5 to 10 years and more (Stead 2001, Banister & Stead, 2002, Tapio, 2005 & 2007, Loo and Banister, 2016), without considering short-term changes. These fixed intervals imply data omission in an area where data are scarce and hard to access. This data omission might hide the true scenario; since

the selected year might show a lower value in intensity, but the omitted data might indicate the opposite. To avoid the omission of information, the indicator's trend is incorporated into the study, allowing for continuous analysis.

Various studies (Loo & Banister and others) consider elasticity work with the second differential of the total accumulation of the negative externality. This is the accumulation function. Given that the data used by those studies are random, it is not directly apparent where along the curve of accumulation function the decoupling is occurring; however, the inclusion of the trend can clarify the situation. The approach taken focuses on the first differential of the accumulation function, which is the intensity reflecting the slope of the curve.³⁴

Although our study is designed to analyze the trend in the long term, it allows us to consider fluctuations that occur in the short term by incorporating annual data. Therefore, variations are captured and analyzed as part of the process to understand the general trend of intensity over time.

The previously cited works suggest that a reduction in intensity is favorable but do not provide a rigorous criterion that indicates when decoupling occurs. Based on intensity as the slope of the accumulation function, a threshold is established when the slope is less than or equal to one. From this threshold, the accumulation function achieves its maximum (the point at which decoupling is achieved, meaning the accumulation function's slope is equal to zero). Actual values are retained so that all values have economic significance and are then useful for policy making, goal setting, and evaluation (unlike elasticity analysis).

3. Data & Methodology

3.1 The data

This study uses three groups of variables to develop the indicators for Spain, Mexico and USA between 1996-2018. First, set X_{EA} , there are economic variables such as GDP, in

³ **This accumulation function can also refer to surface-transport.**

⁴ **When analyzing CO₂-emissions and Surface-transport, the Surface-transport represents the domain**

terms of purchasing power parity. Second, set X_{PC} , the materials production and consumption variables, such as the total primary energy supply in tons of oil equivalent and the transport-volume in tons-kilometer. The third group, set X_{EV} , comprises environmental variables, specifically units of resource use such as tons of oil or CO₂-Emissions (Tapio et al, 2007).

This analysis is based on international sources as the OECD, WB, IEA and prestigious national sources as INE and OTLE (Spain), INEGI and SIE (Mexico), FRED and ORNL (USA) that support the international data. The reliability of these sources guarantees the quality of our assumptions and the robustness of our results (For abbreviations and variables see Glossary at the end of document).

The data from economic activity (1996-2018) in terms of purchasing power parity were obtained from World Bank (WB), INE (Spain), INEGI, (México) and FRED (USA). These variables present a positive annual average growth rate (GR) in the study period (Tables 3.1.1, 3.1.2 and 3.1.3). For various measures of GDP, the following is done to calculate indicators of intensity values.

$$iGDP, i \in \{I, T\}$$

If $i=I$ this is “Industrial GDP” and refers to the contribution of all secondary activities (manufacturing, construction, mining, etc.) to the GDP.

And,

if $i=T$ this is “Transport GDP” and refers to the contribution of the transport sector (passengers and freight in their different modalities) to the GDP.

Table 3.1.1. Data description: Economic activity variables for Spain (1996-2018).

Variable	Description	Unit	Average	Standard Deviation	Max	Min	GR
GDP	Total Economic Activity	Trill. USD	1.61	0.2	1.88	1.18	2.13
TGDP	Transport GDP	Trill. USD	0.07	0.01	0.09	0.06	1.63
IGDP	Industrial GDP	Trill. USD	0.43	0.05	0.52	0.37	0.63

Source: The authors based on data WB and INE (2023). GR is annual average growth rate.

Table 3.1.2. Data description: Economic activity variables for Mexico (1996-2018).

Variable	Description	Unit	Average	Standard Deviation	Max	Min	GR
GDP	Total Economic Activity	Trill. USD	1.98	0.3	2.51	1.45	2.54
TGDP	Transport GDP	Trill. USD	0.12	0.02	0.17	0.08	3.44
IGDP	Industrial GDP	Trill. USD	0.70	0.08	0.81	0.57	1.93

Source: The authors based on data WB and INEGI (2023). GR is annual average growth rate.

Table 3.1.3. Data description: Economic activity variables for USA (1996-2018).

Variable	Description	Unit	Average	Standard Deviation	Max	Min	GR
GDP	Total Economic Activity	Trill. USD	16.17	2.27	20.05	11.89	2.40
TGDP	Transport GDP	Trill. USD	0.48	0.08	0.64	0.34	2.86
IGDP	Industrial GDP	Trill. USD	3.32	0.26	3.75	2.88	1.38

Source: The authors based on data WB and FRED (2023). GR is annual average growth rate.

On the other hand, the data on freight and passenger transport in (t-km) for road and rail were obtained from OECD (1996-2018). The data present a positive GR except for rail passenger transport in Mexico (Tables 3.1.4-3.1.6). As above the following variables starting from (t-km) can be derived

$$T(i-km)j, i \in \{t, p\}, j \in \{C, F\}$$

If $i=t$ this is Freight transport,

And,

if, $i=p$ this is passenger transport,

while,

$j=C$ refers to road mode.

And,

if $j=F$ refers to rail mode.

Table 3.1.4. Data description: Transport of freight and passengers by rail and road in Spain (1996-2018).

Variable	Description	Unit	Average	Standard Deviation	Max	Min	GR
T(t-km)F	Rail Freight Transport	Mill. t-km	10,846	1,271.88	12,411	7,714	0.28
T(t-km)C	Road Freight Transport	Mill. t-km	194,299.7	44,272.99	258,869	102,167	3.94
T(p-km)F	Passenger Rail Transport	Mill. t-km	2,238.74	297.11	2,843.4	1,680	2.42
T(p-km)C	Passenger Road Transport	Mill. t-km	36,190.8	3,877.99	40,744.4	25,686.6	1.71

Source: The authors based on data OECD (2023). GR is annual average growth rate.

Table 3.1.5. Data description: Transport of freight and passengers by rail and road in Mexico (1996-2018).

Variable	Description	Unit	Average	Standard Deviation	Max	Min	GR
T(t-km)F	Rail Freight Transport	Mill. t-km	65,722	16,183.18	87,924	41,723	3.45
T(t-km)C	Road Freight Transport	Mill. t-km	213,892.61	27,951.83	260,642	154,083	1.94
T(p-km)F	Passenger Rail Transport	Mill. t-km	70.32	62.71	179.9	6.7	-0.56
T(p-km)C	Passenger Road Transport	Mill. t-km	43,926.37	5,815.26	53,860.4	32,164.5	1.47

Source: As above.

Table 3.1.6. Data description: Transport of freight and passengers by rail and road in USA (1996-2018).

Variable	Description	Unit	Average	Standard Deviation	Max	Min	GR
T(t-km)F	Rail Freight Transport	Mill. t-km	2,408,999.4	194,983.94	2,709,558	2,010,520	1.04
T(t-km)C	Road Freight Transport	Mill. t-km	2,925,545.9	301,972.92	3,565,779	2,293,964	2.03
T(p-km)F	Passenger Rail Transport	Mill. t-km	2,924.9	494.74	3,645.9	2,186.6	1.85
T(p-km)C	Passenger Road Transport	Mill. t-km	530,142.41	96,385.17	662,670.3	398,506.4	2.34

Source: As above.

Finally, data on environmental damage (1996-2018) in million tons (MT) of Carbon dioxide emissions (CO₂) and the total primary energy supply (TPES in million TOE) both series obtained from IEA, OTLE (Spain), SIE (Mexico) and ORNL (USA) (CO₂TC data available from 2004-2018 and CO₂TF (Spain) from 2010-2018). As in most cases the GR is positive except for CO₂-Emissions from road (Spain), economy-wide CO₂-Emissions and from road transport (USA) that present negative GR (Tables 3.1.7, 3.1.8, and 3.1.9). Different metrics can be used for each sector's CO₂-Emissions.

