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# Cognitive Sustainability

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# Cognitive Sustainability

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# Marginal Cost in Private and Public Transport

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**Abstract:**
For decades, different economic theories have been trying to find an answer to determining the total costs of road transport and the best way to internalise these costs, with the most widespread answer among experts being pricing concerning marginal cost. This article presents a classification of transport costs with their corresponding mathematical functions to finally obtain the marginal cost of both public and private transport to develop an optimal pricing system. Finally, a system of equations for determining the optimal price based on the short term and under the economic premise of maximising social welfare is presented.
**Keywords**
Marginal cost, road transport, emissions, externalities, pricing

## 1. Introduction

Transport is undoubtedly one of the sectors that have most contributed to the growth of modern economies. The rapid mobility of people and goods has been essential to reach the level of globalisation we find ourselves today. Like any other economic sector, the transport sector presents negative externalities which, due to the dynamism of the sector and its heterogeneous nature, have been the subject of debate among economists since the 1960s, with the main point of disagreement always being the determination of the best way to internalise costs.

However, it is not all discrepancies. There is one thing on which economists are unanimous, and that is the answer to the question of what price transport users should pay: the vast majority agree that they should pay the marginal cost, a variable that we define as the cost resulting from adding vehicle or transport unit to the infrastructure. However, the very dynamic characteristics of the transport industry, which means that these costs can vary from minute to minute, mean that we are back to the lack of consensus among economists on how to determine these marginal costs and whether to use those relating to the short or long term to develop the best possible pricing policy.

The big difference between the transport industry and other industries is that many of the sector's externalities are not only borne by the user but are also passed on to society as a whole, which is why in transport economics, the term "social marginal cost" is constantly used when discussing the pricing of transport services. In 1998, in its report "Fair pricing of infrastructure use", the European Commission established a strategy for the implementation of common pricing according to social marginal costs, which can be considered one of the most important events in transport economics, as it was a starting point for Community transport pricing policies, with the environmental objective at the centre of the problem. This environmental approach has gained weight over the years and has become the undisputed protagonist of transport pricing policies.

## 2. The costs of private and public transport:

In any economic activity, we speak of opportunity cost as the value of the productive resources used to carry out that activity. The value of resources must be calculated, considering what other possible alternative uses would be and selecting the best option in terms of cost-benefit for society. In the road transport sector, the cost to society is the sum of the monetary value of all the inputs needed to transport people and goods from one place to another.

One of the characteristics of the transport sector that differentiates it from others is that when we talk about the consumption of productive factors to carry out its activity, we must not only take into account the vehicles, infrastructure, technology or energy consumed by the means of transport, there is a fundamental factor that is at the heart of the demand for transport services, and that is the time invested by users in making these journeys as well as the impact that these journeys have on the rest of society.

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Experts agree on classifying transport costs according to who bears them (*Maibach, 2008*), distinguishing between producer and user. The sum of these three costs allows us to obtain the total social cost that society faces to achieve an acceptable level of transport services (1):

(1) $$Cs = Cp + Cu + Ce$$

The **costs of the producer** include all the expenses necessary to build, operate and maintain the infrastructure, as well as the expenses related to the acquisition, operation and maintenance of the vehicles used to transport passengers, and finally, the operating costs of producing the services (personnel costs, fuel, spare parts).

**User costs** should reflect all the inputs consumed in private and public transport activities. Like the producer of transport, the private consumer faces the costs of purchasing and maintaining his vehicle, fuel costs, vehicle insurance, and the corresponding taxes or charges of the region in which he drives. In public transport, the user does not face any of these costs directly but pays a ticket to the service producer that is used as compensation for those costs that he/she will incur to produce the transport activity.

However, as mentioned above, there is a characteristic that differentiates it from other sectors when determining the total cost of the activity in the transport sector. This factor included in user costs is the importance of making a monetary valuation of the time invested in the transport activity, which is the sum of travel time and waiting time or the time spent on transfers in the case of public transport. This variable is key for analysing policies to solve externalities such as road congestion; congestion occurs due to the capacity limitations of infrastructure when there are additional users. This leads to an increase in time costs and fuel that we pass on to the user's cost function since, although they cause external effects to society, which will be discussed later, the user bears these congestion costs.

The **external costs** of transport are those that have a direct impact on the rest of society, whether or not they are transport users, causing a reduction in their welfare. In recent years, the European Commission has focused its efforts on the transition towards a more sustainable transport system that drastically reduces the external cost of pollution, which directly impacts air quality and the health of citizens.

## 3. The costs of the producer of transport services

For this section, we consider a transport company that produces a single output, measured, for example, in passenger kilometres. Depending on this output, the company will assume two different types of costs, fixed costs that remain constant whether or not there are variations in the output and variable costs that will differ according to the production volume. Fixed costs include, for example, the salary of a bus driver, which will not vary according to the number of passengers he transports. In contrast, variable costs include, for example, the costs of increasing the capacity of a transport element due to a variation in output, in this case, an increase in passengers that requires expenditure to increase supply.

Another classification of the producer's costs would be according to the input used. In this case, there are two types: infrastructure-related and operating costs. Infrastructure costs would include, among others, road maintenance costs, while operating costs would include those related to vehicles, including, among others, personnel costs. This classification of costs would be directly related to the function (2):

(2) $$q = f(K, E, L, F, N; t)$$

Where

$q$ is the level of production in a given unit of time,
$K$ units of infrastructure,
$E$ mobile equipment,
$L$ *labour*,
$F$ energy and spare parts,
$N$ natural resources,
$t$ users' time.

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Taking this function as a starting point and ignoring the elements *t* and *N* that are not part of the producer costs since *t* is in user costs and *N* in external costs, the producer cost function associated with the remaining factors can be defined by the equation (3) by *Campos (2003)*:

(3) $$Cp(q, K) = r(K)\,K + c(q)\,q$$

Where

*r(K)* is the annual cost of each unit of infrastructure,
*c(q)* is the cost per output unit associated with the other factors (*E, L and F*).

**4. The costs of public and private transport users:**

In private transport, the user acts as a producer and therefore shares most of the cost items detailed in the previous section; one of the most relevant costs of the private transport user is operating costs, which include fuel, maintenance, repairs, car insurance costs, and of course taxes related to the vehicle and its circulation.

As for public transport, the price paid by the user in the form of a ticket is not included in the user costs since it is not an input that the user contributes to the transport activity but rather a transfer that the producer receives and which forms part of the general price paid by the user to consume transport services.

The common characteristic in the user costs of public and private transport is that the main cost faced by users in both types of transport is the same: the opportunity cost of the time users spend making a journey. Within this time, we can distinguish two categories: time with congestion, which depends on the number of vehicles on the road, and time without congestion, which depends on the relationship between distance and average vehicle speed.

The opportunity cost of the time spent by users on a journey can be calculated by valuing the time spent on the journey in monetary terms, which in the case of private transport would also include the necessary rest or refuelling breaks, and in the case of public transport would include the transfers and waiting times incurred during the journey. With these assumptions, the opportunity cost of public transport users can be represented by the cost function equation (4) by *Campos (2003)*:

(4) $$Cu(q, t) = vtq$$

Where

*t* is the time consumed in the journey (with the assumptions defined above),
*v* is the value assigned to this time, which in this example is constant,
*q* is the number of passengers or journeys made.

In the case of the private transport user, as described at the beginning of the chapter, if he owns the car, he acts as an operator-product, and therefore, user costs and related producer costs, namely operating costs, are combined in his total cost equation (5) by *Campos (2003)*:

(5) $$Cu(q, t) + Cp(q) = (c + vt)q$$

Where c is the **marginal cost** of the user when acting as a producer, as in the case of the private car, this cost includes fuel and wear and tear on the vehicle, among others.

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### 5. The external costs of public and private transport:

Within the external costs defined in the introduction, the most relevant are environmental, noise, and accident costs.

In terms of environmental costs, a function can be defined to determine the costs of climate change caused in a 1 km interval, valued in *€/hour*, which will be determined by the value assigned to the tonne of $CO_2$, the intensity of traffic and fuel consumption equation (6) by *Ciommo et al., (2008)*:

(6) $$C_{CO_2} = CO_2 * \mathrm{K} * \sum I * C(v)$$

where

*In* the hourly vehicle intensity (veh/h),
*C(v)* fuel consumption as a function of speed,
$CO_2$ the cost of $CO_2$ (average value in 2022 of 83.02 €/tonne)
K the ratio between emission and consumption (*Friedrich and Bickel, 2001*).

For accidents, the cost (veh-km) will depend on the hourly intensity and will be calculated based on the ratio of injuries according to severity or fatalities, in addition to the medical cost incurred (7) by *Ciommo et al., (2008):*

(7) $$Cacc = \frac{l}{h} * (Rhl * VRhl + Rhg * VRhg + Rm * VRm + \emptyset)$$

where

*l/h* is the hourly intensity in veh/hour,
*Rhl* is the ratio of light casualties per veh-km,
*VRhl* is the value of the risk of light casualties (calculated as a function of GDP for all classes of casualties and fatalities),
*Rhg* is the ratio of severe casualties per veh-km,
*VRhg* value of the risk of serious injuries,
*Rm* ratio of fatalities per vehicle-km,
*VRm* value of the risk of fatalities, also calculated as a function of GDP
*Ø* losses of human capital, medical, administrative or infrastructure/property damage costs.