$CO_2i, i \in \{T, TC, TF\}$

If $i=T$ refers to transport sector CO₂

And if $i=TC$ refers to road transport CO₂

Similarly, if $i=TF$ refers to rail transport CO₂.

Table 3.1.7. Data description: Environmental damage variables (CO₂) for Spain (1996-2018).

Variable	Description	Unit	Average	Standard Deviation	Max	Min	GR
<i>CO₂</i>	Emissions	Mill. Tons	274.63	35.04	337.86	218	0.60
<i>CO₂T</i>	Transport Emissions	Mill. Tons	93.9	11.39	116.08	76.71	0.70
<i>CO₂TF</i> *	Rail Transport Emissions	Mill. Tons	1.18	0.04	1.26	1.12	0.01
<i>CO₂TC</i> **	Road Transport Emissions	Mill. Tons	85.38	9.5	100.61	69.8	-0.48
<i>TPES</i>	Total Primary Energy Supply	MTOE	124.62	11.49	143.33	99.3	1.05

Source: The authors based on data IEA (2023). *For the average of the CO₂TF variable is based on the period 2010-2018. **For the average of the CO₂TC variable is based on the period 2004-2018. In all cases CO₂TC + CO₂TF < CO₂T due to CO₂T include CO₂ emission from other modes of transport. GR is annual average growth rate.

Table 3.1.8. Data description: Environmental damage variables (CO₂) for Mexico (1996-2018).

Variable	Description	Unit	Average	Standard Deviation	Max	Min	GR
<i>CO₂</i>	Emissions	Mill. Tons	404.5	46.77	459.46	304.78	1.43
<i>CO₂T</i>	Transport Emissions	Mill. Tons	131.52	22.71	155.27	91.73	2.05
<i>CO₂TF</i>	Rail Transport Emissions	Mill. Tons	1.82	0.2	2.21	1.49	0.63
<i>CO₂TC</i> **	Road Transport Emissions	Mill. Tons	142.41	9.08	151	118.02	0.95
<i>TPES</i>	Total Primary Energy Supply	MTOE	172.07	17.67	191.92	134.69	1.45

Source: The authors based on data IEA (2023). **For the average of the CO₂TC variable is based on the period 2004-2018. If we consider same period 2004-2018 for CO₂T variable, the average is 146.5 Mill. Tons. In all cases CO₂TC + CO₂TF < CO₂T due to CO₂T include CO₂ emission from other modes of transport. GR is annual average growth rate.

Table 3.1.9. Data description: Environmental damage variables (CO₂) for USA (1996-2018).

Variable	Description	Unit	Average	Standard Deviation	Max	Min	GR
<i>CO₂</i>	Emissions	Mill. Tons	5,332.48	330.34	5,729.82	4,761.3	-0.29
<i>CO₂T</i>	Transport Emissions	Mill. Tons	1,861.42	79.4	2,017.86	1,723.8	0.49
<i>CO₂TF</i>	Rail Transport Emissions	Mill. Tons	42.98	2.44	47.84	37.6	0.2
<i>CO₂TC</i> **	Road Transport Emissions	Mill. Tons	1,462.06	46.23	1,527.6	1,400.5	-0.21
<i>TPES</i>	Total Primary Energy Supply	MTOE	2,216	63.89	2,336.35	2,113.28	0.21

Source: The authors based on data IEA (2023). **For the average of the CO₂TC variable is based on the period 2004-2018. In all cases CO₂TC + CO₂TF < CO₂T due to CO₂T include CO₂ emission from other modes of transport. GR is annual average growth rate.

All units of measurement were standardized to base units for uniform analysis. For example, MTOE was converted to kilograms, t-km units were also analyzed in kilograms,

and GDP measured in trillions was analyzed in dollars. This standardization helps to interpret the trends between different variables for each country **by using a ratio with economic significance that helps to pursue economic goals**. For example, if the theoretical relationship suggests a quotient $r \leq 1$ it means that for every dollar earned or produced, less than 1 kg of CO₂ is moved or obtained (interpretation similar for $r > 1$).

3.2 Identities of transport-volume

The study is new since it builds decoupling indicators – Immaterialization and Decarbonization – that are more rigorous and are based on the accumulation function. These indicators are based on a new methodology, but they are derived from the transport intensity indicators (Stead, 2001; Banister and Stead, 2002). We do not implement a sensitivity analysis.

In the study, T means total surface-transport in millions of (t-km). It can be calculated in two ways: as the sum of the total freight volume-transport, T(t-km), and the total passenger volume-transport, T(p-km), after converting passengers to tons (equation 1 and 2); or as the sum of total road volume-transport, TC, and total rail volume-transport, TF (equations 3 and 4). Both TC and TF are sums of goods and passengers transported by road or rail, respectively (equations 5 and 6). Tables 3.2.1, 3.2.2 and 3.2.3 present data created using the above identities, and it can be seen that all the variables created have a GR positive in study period.

$$T(t-km) = T(t-km)C + (1/10)T(t-km)F \quad (1)$$

$$T(p-km) = T(p-km)C + (1/10)T(p-km)F \quad (2)$$

$$T = T(t-km) + T(p-km) \quad (3)$$

$$T = TC + TF \quad (4)$$

$$TC = T(t-km)C + T(p-km)C \quad (5)$$

$$TF = T(t-km)F + T(p-km)F \quad (6)$$

The study needs the creation of the variable T to measure aggregated and sectoral indicators in the industrial and transport sectors, and the TC and TF variables for modal indicator. To align units of measurement, the number of passengers is converted to tons. An average

passenger and their luggage weigh approximately 100 kilograms, which is equivalent to 10 passengers per 1 ton (Banister and Loo, 2011). By dividing the total number of passengers by 10, the data is standardized in tons, allowing uniform analysis of all indicators. This ensures consistency in assessing the performance of the transport sector.

Table 3.2.1. Total and modal Transport-volume for Spain (1996-2018).

	Variable	Description	Unit	Average	Standar Deviation	Max	Min	GR
A	T(t-km)	Total Freight Transport-Volume	Mill. t-km	205,145.7	44,010.08	27,0081	112,323	3.70
B	T(p-km)*	Total Passenger Transport-Volume	Mill. t-km	38,429.53	4,053.48	43,058.1	27,366.6	1.75
C	TF	Total Rail Transport-Volume	Mill. t-km	13,084.74	1,205.11	14,523.7	10,027.7	0.65
D	TC	Total Road Transport-Volume	Mill. t-km	230,490.4	47,784.33	299,114.6	127,853.6	3.56
E	T	Total Surface Transport-Volume	Mill. t-km	243,575.2	47,718.66	312,512.3	139,689.6	3.37

Source: The authors based on data OECD (2023). TF: Total (goods and passengers) rail transport-volume. TC: Total (goods and passengers) road transport-volume. T=Total surface transport-volume in millions of tons (t-km) and is equal to the sum of the total freight transport-volume, T(t-km), and the total passengers transport-volume, T(p-km); or T is equal to the sum of total rail transport-volume and total road transport-volume. Rows A+B = Row E. Rows C+D = Row E. *Variable T(p-km) has been transformed to Tons-Km. GR is annual average growth rate.

Table 3.2.2. Total and modal Transport-volume for Mexico (1996-2018).

	Variable	Description	Unit	Average	Standar Deviation	Max	Min	GR
A	T(t-km)	Total Freight Transport-Volume	Mill. t-km	279,614.6	43,597	348,566	196,525	2.27
B	T(p-km)*	Total Passenger Transport-Volume	Mill. t-km	43,320.58	5,538.91	53,028.5	32,210.5	1.47
C	TF	Total Rail Transport-Volume	Mill. t-km	65,792.32	16,208.81	88,083.1	41,902.9	3.43
D	TC	Total Road Transport-Volume	Mill. t-km	257,142.8	33,023.94	313,511.4	193,129.6	1.86
E	T	Total Surface Transport-Volume	Mill. t-km	322,935.1	48,749.43	401,594.5	235,722.4	2.16

Source: As above.