### 6. The problems in pricing concerning marginal cost:

As described earlier in the article, the dynamic characteristics of the transport sector make the determination of its exact costs particularly complex, high fixed costs, for example, in the case of public transport, make it difficult to calculate the exact marginal cost of carrying one more passenger. In addition, the wide variety of services depending on route, speed, and other variables that make transport activities multi-product adds to the complication of pricing the exact cost and the optimal price for each trip.

Another reason for public transport is the market power that an operator may have to set prices above the cost of production in the absence of competition. Finally, and most importantly, the prices of transport services are mainly unrelated to the marginal costs of production because political acceptability criteria come into play when making decisions. In many cases, the transport service operator is forced to charge below marginal cost to make a route more attractive or encourage public transport use by administrations. This is achieved through subsidies.

The price faced by transport users is determined by the equation (8) by *Campos (2003)*:

(8) $$g = p + tv + \emptyset$$

This equation contains the elements described in the chapter on costs, where *p* is the monetary cost of the ticket or the variable cost of a vehicle in the case of private transport, *tv* is the monetary valuation of the time invested, and *Ø* is the

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monetary valuation of other external elements associated with the journey. This element *p* is the one that should reflect the marginal cost of the production of the service. However, this is not usually what happens in practice because the price rarely includes all the costs of the producer and the external costs generated by the transport activity that society bears.

**7. The optimal price system: short term**

Following the concept of economic efficiency and maximisation of social welfare, as discussed at the beginning of the article, the price to be paid by transport users must be equal to the marginal cost they incur. In this case, we detail how the marginal costs can be obtained in the short term. To this end, the possibility of increasing the capacity of the infrastructure is ruled out, and the hypothesis is focused on achieving the maximum possible efficiency with a fixed capacity component.

To obtain the costs, we return to the formula detailed in the first section of the article for total costs, but this time as a function of the output *Q*, which represents the flow of vehicle-km per unit of time in equation (9) by *Matas (2004)*:

(9) $$CT = Cp\,(Q) + Cu\,(Q) + Ce(Q)$$

The total user cost is the product of the output *Q* by the average cost of each infrastructure user (ACu). This average user cost is the equivalent of the private marginal cost in equation (10) by *Matas (2004)*:

(10) $$CTu = Q * ACu\,(Q)$$

Following this scheme, the short-run marginal cost is determined by the following equation (11) by *Matas (2004)*:

(11) $$CM = CMp + Q * \frac{\partial ACu}{\partial Q} + ACu + CMe$$

Representing *ACu* as the monetary costs of circulation and the time-related costs that the user already internalises, the optimal price can be determined according to the short-run marginal cost through the equation (12) by *Matas (2004)*:

(12) $$P = CMp + Q * \frac{\partial ACu}{\partial Q} + CM$$

The three components of the equation are the producer's marginal costs, that have been summarised in the first point of the article, and the second component, the marginal cost of congestion. Moreover, the third component relates to the external marginal costs imposed on society not internalised by the sector.

**8. Conclusion:**

Determining the marginal cost of road transport continues to be a challenge for economists due to the multi-product characteristics of the sector and the variety of different types of vehicles that coexist on the road. Thanks to new technological tools that facilitate traffic control, we are getting closer to developing a reliable marginal cost pricing model. As described in this article, mathematical methods exist for obtaining short-run marginal costs assuming a fixed infrastructure level. However, the challenge is to develop a model for obtaining the dynamic long-run marginal cost that allows obtaining the most efficient pricing system according to the constant changes in traffic volume and infrastructure variations.

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# Environmental impact of mortgage bond purchases: presentation of a possible estimation methodology

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**Abstract**

This article presents a methodological framework for estimating the environmental impact of mortgage bond purchases. The model presented through the Mortgage bond purchase programme of the Magyar Nemzeti Bank (MNB), the Central Bank of Hungary builds on the changing composition of the Hungarian housing stock, and its main assumption is that, while maintaining the total floor area of the housing stock unchanged, financing residential property modernises the housing stock as a result of tightening building energy requirements, which reduces emissions. In our estimate, thanks to the MNB's Mortgage bond purchase programme, the Hungarian building stock could reduce its $CO_2$ emissions by 13-41 thousand tonnes per year. We have made several assumptions and simplifications in our calculations, and the results can only be evaluated in this context.