Table 3.2.3. Total and modal Transport-volume for USA (1996-2018).

	Variable	Description	Unit	Average	Standar Deviation	Max	Min	GR
A	T(t-km)	Total Freight Transport-Volume	Mill. t-km	5,334,545.43	417,802.48	6,090,505	4,304,484	1.59
B	T(p-km)*	Total Passenger Transport-Volume	Mill. t-km	533,067.31	96,857.67	665,943.8	400,693	2.34
C	TF	Total Rail Transport-Volume	Mill. t-km	2,411,924.37	195,303.36	2,712,287.6	2,012,706.6	1.04
D	TC	Total Road Transport-Volume	Mill. t-km	3,455,688.37	326,050	4,228,449.3	2,692,470.4	2.07
E	T	Total Surface Transport-Volume	Mill. t-km	5,867,612.74	460,393.48	6,756,448.8	4,705,177	1.66

Source: As above.

3.3 The indicators

The literature highlights the importance of relating environmental and energy factors with production or transport variables (Tapio, 2007). Based on this, a matrix configuration is suggested, aligning groups of variables in rows and columns, to visualize the derived relationships (Table 3.3.1). As expected, the diagonal reflects the value '1' when a group of variables is related to itself. The elements $a_{ij}=a_{ji}$ are equivalents, in terms of the category decoupling they represent, and the main interpretation is given to the elements located above the diagonal (Stead, 2001; Banister and Stead, 2002). Subscripts i, j represent the set to which each variable belongs. These subscripts are unit free and are elements of the matrix.

Table 3.3.1 Matrix of Relationships among variables

$\frac{X_t}{Y_t}$	X_{EA} : Economic activity (GDP)	X_{PC} : Production-Consumption of Material	X_{EV} : Environmental Damage (CO_2 Emissions)
X_{EA} : Economic Activity (GDP)	1	Immaterialization	Decarbonization
X_{PC} : Production-Consumption of Material	Immaterializacion	1	Dematerialization
X_{EV} : Environmental Damage (CO_2 Emissions)	Decarbonizacion	Dematerialization	1

Source: The authors. X,Y are time serie variables that belong to one of the three sets of variables mentioned: X_{EA} , X_{PC} and X_{EV} . See section 3.1.

The present research is based on and complements the methodology of previous studies by incorporating the concepts of threshold and trends. According to the methodology previously cited (Stead, 2001; Banister and Stead, 2002; Tapio, 2005; Loo and Banister, 2016), the behavior of intensity indicators depends on the position of the variables in the

quotient (numerator and denominator), and to which group the variable belongs (EA, PC, and EV).

Considering this, it's important not to lose sight of how the indicator has been presented when interpreting it. Let's assume there is an intensity indicator in absolute value, $r_t < 1$, t as the sequential values in chronological order (equation 5). Thus, r_t , defined as absolute intensity, has the advantage of revealing direct economic information that is easy to interpret and compare.

$$\text{Intensity: } \frac{X_t}{Y_t} = r_t, t = 1, \dots, n \quad (5)$$

Considering intensity as the slope of the accumulation function, a decision threshold is established when the intensity value is less than one within the time interval of the period, $r_t \leq 1, t \in (1, n)$, and if the inequality is maintained for the rest of the period, $r_j \leq 1, t < j$, then the quotient criterion is met. This threshold establishes that increases in the denominator (regardless of their magnitude) are accompanied by marginal increases in the numerator (decoupling phase). It should be observed that when the value of the slope, r_t , exceeds one, this indicates that increments in the denominator are accompanied by proportionally larger increments in the numerator (coupling phase) (see Appendix A.0).

The determination of the objective quotient depends on the variables involved and which goes in the numerator, and which goes in the denominator. To avoid confusion later and be in accordance with the literature, Economic-Activity will be taken in the denominator (most cases), therefore the theoretical relationship suggests that the quotient $r \leq 1$. Ideally, the quotient should be less than one, and quotient should converge over time to zero (this convergence implies the maximum of the accumulation function and the point at which decoupling is obtained, the point at which increases in the denominator do not lead to increases in the numerator).

On the other hand, the trend is obtained from the equation of a simple linear regression model (equation 6), considering r_t as the time series variable at a specific point, $t = 1, \dots, n$. Where the coefficient b_0 represents the intercept, and the coefficient b_1 captures the trend of

the variable. So, if the coefficient $b_1 < 0$, the trend is downward, and conversely, if $b_1 > 0$, the trend is upward. Similarly, if the coefficient associated with the slope of the trend satisfies $b_1 < 0$, then the criterion for a decreasing trend is met. The downward trend reflects the goal of reducing intensity during the study period. This downward trend reflects the behaviors that intensity should follow in the decoupling process. And mathematically it is the reduction in the slope of the accumulation function.

$$r_t = b_0 + b_1 t + u \quad (6)$$

Thus, this study complements the previous work carried out by Stead (2001), Banister and Stead (2002), Tapio (2005) and Loo and Banister (2016) by incorporating the trend of the indicators into the study of decoupling. Previous studies allowed indicators to be compared over time but were local in the sense that they did not provide information beyond what was happening in a particular year. Furthermore, this study allows analyzing and shaping the general behavior of the accumulation function

In this way, the analysis of the indicators was biased towards “good” and “bad” years, that is, a good year would yield a good indicator (a reduction in the index of intensity) without considering whether the previous and subsequent years were bad, and vice versa with bad years. The variables in question are susceptible to sudden changes. Therefore, this study improves the analysis by incorporating past information through the trend of the indicators, thus providing a clearer indication of the direction of change.

A downward trend in the indicator is desirable in the study period (in line with convergence) and eliminates ambiguity in certain scenarios because, regardless of the value of the indicator, it must adhere to the convergence of the proposed relationship. Additionally, it allows for better analysis over long periods by incorporating all available information.

Consequently, incorporating these two concepts into intensity indicators not only provides complementary analysis to what has already been proposed but also establishes a more rigorous and restrictive decoupling criterion. This means that to speak of decoupling

between variables, it is necessary for the indicator's evolution to show convergence and a downward trend.

The possible scenarios are the following for the case in which the theoretical relationship suggests a quotient less than or equal to one. In any case, to speak of decoupling (immaterialization and decarbonization) both objective conditions must be met, namely that: 1) the theoretical specification of the quotient ($r \leq 1$) and 2) the trajectory of the quotient itself must be met (downward trends). Meanwhile, if none of the objective conditions are met, then coupling (materialization, and carbonization) is taking place.

Similarly, if one of the two objective conditions is met, a coupling-process is taking place as one of the two conditions is missing. In this regard, if the objective quotient is met but not by the trend condition, there is "coupling by trend," alluding to the possible coupling-process arising from this source. Likewise, if the objective quotient is not met but that of the trend does so, there is "coupling by quotient," suggesting this as the cause of the coupling-process (Tables 3.3.2).

Even though past information is being incorporated through the trend, the study is concise. To enrich this analysis, one can detail whether the variations are caused by increases or decreases in the numerator or denominator (sensitivity analysis), as done by Tapio (2005), Loo and Banister (2016). However, such an analysis goes beyond the scope of this paper since our study focuses on the first difference.

Table 3.3.2 Decoupling Scenarios if $r \leq 1$

<i>Trend \ r</i>	$r \leq 1$	$r > 1$
Downward (∨)	Decoupling	Coupling by quotient
Upward (∧)	Coupling by Trend	Coupling

Source: The authors. For C_t defined this way (GDP in denominator), small values of "r" are desirable. However, if we interpret it as $r'_t > 1$, this relationship will require large values of "r'". At this point, it's essential to consider that $r' = 1/r$ (for small values of "r", its reciprocal "1/r" is large). Without keeping this in mind, the results can be counterintuitive.

4 Results and Recommendations

Key economic and environmental variables have been examined using transport intensity indicators in the context of decoupling. The methodology described in Section 3 guided the four-phase analysis. The first phase studies aggregate variables from the period 1996-2018, while the second phase disaggregates them at the sectoral level, highlighting the evolution of the transport sector.