**Keywords**

Mortgage bond, environmental impact, building stock, carbon emission

## 1. Introduction

Today, it is clear that climate change and sustainability are one of the greatest challenges facing humanity. Every day there are news stories about temperature peaks, droughts or even floods caused by climate change. Climate change affects all our lives in different ways and to different degrees. Accordingly, it is also essential to look at how we are influencing climate change and the factors that cause it. Data and various calculations and estimates play an essential role in mapping these. Without data, there are no calculations; without calculations, there is no point in discussing effects.

In this article, we try to estimate the environmental impact of a previous asset purchase programme of the Magyar Nemzeti Bank, the Mortgage bond purchase programme, using a model-based calculation. This paper was inspired by the MNB's Climate-related Financial Disclosure, the TCFD report (MNB, 2022a). We started to address the issue in the context of this report. We believe that, despite the methodology and the estimation difficulties, it can be a useful input for the analysis of other assets or asset purchase programmes, and that is why we have written this article.

In the article, we first briefly review the, mostly technical, literature and the Mortgage bond purchase programme itself. We then present the methodology and the model's logic, assumptions and estimation results. Finally, we summarise our writing.

## 2. Literature, background

Renewing and financing the renewal of housing stock is a goal for many countries worldwide. Unsurprisingly, the built environment is a major contributor to emissions, accounting for almost half of the annual global $CO_2$ emissions. Of those total emissions, building operations are responsible for 27% annually.

In 2040 approximately two-thirds of the global building stock will be buildings that exist today, so without improvements, it will continue to burden the environment (Architecture2030, 2022).

Renewing the building stock is also a major challenge in Hungary, where the housing stock is outdated and has poor energy performance (Nagy, T. & Winkler, S., 2021). In this context, 40 per cent of the final energy consumption in Hungary is related to buildings (MNB, 2022b). In their comprehensive study on the Hungarian green bond market, Becsi et al. (2022) also highlight the high share of real estate in emissions and the need for modernisation in Europe and Hungary.

Due to the specific nature of the study, the available literature on the environmental impact of securities is very limited. Generally, we found that one direction of dual materiality, the financial materiality approach, appears in the literature. By dual materiality, we mean the concept that not only does climate change have an impact on companies (and other institutions), but they also have an impact on the climate, as shown in Figure 1:

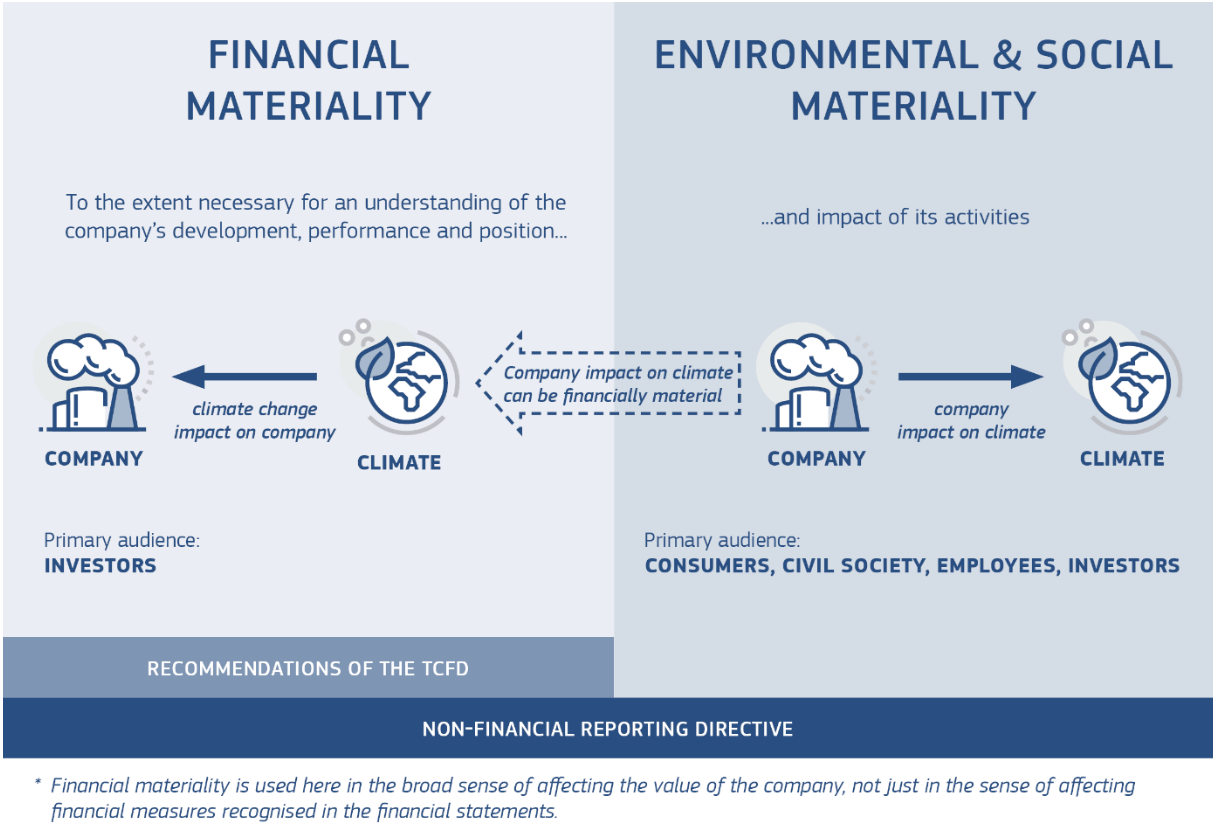


Figure 1. Double materiality

*(Source: European Commission, 2019)*

There is more literature on the former branch of dual materiality. Climate change's impact on companies and the prices and risks of securities and other financial instruments has been the subject of several studies, and the TCFD reports mentioned above typically follow this logic[1]. *Kolozsi et al. (2022)* conducted a comprehensive study on this topic, analysing TCFD reports from central banks and examining the measurement options and methodological challenges of climate risk regarding financial instruments.

[1] It is important to highlight that the TCFD (Task Force on Climate-Related Financial Disclosures) provides recommendations, so although the reports are similar in structure, they may differ in methodology and depth.

There is much less literature on the other direction of dual materiality, specifically on financial instruments' environmental impact. This and the unavailability of data led us to try a new methodology in this article. However, besides the lack of literature, it is also important to note that environmental impact reports already exist, which, although not considered literature, contain much useful technical information on green mortgage bonds. We also show examples of these for comparison when presenting our results.

## 3. Brief description of the MNB's Mortgage bond purchase programme

In 2018, the Magyar Nemzeti Bank entered the mortgage bond market as a buyer under a programme, and in 2020, to mitigate the negative economic impact of the coronavirus pandemic, it reintroduced its Mortgage bond purchase programme. These two phases of the programme successfully supported the objectives pursued: domestic mortgage bond issuance increased substantially, and the MNB helped banks to obtain long-term, stable forint funding. Under the programmes, the MNB purchased fixed-rate mortgage bonds denominated in forint from domestic mortgage banks and strongly emphasised participation conditions enhancing transparency.

In the programme's first phase, the MNB made purchases in the primary and secondary markets for HUF 381 billion in nominal value throughout 2018 and HUF 307 billion in nominal value in the second phase, from May 2020 to July 2021. In this article, we show how the environmental impact of mortgage bonds on the central bank's balance sheet can be estimated and the exposure of the MNB.[2]

Mortgage bonds are securities issued against a specific regulatory background. Following Hungarian law, at least 80 per cent of their collateral consists of so-called ordinary assets and the remainder of margin assets. An ordinary asset is a principal amount outstanding from mortgage loans and interest due under the contract [3]. These loans are backed by real estate as collateral, so the mortgage bond purchases indirectly finance the construction, purchase, modernisation and extension of real estate. However, the link between mortgage bond purchases and real estate is indirect, as the common collateral pool does not allow a clear link between the actual transactions financed by the mortgage bonds and the contribution of MNB purchases to these transactions. A further challenge is that, before the emergence of the MNB's green initiatives, banks typically did not collect data on the energy performance and environmental impact of the properties in connection with the real estate transactions, so this data was not available for us. Overall, data scarcity and limited data availability strongly determine the methodology that can be used to estimate the environmental impact of mortgage bond purchases.

## 4. Description of the methodology (model)

The ultimate aim of the model is to estimate how much $CO_2$ emission reductions could result from the non-green phases of the MNB's Mortgage bond purchase programme. We try to illustrate this by looking at the change in the composition of the Hungarian housing stock, linking it to total mortgage lending and the MNB's purchases of mortgage bonds.

The model is based on the National Building Energy Performance Strategy published in 2015 (*Ministry of National Development, 2015*). The document presents, among other things, the composition of the Hungarian housing stock in 2013, broken down into 15 types of residential buildings, and also includes the total floor area ($m^2$) and specific energy consumption ($kWh/m^2/year$). We previously explored other data sources, but this was the only one we found sufficiently reliable and appropriate. We used the following table in our model:

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[2] A new phase of the Programme was later launched, the Green Mortgage Bond Purchase Programme. This programme already introduced reporting requirements, which would allow participating banks to provide their own, presumably more accurate, estimates of the environmental impact of their mortgage bonds. However, the incentive effect of the Green Mortgage Bond Purchase Programme will come later than the period under review, so this phase of the programme was not taken into account.

[3] See more details: Act XXX of 1997 on Mortgage Loan Companies and Mortgage Bonds – https://net.jogtar.hu/jogszabaly?docid=99700030.tv

| | Building type | Total floor area ($m^2$) | Specific primary energy consumption ($kWh/m^2a$) | Calculated annual energy consumption (kWh) |
|---|---|---|---|---|
| 1. | **family houses below 80 m² before 1945** | 15,918,873 | 551 | 8,771,299,023 |
| 2. | **family houses above 80 m² before 1945** | 29,610,378 | 408 | 12,081,034,224 |
| 3. | **the family house below 80 m² 1946–1980** | 25,746,455 | 517 | 13,310,917,235 |
| 4. | **the family house above 80 m² 1946–1980** | 83,997,263 | 405 | 34,018,891,515 |
| 5. | **family houses 1981–1990** | 39,914,396 | 336 | 13,411,237,056 |
| 6. | **family houses 1991–2000** | 23,667,465 | 227 | 5,372,514,555 |
| 7. | **family or terraced houses (1 to 3 apartments) after 2001** | 24,466,147 | 173 | 4,232,643,431 |
| 8. | **multi-apartment buildings (4 to 9 apartments) before 2000** | 17,471,243 | 312 | 5,451,027,816 |
| 9. | **multi-apartment buildings (4 to 9 apartments) after 2001** | 2,929,898 | 125 | 366,237,250 |
| 10. | **multi-apartment buildings (10 or more apartments) before 1945** | 14,066,410 | 344 | 4,838,845,040 |
| 11. | **multi-apartment buildings (10 or more apartments) 1946–2000** | 10,260,214 | 299 | 3,067,803,986 |
| 12. | **multi-apartment buildings (10 or more apartments)** | 11,346,937 | 244 | 2,768,652,628 |
| 13. | **multi-apartment buildings (10 or more apartments) 1946–1980** | 16,174,606 | 218 | 3,526,064,108 |
| 14. | **multi-apartment buildings (10 or more apartments) after 1981** | 9,877,417 | 200 | 1,975,483,400 |
| 15. | **multi-apartment buildings (10 or more apartments) after 2001** | 11,392,046 | 100 | 1,139,204,600 |
| **Total** | | **336 839 748** | **339** | **114,331,855,867** |

Table 1. Building types with total floor area and energy consumption

*(Source: Ministry of National Development, 2015)*

In our model, we have assumed that mortgage-financed housing construction, new housing purchases and renovations are likely to improve (reduce) the environmental burden of energy use in the building stock through changes in the composition of the housing stock. It is important to emphasise here that we do not estimate the environmental effect of construction in our model, but only the impacts of compositional change due to the operation of the building, mainly related to energy use.

The "Bilan-Carbon" carbon footprint calculation method was used to calculate the initial environmental burden, which is compatible with existing standards (ISO 14064) and the GHG Protocol[4]. To this methodology, using the emission factors from the Clim'Foot database, so-called estimated average emission factors (tonne/kWh) were determined for different building types. To determine this, we estimated the average factors for each building type in terms of the proportion of energy used annually for lighting and heating/cooling (20–80 per cent). Based on the emission factors thus determined, an aggregate $CO_2$ emission

[4] The Bilan Carbone method was developed by the French ABC and ADEME, and it is based on the Base Carbone database, a publicly available emission factor database. The GHG Protocol and the ISO standard provide the framework for calculating the carbon footprint, while the specific emission factors are provided by databases compiled by research institutes.

was calculated for this baseline period of 2013.[5] In 2017, Hungarian emission factors were developed for the Bilan Carbone method under the LIFE Clim'Foot programme.

Aggregate $CO_2$ emissions were also calculated using another method. As a tool for this, the "emission factor" value of each building type – energy rating pair was taken from the European (including Hungarian) residential property emission database of the Partnership for Carbon Accounting Financials. The results were lower baseline $CO_2$ emissions in 2013, resulting in lower $CO_2$ emission savings associated with the assumed modernisation of the building stock. Considering that the most reliable information in the baseline database is the m2 data for the dwelling types, it is preferable to use emission factors (tonne/$m^2$) from this database to obtain results that best approximate reality. We could work with this methodology from February 2022, when the Partnership for Carbon Accounting Financials database became available.