The third phase further breaks down data on surface-transport modes by road and rail. The fourth phase focuses on modal transport-volume (t-km), defined as above, where goods and passengers are combined to produce transport-volume data (To see all indicators and meaning for disaggregate level and category see Appendix A.1 and A.2). This multilevel analysis supports the hypotheses: i) Transport-volume growth outstrips economic expansion, signaling a decoupling opportunity. ii) CO₂ emissions from transport may increase less than economic growth, suggesting decoupling potential but needing deeper analysis.

It is important to note that the analysis focuses only on the quotient value and the trend, excluding absolute or relative coupling-decoupling (in deed this analysis exceeds the scope of this study); although it is possible to infer, based on GR (see section 3.1) that most of the indicators represent expansive relative coupling-decoupling, in accordance with the elasticity analysis (see section 2.2.2 and 3.1, Appendix A.3 to A.8, Loo and Banister, 2016).

A decoupling-process (immaterialization-decarbonization) occurs when the quotient $r < 1$ and the trend decreases (see section 3.3). Meanwhile, a coupling-process (materialization-carbonization) is when $r < 1$ and upward trend. If it is a quotient coupling-process (materialization-carbonization), the trend downwards (TD), but $r > 1$. If it is a trend coupling-process the quotient is $r < 1$ and the trend upward (TU).

4.1 Aggregate results

In the first phase, the aggregate transport intensity indicators show (Table 4.1) that Spain, Mexico and USA show an immaterialization-process in TPES/GDP, indicating a reduction in energy use per unit of GDP. In CO₂/TPES, Spain and USA present a carbonization-process by quotient ($r>1,TD$), while Mexico shows Carbonization ($r>1,TU$). The three countries exhibit a decarbonization-process in CO₂/GDP. Regarding GDP/T, a Materialization-process ($r>1,TU$) is observed in the three countries, although in the case of USA it is by quotient ($r>1,TD$). Finally, in CO₂/T and TPES/T, all countries show trends towards Decarbonization and immaterialization respectively.

Table 4.1. Scenarios of aggregate indicators: Spain, USA & Mexico (1996-2018)

Indicator	r	Trend	Spain	Mexico	USA
$\frac{TPES}{GDP}$	<1	↘	Immaterializarion	Immaterializarion	Immaterializarion
$\frac{CO_2}{GDP}$	<1	↘	Decarbonization	Decarbonization	Decarbonization
$\frac{T}{GDP}$	<1	↘	Materialization	Materialization	Materialization by quotient
$\frac{CO_2}{TPES}$	<1	↘	Carbonization by quotient	Carbonization	Carbonization by quotient
$\frac{CO_2}{T}$	<1	↘	Decarbonization	Decarbonization	Decarbonization
$\frac{TPES}{T}$	<1	↘	Immaterializtion	Immaterialization	Immaterialization

Source: The authors based on WB (2023), IEA (2023), OECD (2023), INE (2023). T=Total land transport in millions of tons (t-km) and is equal to the sum of the total goods transported, T(t-km), and the total passengers transported, T(p-km), See section 3 for the definition of “T”. TPES variable is considered as a proxy of total energy consumption (CET) for whole economy. ↘ Downward trend. ↗ Upward trend.

4.2 Results by Sector

According to the second level of analysis (sectoral), (Table 4.2), the intensity of transport CO₂-Emissions to IGDP indicates that USA show a decarbonization-process. While Mexico and Spain present a carbonization-process ($r>1, TU$) in both indicators (IGDP & TGDP), which indicates that industrial activity contributes to increase in transport CO₂-Emissions. The T/TGDP and T/IGDP indicators relate transport and industrial GDP to the transport-volume (t-km), showing a materialization-process ($r>1, TU$) in Spain, ($r<1, TD$) in USA and Mexico exhibits both cases. That is, the industry is closely linked to the increase in transport. Finally, CO₂T/T compares transport CO₂-Emissions from the transport sector and the transport-volume (t-km); Spain and the US are achieving a decarbonization-process, while Mexico shows carbonization by quotient ($r>1, TD$).

Table 4.2. Scenario of Sectoral Indicators: Spain, USA & y Mexico (1996-2018)

Indicator	r	Trend	Spain	Mexico	USA
$\frac{CO_2T}{TGDP}$	<1	↘	Carbonization by quotient	Carbonization by quotient	Carbonization by quotient
$\frac{CO_2T}{IGDP}$	<1	↘	Carbonization by Trend	Carbonization by Trend	Decarbonization
$\frac{T}{TGDP}$	<1	↘	Materialization	Materialization by quotient	Materialization by quotient
$\frac{T}{IGDP}$	<1	↘	Materialization	Materialization	Materialization by quotient
$\frac{CO_2T}{T}$	<1	↘	Decarbonization	Carbonization by Trend	Decarbonization

Source: The authors based on World bank data (2023), IEA (2023), OECD (2023), INE (2023), INEGI (2023), FRED (2023). See figure 4.1 and section 3 for a definition of “T” and other variables. TGDP: Transport GDP. IGDP: Industrial GDP. ↘ Downward trend. ↗ Upward trend.

4.3 Results for transport Modes

In both tables (4.3.1 and 4.3.2), TC/GDP and TF/GDP demonstrate a materialization process ($r>1, TU$) for all three nations, suggesting transport-volume (t-km) growth outpaces economic growth in certain instances. The CO₂TC/TC and CO₂TF/TF indicators present a decarbonization process across these countries, implying reduced modal CO₂-Emissions despite transport expansion. For CO₂TC/TGDP and CO₂TF/TGDP, Spain

undergoes decarbonization, whereas Mexico and USA exhibit Carbonization by quotient ($r > 1, TD$) in the former, meaning road transport CO₂-Emissions outweigh GDP contributions. Yet, both nations lean towards decarbonization in the latter. Notably, recent trends in Spain and Mexico hint at either deviating from decoupling or intensifying the coupling scenario (detail in section 4.4).

Table 4.3.1. Scenario for Indicators of Road Transport: Spain, USA & Mexico (1996-2018)

Indicator	r	Trend	Spain	Mexico	USA
$\frac{TC}{GDP}$	<1	↘	Materialization	Materialization by quotient	Materialization by quotient
$\frac{TC}{TGDP}$	<1	↘	Materialization	Materialization by quotient	Materialization by quotient
$\frac{CO_2TC^*}{TGDP}$	<1	↘	Decarbonization	Carbonization by quotient	Carbonization by quotient
$\frac{CO_2TC^*}{TC}$	<1	↘	Decarbonization	Decarbonization	Decarbonization

Source: The authors based on World Bank data (2023), IEA (2023), OECD (2023), INE (2023), INEGI (2023), FRED (2023). See Table 4.1 and section 3 for a definition of “T” and other variables. TC: total (goods and passengers) road transport. TGDP: total GDP of transport. ↘ Downward trend. ↗ Upward trend. *For CO₂TC variable the period 2004-2018 is considered.

Table 4.3.2. Scenario of Indicators of Rail Mode: Spain, USA & México (1996-2018)

Indicator	r	Trend	Spain	Mexico	USA
$\frac{TF}{GDP}$	<1	↘	Materialization by quotient	Materialization	Materialization by quotient
$\frac{TF}{TGDP}$	<1	↘	Materialization by quotient	Materialization	Materialization by quotient
$\frac{CO_2TF^*}{TGDP}$	<1	↘	Decarbonization	Decarbonization	Decarbonization
$\frac{CO_2TF^*}{TF}$	<1	↘	Decarbonization	Decarbonization	Decarbonization

Source: The authors based on World bank data (2023), IEA (2023), OECD (2023), INE (2023), OTLE (2023), INEGI (2023), SIE (2023), FRED (2023), ORNL (2023).TF: Total (goods and passengers) rail transport. See figure 4.1 and section 3 for a definition of “T” and other variables. ↘ Downward trend. ↗ Upward trend. *CO₂TF variable for Spain the period 2010-2018 is considered.