In the next step, we used the model to try and reproduce how this initial state might have changed due to mortgage lending over eight years until the end of the period in 2021. For this purpose, we used the Hungarian Central Statistical Office's data table on mortgage lending for housing purposes[6], which distinguishes seven lending purposes: construction, new home purchase, modernisation/extension, purchase of a second-hand home, swing loan, loan conversion and other purposes.

In line with the modernisation of the housing stock, the stock of construction, new home purchase and modernisation/extension loans are fully considered in our model, as these are sure to finance more energy efficient and, therefore, "greener" properties due to increasingly stringent building regulations and energy requirements over the years.

In the case of loans for the purchase of a second-hand home, under the assumption that the buyer is likely to move into or rent out the property after some renovation, and thus energy efficiency improvements are also made, we also include some of these transactions (at rates of 5, 10, 15, 20 and 25 per cent) (see later). Swing loans, loan conversion and other loans were excluded.[7]

Based on the above, the number of loans available to make the composition of the building stock more favourable from energy-efficiency and, therefore, environmental point of view. In addition, to estimate the change in composition, we used the annual price per square metre statistics of new dwellings (HUF/$m^2$) published by the Hungarian Central Statistical Office for residential properties.

This was calculated annually and then summed over the period to determine how many square metres of the more modern property could be built or modernised with a given amount of mortgage loans. A very important feature and simplification of the model is that the total floor area of the building stock is kept unchanged. As the floor area of the more modern buildings was added, the floor area of all types was reduced proportionately, so the total square metres of the housing stock remained the same. Only the composition of the stock changed, becoming more modern. This gives us an essentially fictitious housing stock composition for the period under consideration, and we calculate an aggregate $CO_2$ emission for this condition.

As a last step, the difference between the $CO_2$ emissions in the current period (2021) and the baseline period (2013) is used to obtain the annual $CO_2$ emission reduction due to the modernisation of the housing stock thanks to mortgage lending.

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[5] Databases containing carbon footprint calculation emission factors: Base Carbone - https://bilans-ges.ademe.fr/en/accueil/contenu/index/page/bc_introduction/siGras/0, GHG Protocol - https://ghgprotocol.org/life-cycle-databases, EcoInvent Database - https://ecoinvent.org/the-ecoinvent-database/

[6] 18.1.1.16. Housing loans - https://www.ksh.hu/stadat_files/lak/hu/lak0016.html

[7] In the case of swing loans, no property modernisation can be expected, and the inclusion of loan conversions would result in duplication. Other loans (e.g. general purpose mortgage loans) are generally not for housing modernisation purposes, as the terms are less favourable than for housing loans.

A certain part of mortgage lending was financed by the MNB's Mortgage bond purchase programme, so in our model, based on a simple assumption, the MNB also contributes to the reduction of $CO_2$ emissions in the proportion of the amount of mortgage lending financed by its mortgage bond purchases and the amount of all mortgage loans in HUF.