4.4 Results Transported services (Goods & Passengers)

The three countries present materialization-process (Table 4.4.1). The result suggests a connection between the Economic-Activity and freight transport-volume (t-km). In USA the materialization-process is due to quotient ($r > 1$, TD). For passenger transport (Table 4.4.2), results mirror freight transport, with most exhibiting a Materialization-process ($r > 1$, TU) in both road and rail. Some trends vary as quotient or trend, indicating diverse Economic-Activity transport ties. In essence, these indicators reveal each nation's equilibrium between economic growth and transport's environmental effects from 1996-2018. Country and modal nuances, while slight, are crucial for a comprehensive understanding.

Table 4.4.1. Scenario of Indicators of Rail, Road and Total Freight Transport: Spain, USA & Mexico (1996-2018)

Indicators Rail Freight Transport					
Indicator	r	Trend	Spain	Mexico	USA.
$\frac{T(t - km)F}{GDP}$	<1	↘	Materialization by quotient	Materialization	Materialization by quotient
$\frac{T(t - km)F}{TGDP}$	<1	↘	Materialization by quotient	Materialization	Materialization by quotient
$\frac{T(t - km)F}{IGDP}$	<1	↘	Materialization by quotient	Materialization	Materialization by quotient
Indicators Road Freight Transport					
$\frac{T(t - km)C}{GDP}$	<1	↘	Materialization	Materialization by quotient	Materialization by quotient
$\frac{T(t - km)C}{TGDP}$	<1	↘	Materialization	Materialization by quotient	Materialization by quotient
$\frac{T(t - km)C}{IGDP}$	<1	↘	Materialization	Materialization	Materialization by quotient
Indicators Land Freight Transport					
$\frac{T(t - km)}{GDP}$	<1	↘	Materialization	Materialization	Materialization by quotient
$\frac{T(t - km)}{TGDP}$	<1	↘	Materialization	Materialization by quotient	Materialization by quotient
$\frac{T(t - km)}{IGDP}$	<1	↘	Materialization	Materialization	Materialization by quotient

Source: The authors based on World Bank (2023), OECD (2023), INE (2023), INEGI (2023), FRED (2023). See Table 4.1 and section 3 for a definition of “T” and other variables. “F”: rail mode. “C”: road mode. “t-km” tonne-km. IGDP: industrial GDP, TGDP: transport GDP. ↘ Downward trend. ↗ Upward trend.

Table 4.4.2 Scenario of Indicators of Rail, Road and Total Passenger Transport: Spain, USA & Mexico (1996-2018).

Indicators Rail Transport (Passengers)					
Indicator	r	Trend	Spain	Mexico	USA
$\frac{T(p - km)F}{GDP}$	<1	↘	Materialization	Materialization by trend	Materialization by trend
$\frac{T(p - km)F}{TGDP}$	<1	↘	Materialization	Materialization by trend	Materialization
Indicators Road Transport (Passengers)					
$\frac{T(p - km)C}{GDP}$	<1	↘	Materialization by quotient	Materialization by quotient	Materialization
$\frac{T(p - km)C}{TGDP}$	<1	↘	Materialization by quotient	Materialization by quotient	Materialization
Indicators Land Transport (Passengers)					
$\frac{T(p - km)}{GDP}$	<1	↘	Materialization by quotient	Materialization by quotient	Materialization
$\frac{T(p - km)}{TGDP}$	<1	↘	Materialization by quotient	Materialization by quotient	Materialization

Source: The authors based on data: IEA (2023), OECD (2023), INE (2023), INEGI (2023), FRED (2023). ↘ Downward trend. ↗ Upward trend.

4.5 Results: Freight transport Emissions (M&CO₂)

Considering road and rail are chiefly influenced by freight transport-volume (t-km) with most CO₂-Emissions tied to freight (Table 4.5), a decarbonization-process for the three countries (1996-2018) can be observed.

Table 4.5. Scenario for Indicators for CO₂ emissions of Freight transport (M&CO₂): Spain, USA & México (1996-2018)

Indicator	r	Trend	Spain	Mexico	USA
$\frac{CO_2TF^{**}}{T(t - km)F}$	<1	↘	Decarbonization	Decarbonization	Decarbonization
$\frac{CO_2TC^*}{T(t - km)C}$	<1	↘	Decarbonization	Decarbonization	Decarbonization

Source: The authors based on data: IEA (2023), OECD (2023). *Change in trend observed last three or five years. ↘ Downward trend. ↗ Upward trend. *For CO₂TC variable the period 2004-2018 is considered. **CO₂TF variable for Spain the period 2010-2018 is considered.

4.6 Recommendations

Several factors may contribute to the observed trends in transport. For instance, the industrial sector's demand to move goods can be indicative of materialization. Furthermore, international trade affects the transport of goods (t-km) within and outside the country. Although reducing trade is not an option to reduce transport activity, there are measures that can be adopted to minimize transport related impacts on emissions through decoupling transport from economic expansion.

As far as the coupling and decoupling results from sections 4.1 to 4.6, the following four actions can help mitigate the intensity relations (1996-2018) to weaken the path of the trend from coupling towards decoupling. These four actions have already been proposed, along with another 32 actions (Helmreich & Keller, 2011); and they strongly promote emission reductions and the modal shift from road to rail (McKinnon, 2007). Likewise, these measures are equally valid (universal) and can be implemented in both geographical zones to change the coupling trajectories. To achieve modal shift from road to rail the following four measures are recommended although there are far more measures available in the policy literature, these are most essential.

4.7.1 Internalization of External Costs

External costs are those borne by society that are not reflected in the market price of goods and services produced. In the case of transport, these include congestion, CO₂ emissions, and other environmental impacts, etc. Thus, the internalization of external costs is the inclusion of costs not considered in production in market prices. This action is aimed at promoting sustainable transport (influencing the behavior of users and providers). Its implementation can be through price differentiation based on external costs, taxes that reflect costs, incentives for sustainable transport, funds in support of efficiency (Streimikiene, 2017; Euchi and Kalle, 2021). Mexico nor the USA has not introduced carbon taxes to internalize externalities; while Spain has imposed a fuel duty on diesel.

4.7.2 Price Differentiation by Type of Load

This price differentiation is to establish different prices for different groups of users or different service characteristics. This action can improve resource allocation in transport, as well as influence users' modal choice, manage congestion, and promote efficient use of infrastructure. It can be carried out by differentiating by the type of user (passenger-freight), by origin and destination, by route within the transport network (Van der Weijde, 2014). None of the countries have implemented price differentiation for transport movements.

4.7.3 Investment in Infrastructure

This is the allocation of financial and technical resources for the development, maintenance, and improvement of transport-related infrastructure. Therefore, policies in this area must consider sustainable development and regional integration (electric vehicles, expansion of public transport, bicycle lanes), planning (innovative technologies and promotion of sustainable mobility), innovation, and technology (collaboration of public-private partnerships for the development and implementation of infrastructure) (Kadyraliev, et al., 2022; Ur Rehman, et al., 2023). Mexico has been less successful in this regard than other countries due to lack of available development finance, large external debt payments and slower economic growth.

4.7.4 Optimization of Transport Network

It focuses on the design of a cargo logistics network (people) that minimizes the costs associated with transport and maximizes benefits in terms of efficiency, reliability, and service capacity (sustainable). This design can optimize-minimize the use of resources, emissions, and vehicular congestion. This can be achieved through planning among various entities, the use of technologies, and electric vehicles. (Bai, et al., 2018 and Aloui, et al., 2021).

5. Conclusions

Our results confirm our first hypothesis: the growth of transport-volume disproportionately exceeds economic growth, indicating that that relationship enters a phase of coupling below the threshold is fulfilled for next reasons: The intensity indicators of transport produce a ratio, $r > 1$ in the relationship between the transport-volume and economic activity (GDP) with an upward trend, or both, at all levels studied; this ratio is also present at all levels for the countries in question. Thus, it is possible to conclude that the ratio of absolute intensity (the transport sector: goods and passengers (t-km) as a quotient of economic activity) remains greater than 1. The confirmation of this hypothesis will have strong implications for the future: our indicators show a growing trend, and thus a setback in decarbonization trends.

The findings also confirm the second hypothesis: the increase in CO₂-Emissions caused by surface-transport grows less than proportional to economic growth, which could signal a phase of decoupling because the transport-economy relationship lies above the threshold, this decarbonization process (decoupling phase) was observed, primarily in Spain and the United States, and to a lesser extent in Mexico, across all levels of indicators. There is a reduction in environmental damage intensity (confirmed by the proposed threshold and trend in our methodology) concerning both sets of variables: economic activity and transport-volume (t-km) in the transport sector (road and rail). This result confirms the hypothesis for specific cases (Spain and the United States), but not in a general sense.

The main results, as described above, were obtained by analyzing the trends and quotients of efficiency and intensity indices calculated using three groups of variables: economic activity variables, material production-consumption variables, and environmental damage variables (with their respective units of measurement) during the period 1996-2018. The variables were analyzed from the most aggregated level to the least disaggregated level possible and through their basic units.

The standardization into basic units proposed allows obtaining information with economic significance, unlike the sensitivity analysis of other authors (Tapio, 2005 and 2007; Loo and Banister, 2016), in which an analysis of the economic significance of those units is omitted. This information is useful for the formulation of objectives, goals, and evaluations with economic interpretation (linked to the variables). Generally, these studies are carried

out over time spans of 5-10 years or more (Stead, 2001; Banister & Stead, 2002; Tapio, 2005 and 2007; Loo and Banister, 2016). This causes the loss of information within both the study periods and the unconsidered interval. This paper focuses on the general trend and not a more specific one (obtained by only two points).

To avoid omitting essential information, all available information (by obtaining the trend of the data) is used, a threshold (the quotient) is identified that starts from the concept of the slope of a function when representing the intensity of the movement of one variable (numerator) given the movement of the other (denominator). The conjunction of these characteristics helps in the formulation of policies oriented towards the sustainability of transport.

This study seeks to complement the studies previously carried out by expanding the analysis of intensities (quotient of variables at levels). Elasticities are not used in this study (quotient of variations of the involved variables), and this has the advantage of i) extending the analysis to more subperiods within the study period and ii) the establishment of thresholds that complement the evaluation of the indicators. The interpretation of the results means that the level of intensities should decrease within the study periods, and that the ratio of the indicators should be "small." The proposed methodology captures these notions by introducing the concept of trend (decreasing or increasing, based on the proposed ratio) within the study period and the ratio ($r < 1$, depending on how the relationship between the variables is defined).

The aggregated indicators (first phase) show a decoupling for Spain between the relationships TPES-GDP, TPES-T, and CO₂-GDP, CO₂-T ($r < 1$ and a decreasing trend). However, there is coupling between GDP-T ($r > 1$ and increasing trend), and coupling based on the ratio between CO₂-TPES ($r > 1$, decreasing trend). On the one hand, the first case of coupling (GDP-T) is the most concerning as it doesn't meet any of the desired conditions. On the other hand, the second case (CO₂-TPES) shows a decreasing trend, and if the trend continues, the decoupling goal will be achieved, and the ratio will register as < 1 .

In the sector-specific indicators (second phase), Spain shows that the relationship CO₂T-TGDP could achieve decarbonization, just like the other indicators in the same category. However, there is clear materialization in the second phase. Regarding modal indicators

(third phase), materialization is evident, with a more severe impact in the road mode. Nevertheless, decarbonization is tangible in both modes in this phase. As for indicators of freight and passenger transport (fourth phase), there is a strong trend towards materialization. Although it is expected that there will be decoupling in the coming years in freight transport by train and passenger transport by road. Finally, the indicators for freight transport in both modes show advanced decarbonization; this is shown by 10 indicators out of 12.

In the first phase, Mexico shows the same results as Spain. The only difference between Mexico and Spain is that the GDP-T relationship in the former could potentially decouple soon if the trend continues. However, in the second phase, there is a significant coupling challenge for Mexico.

The next phase presents an encouraging trend in road transport, and if the current momentum is maintained, decoupling can be achieved in all indicators. In contrast to road mode, rail transport shows the opposite, with a possible coupling.

In the fourth phase, materialization of both freight and passenger transport is evident. Road transport for both freight and passengers seems to be on track to meet the proposed decoupling conditions. Finally, decarbonization is favorable in road and rail freight transport, although attention needs to be paid to the decarbonization of rail freight transport.

In the first phase, for the USA, it is analogous to the one described for Spain, with the caveat that the TPES-T relationship could potentially couple in the coming years. In the second phase, there is decoupling in all indicators if a decreasing trend is maintained, and if the increasing trend in the CO₂T-T relationship is reversed.

The third phase reveals a situation similar to Mexico, with the difference that there are no signs of a change in the decarbonization trend of rail transport, which could lead to future coupling.

In the fourth phase, there is also coupling. In freight transport, the current trend needs to be continued to achieve decoupling, while in passenger transport, the current trend reflects a ratio for that sector that is increasing and moving away from the desired level. Finally, like Spain and Mexico, there is possibly a faster decarbonization in the USA, especially in road

and rail freight transport. This work helps identify trends that favour energy transition policies based on the decarbonization of transport.

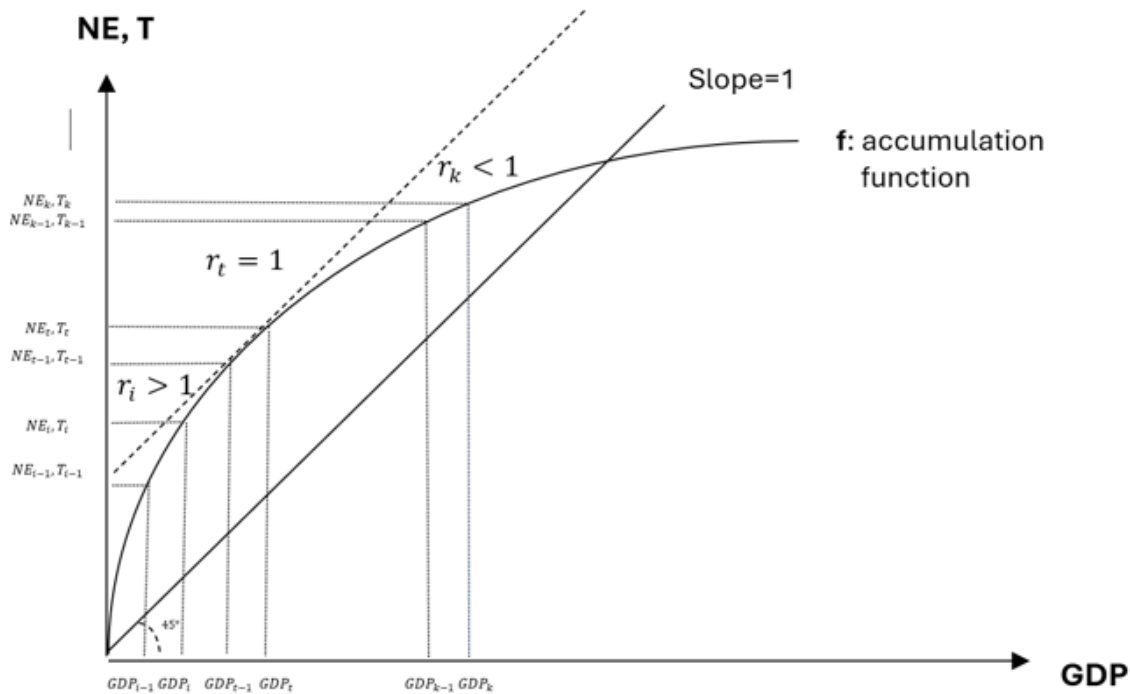
Glossary of terms

<i>Abbreviation</i>	<i>Meaning</i>
<i>C</i>	Road
<i>CO₂</i>	Carbon Dioxide
<i>CO₂T</i>	CO ₂ Emissions of Transport
<i>CO₂TC</i>	CO ₂ Emissions of Road Transport
<i>CO₂TF</i>	CO ₂ Emissions of Rail Transport
<i>CET</i>	Transport Energy Consumption
<i>GDP</i>	Gross Domestic Product
<i>GDPI</i>	Gross Domestic Product of Industry
<i>GDPT</i>	Gross Domestic Product of Transport
<i>GR</i>	Average Annual Growth Rate
<i>F</i>	Rail
<i>FRED</i>	Federal Reserve of Economic Data
<i>IEA</i>	International Energy Agency
<i>INE</i>	National Institute of Statistics (España)
<i>INEGI</i>	National Institute of Statistics and Geographical Information (Mexico)
<i>MMN</i>	Net Mass Movement
<i>MT</i>	Million Tons
<i>MTOE</i>	Millions Tons of Oil Equivalent
<i>OECD</i>	The Organization for Economic Co-operation and Development
<i>ORNL</i>	Oak Ridge National Laboratory
<i>T</i>	Total Surface Transport Volume
<i>TC</i>	Total Road Transport Volume
<i>Type M</i>	Indicators that consider freight transport volume
<i>Type P</i>	Indicators that consider passengers transport volume
<i>TF</i>	Total Rail Transport Volume
<i>TPES</i>	Total Primary Energy Supplied
<i>T(t-km)</i>	Total Freight Transport Volume
<i>T(t-km)C</i>	Road Freight Transport Volume
<i>T(t-km)F</i>	Rail Freight Transport Volume
<i>T(p-km)</i>	Total Passenger Transport Volume
<i>T(p-km)C</i>	Road Passenger Transport Volume
<i>T(p-km)F</i>	Rail Passenger Transport Volume
<i>USA</i>	The United States of America
<i>OTLE</i>	Transport and Logistic Observatory in Spain
<i>WB</i>	World Bank
<i>(p-km)</i>	Passenger(s) per Kilometer
<i>(t-km)</i>	Ton(s) per Kilometer

Source: The authors.

Appendix

A.0 Decoupling-Coupling phase criteria



Source: The authors.

If we consider the total accumulation of Negative Externality, NE, or the volume (total, modal, by object) of transport, T, as the function (image) of the production level, GDP (domain), we can see that the values at t represent annual increments. And the intensity $r_t = NE_t/GDP$ or $r_t = T/GDP$ is the slope of that function. As can be appreciated, the intensity at $C_t = 1$ is the point at which increases in the numerator (NE, T) and the denominator (GDP) are proportional and establishes the threshold proposed by our methodology. We note that for all $i < t$ the intensities, $r_i > 1$ and $r_{i-1} > r_i > r_t = 1$. These intensities are characterized because the increases in the numerator are more than proportional to the increases in the denominator (coupling phase). Therefore, the intensities are greater than 1. On the other hand, for all $t < k$ we have $r_k < 1$ and $1 = r_t > r_{k-1} > r_k$. Conversely, these intensities are characterized by increases in the numerator that are less than proportional to the denominator (decoupling phase). Hence, these intensities are less than 1. It is also possible to appreciate that for every t in the study period, it holds that $r_1 > \dots > r_{i-1} > r_i > \dots > r_{t-1} > r_t = 1 > \dots > r_{k-1} > r_k > \dots \geq 0$; these relationships between the slopes suggest the condition of a decreasing trend of intensity. Likewise, this trend suggests the convergence $r_t \rightarrow 0$, if $t \rightarrow \infty$ which refers to the point at which there is a null increase in the numerator (NE, T) with increments in the denominator (GDP), that is, the maximum point of the accumulation function.

A.1 Immaterialization indicators

AGREEGATE LEVEL	
1. TPES/GDP	Amount of primary energy required to produce one unit of GDP
2. T/GDP	Unit of GDP generated per unit of total land transport volume
3. TPES/T	Energy required to move one unit of total transport volume
SECTORAL LEVEL	
4. TGDP/T	Economic value produced in the transport sector per unit of total land transport volume
5. IGDP/T	Economic value produced in the industrial sector per unit of total land transport volume
MODAL LEVEL	
6. TC/GDP	Amount of railway transport volume require to produce one unit of GDP
7. TF/GDP	Amount of road transport volume require to produce one unit of GDP
8. TC/TGDP	Road transport volume required to produce one unit of GDP in the transport sector
9. TF/TGDP	Railway transport volume required to produce one unit of GDP in the transport sector
OBJECT LEVEL	
10. I(T-KM)F/GDP	Amount of freight volume by rail required to generate one unit of GDP
11. I(T-KM)F/TGDP	Amount of freight volume by rail required to generate one unit of GDP in the transport sector
12. I(T-KM)F/IGDP	Amount of freight volume by rail required to generate one unit of GDP in the industrial sector
13. I(T-KM)C/GDP	Amount of freight volume by road required to generate one unit of GDP
14. I(T-KM)C/TGDP	Amount of freight volume by road required to generate one unit of GDP in the transport sector
15. I(T-KM)C/IGDP	Amount of freight volume by road required to generate one unit of GDP in the industrial sector
16. I(T-KM)/GDP	Total freight transport volume required to generate one unit of GDP
17. I(T-KM)/TGDP	Total freight transport volume required to generate one unit of GDP in the transport sector
18. I(T-KM)/IGDP	Total freight transport volume required to generate one unit of GDP in the industrial sector
19. I(P-KM)F/GDP	Passenger transport volume by rail required to generate one unit of GDP
20. I(P-KM)F/TGDP	Passenger transport volume by rail required to generate one unit of GDP in the transport sector
21. I(P-KM)C/GDP	Passenger transport volume by road required to generate one unit of GDP
22. I(P-KM)C/TGDP	Passenger transport volume by road required to generate one unit of GDP in the transport sector
23. I(P-KM)/GDP	Total passenger transport volume required to generate one unit of GDP
24. I(P-KM)/TGDP	Total passenger transport volume required to generate one unit of GDP in the transport sector

Source: The authors

A.2 Decarbonization indicators

AGREEGATE LEVEL	
25. CO₂/TPES	Amount of CO ₂ emissions emitted per unit of energy consumed
26. CO₂/GDP	Amount of CO ₂ emissions emitted per unit of economic output
27. CO₂/T	Amount of CO ₂ emissions emitted per unit of total land transport volume
SECTORAL LEVEL	
28. CO₂T/TGDP	Unit of GDP generated in the transport sector per amount of CO ₂ emissions emitted in the transport sector
29. CO₂T/IGDP	Unit of GDP generated in the industrial sector per amount of CO ₂ emissions emitted in the transport sector
30. CO₂T/T	Amount of CO ₂ emissions emitted in the transport sector per unit of total land transport volume
MODAL LEVEL	
31. CO₂TC/TC	Amount of CO ₂ emissions per unit of road transport volume conducted
32. CO₂TF/TF	Amount of CO ₂ emissions per unit of railway transport volume conducted
33. CO₂TC/TGDP	Amount of CO ₂ emissions emitted in road transport per unit of GDP generated in the transport sector
34. CO₂TF/TGDP	Amount of CO ₂ emissions emitted in railway transport per unit of GDP generated in the transport sector
FREIGHT TRANSPORT EMISSIONS	
35. CO₂TF/T(T-KM)F	Efficiency of freight railway transport volume in CO ₂ emissions per unit volume of goods transported by rail
36. CO₂TC/T(T-KM)C	Efficiency of freight road transport volume in CO ₂ emissions per unit volume of goods transported by road

Source: The authors

A.3. Immaterialization results considering elasticity analysis for Spain.

AGREEGATE LEVEL	
1. TPES/GDP	Expansive Relative Decoupling
2. T/GDP	Expansive Relative Coupling
3. TPES/T	Expansive Relative Decoupling
SECTORAL LEVEL	
4. TGDP/T	Expansive Relative Coupling
5. IGDP/T	Expansive Relative Coupling
MODAL LEVEL	
6. TC/GDP	Expansive Relative Coupling
7. TF/GDP	Expansive Relative Coupling
8. TC/TGDP	Expansive Relative Coupling
9. TF/TGDP	Expansive Relative Coupling
OBJECT LEVEL	
10. T(T-KM)F/GDP	Expansive Relative Coupling
11. T(T-KM)F/TGDP	Expansive Relative Coupling
12. T(T-KM)F/IGDP	Expansive Relative Coupling
13. T(T-KM)C/GDP	Expansive Relative Coupling
14. T(T-KM)C/TGDP	Expansive Relative Coupling
15. T(T-KM)C/IGDP	Expansive Relative Coupling
16. T(T-KM)/GDP	Expansive Relative Coupling
17. T(T-KM)/TGDP	Expansive Relative Coupling
18. T(T-KM)/IGDP	Expansive Relative Coupling
19. T(P-KM)F/GDP	Expansive Relative Coupling
20. T(P-KM)F/TGDP	Expansive Relative Coupling
21. T(P-KM)C/GDP	Expansive Relative Coupling
22. T(P-KM)C/TGDP	Expansive Relative Coupling
23. T(P-KM)/GDP	Expansive Relative Coupling
24. T(P-KM)/TGDP	Expansive Relative Coupling

Source: The authors, based on Loo and Banister (2016). Category of Coupling or Decoupling is considered from the methodology proposed in this document.

A.4. Decarbonization results considering elasticity analysis for Spain.

AGREEGATE LEVEL	
25. CO ₂ /TPES	Expansive Relative Coupling
26. CO ₂ /GDP	Expansive Relative Decoupling
27. CO ₂ /T	Expansive Relative Decoupling
SECTORAL LEVEL	
28. CO ₂ T/TGDP	Expansive Relative Coupling
29. CO ₂ T/IGDP	Expansive Relative Coupling
30. CO ₂ T/T	Expansive Relative Decoupling
MODAL LEVEL	
31. CO ₂ TC/TC	Expansive Absolute Decoupling
32. CO ₂ TF/TF	Expansive Relative Decoupling
33. CO ₂ TC/TGDP	Expansive Relative Decoupling
34. CO ₂ TF/TGDP	Expansive Relative Decoupling
FREIGHT TRANSPORT EMISSIONS	
35. CO ₂ TF/T(T-KM)F	Expansive Relative Decoupling
36. CO ₂ TC/T(T-KM)C	Expansive Absolute Decoupling

Source: As above.

A.5. Immaterialization results considering elasticity analysis for Mexico.

AGREEGATE LEVEL	
1. TPES/GDP	Expansive Relative Decoupling
2. T/GDP	Expansive Relative Coupling
3. TPES/T	Expansive Relative Decoupling
SECTORAL LEVEL	
4. TGDP/T	Expansive Relative Coupling
5. IGDP/T	Expansive Relative Coupling
MODAL LEVEL	
6. TC/GDP	Expansive Relative Coupling
7. TF/GDP	Expansive Relative Coupling
8. TC/TGDP	Expansive Relative Coupling
9. TF/TGDP	Expansive Relative Coupling
OBJECT LEVEL	
10. T(T-KM)F/GDP	Expansive Relative Coupling
11. T(T-KM)F/TGDP	Expansive Relative Coupling
12. T(T-KM)F/IGDP	Expansive Relative Coupling
13. T(T-KM)C/GDP	Expansive Relative Coupling
14. T(T-KM)C/TGDP	Expansive Relative Coupling
15. T(T-KM)C/IGDP	Expansive Relative Coupling
16. T(T-KM)/GDP	Expansive Relative Coupling
17. T(T-KM)/TGDP	Expansive Relative Coupling
18. T(T-KM)/IGDP	Expansive Relative Coupling
19. T(P-KM)F/GDP	Expansive Relative Coupling
20. T(P-KM)F/TGDP	Expansive Relative Coupling
21. T(P-KM)C/GDP	Expansive Relative Coupling
22. T(P-KM)C/TGDP	Expansive Relative Coupling
23. T(P-KM)/GDP	Expansive Relative Coupling
24. T(P-KM)/TGDP	Expansive Relative Coupling

Source: The authors, based on Loo and Banister (2016). Category of Coupling or Decoupling is considered from the methodology proposed in this document.

A.6. Decarbonization results considering elasticity analysis for Mexico.

AGREEGATE LEVEL	
25. CO ₂ /TPES	Expansive Relative Coupling
26. CO ₂ /GDP	Expansive Relative Decoupling
27. CO ₂ /T	Expansive Relative Decoupling
SECTORAL LEVEL	
28. CO ₂ T/TGDP	Expansive Relative Coupling
29. CO ₂ T/IGDP	Expansive Relative Coupling
30. CO ₂ T/T	Expansive Relative Coupling
MODAL LEVEL	
31. CO ₂ TC/TC	Expansive Relative Decoupling
32. CO ₂ TF/TF	Expansive Relative Decoupling
33. CO ₂ TC/TGDP	Expansive Relative Coupling
34. CO ₂ TF/TGDP	Expansive Relative Decoupling
FREIGHT TRANSPORT EMISSIONS	
35. CO ₂ TF/T(T-KM)F	Expansive Relative Decoupling
36. CO ₂ TC/T(T-KM)C	Expansive Relative Decoupling

Source: As above.

A.7. Immaterialization results considering elasticity analysis for USA.

AGREEGATE LEVEL	
1. TPES/GDP	Relative Expansive Decoupling
2. T/GDP	Relative Expansive Coupling
3. TPES/T	Relative Expansive Decoupling
SECTORAL LEVEL	
4. TGDP/T	Relative Expansive Coupling
5. IGDP/T	Relative Expansive Coupling
MODAL LEVEL	
6. TC/GDP	Relative Expansive Coupling
7. TF/GDP	Relative Expansive Coupling
8. TC/TGDP	Relative Expansive Coupling
9. TF/TGDP	Relative Expansive Coupling
OBJECT LEVEL	
10. T(T-KM)F/GDP	Relative Expansive Coupling
11. T(T-KM)F/TGDP	Relative Expansive Coupling
12. T(T-KM)F/IGDP	Relative Expansive Coupling
13. T(T-KM)C/GDP	Relative Expansive Coupling
14. T(T-KM)C/TGDP	Relative Expansive Coupling
15. T(T-KM)C/IGDP	Relative Expansive Coupling
16. T(T-KM)/GDP	Relative Expansive Coupling
17. T(T-KM)/TGDP	Relative Expansive Coupling
18. T(T-KM)/IGDP	Relative Expansive Coupling
19. T(P-KM)F/GDP	Relative Expansive Coupling
20. T(P-KM)F/TGDP	Relative Expansive Coupling
21. T(P-KM)C/GDP	Relative Expansive Coupling
22. T(P-KM)C/TGDP	Relative Expansive Coupling
23. T(P-KM)/GDP	Relative Expansive Coupling
24. T(P-KM)/TGDP	Relative Expansive Coupling

Source: The authors, based on Loo and Banister (2016). Category of Coupling or Decoupling is considered from the methodology proposed in this document.

A.8. Decarbonization results considering elasticity analysis for USA.

AGREEGATE LEVEL	
25. CO ₂ /TPES	Absolute Expansive Coupling
26. CO ₂ /GDP	Absolute Expansive Decoupling
27. CO ₂ /T	Absolute Expansive Decoupling
SECTORAL LEVEL	
28. CO ₂ T/TGDP	Relative Expansive Coupling
29. CO ₂ T/IGDP	Relative Expansive Decoupling
30. CO ₂ T/T	Relative Expansive Decoupling
MODAL LEVEL	
31. CO ₂ TC/TC	Absolute Expansive Decoupling
32. CO ₂ TF/TF	Relative Expansive Decoupling
33. CO ₂ TC/TGDP	Absolute Expansive Coupling
34. CO ₂ TF/TGDP	Relative Expansive Decoupling
FREIGHT TRANSPORT EMISSIONS	
35. CO ₂ TF/T(T-KM)F	Relative Expansive Decoupling
36. CO ₂ TC/T(T-KM)C	Absolute Expansive Decoupling

Source: As above.

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