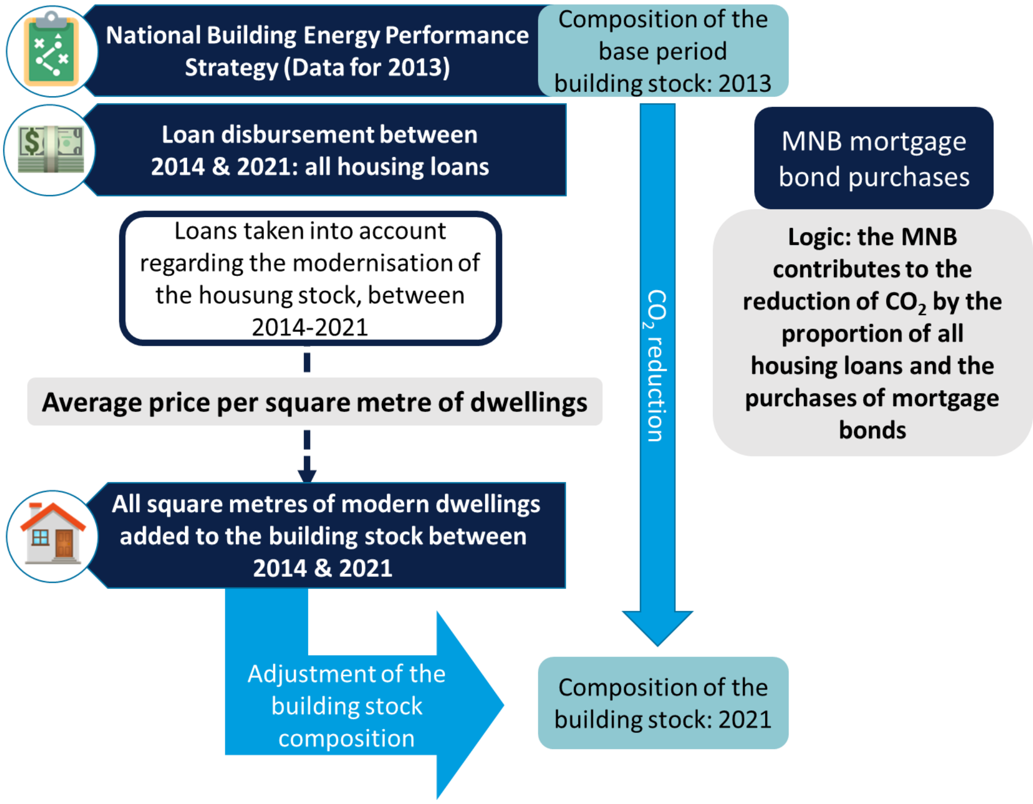


Figure 2. Presentation of the logic of the model

*(Source: own edit)*

## 5. Assumptions and estimation difficulties in the model

Regarding the methodology and the model, it is important to point out that several simplifying assumptions have been made. One of the key simplifications is that our calculations assume that the total area of the total housing stock does not change. This is a necessary simplification for the model, based on the assumption that the number of occupied properties where actual energy use takes place does not increase in the case of stagnating or decreasing population. In addition, the time elapsed between the disbursement of the loan and the construction of the property may also be a factor of uncertainty, but we do not believe this introduces a significant bias.

In addition, there are parameters to the assumption to which the model and its results are sensitive. As mentioned above, our calculations considered the number of mortgage loans used to purchase second-hand dwellings at a rate of between 5 per cent and 25 per cent for the improvement and modernisation of the composition of the housing stock. Another important factor is the energy efficiency of the "modern" square metres in the stock. We used values between 100 and 120 kWh/m$^2$/year in our calculations based on information from the Hungarian Central Statistical Office.

In addition, we explore several possibilities for the distortion caused by the collateral behind mortgage bonds. As described earlier, the underlying collateral for mortgage bonds must be ordinary assets (mortgage loans) of at least 80 per cent, but the proportion of ordinary assets is typically higher (varying by mortgage bond). The full possible range of 80 to 100 per cent was examined in this case. Furthermore, within ordinary assets, loans are secured by residential and commercial real estate. Nevertheless, the collateral for loans is typically residential property, in 98–99 per cent, so we do not include this in our analysis. Finally, it is very important to point out that the theoretical $CO_2$ emissions of the housing stock presented in the above model may differ significantly from the actual emissions because the building stock includes vacant properties and properties that are only used temporarily (holiday homes). In our model, therefore, we do not attempt to calculate accurate $CO_2$ emissions from actual energy consumption data based on the baseline (2013) or the current period (2021) composition of the building stock but to estimate the environmental burden reduction associated with the modernisation of the housing stock based on mortgage loan disbursement data for the period.

## 6. Presentation of the results

Based on our calculations, annual emission avoidance of between 13 and 41 thousand tonnes is estimated to result from the MNB's Mortgage bond purchase programme by modernising the housing stock. It can be seen that there is considerable uncertainty in the estimate, covering a relatively wide range, due to the assumptions and different scenarios tested.

By comparison, the actual $CO_2$ emissions from the cooling/heating of households in Hungary averaged around 15 million tonnes per year in the period under review. In comparison, the average annual $CO_2$ emissions from the operational activities of the Magyar Nemzeti Bank were around 6 thousand tonnes. Thus, according to the model, the MNB's Mortgage bond purchase programme can save Hungary approximately 2–7 times the MNB's annual carbon footprint on an annual basis due to the effect of the housing stock modernisation.

We want to organise and interpret the results. The best way to do this is to compare with impact reports. The impact reports show the environmental impact of the resources invested in green projects. The impacts are compared to an alternative scenario (in this aspect, they are similar to the model), which aims to show the positive environmental change that can be achieved by implementing the green project. In the case of mortgage bonds, this typically means the emissions saved through making the property more energy efficient.

Our results are compared with the impact reports of green mortgage bonds previously issued in Western Europe.[8] These are the basis for the comparison: each tonne of $CO_2$ emission avoided is calculated per year per million euros[9]. This is illustrated in the figure below, where light blue represents our estimated range of the MNB's contribution to emission avoidance:

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[8] The green mortgage bonds of these financial institutions have similar characteristics to Hungarian mortgage bonds (except for their green character), which is why they were chosen as a basis for comparison and because impact reports are available for these few institutions.

[9] Using ECB exchange rate data: https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/index.en.html

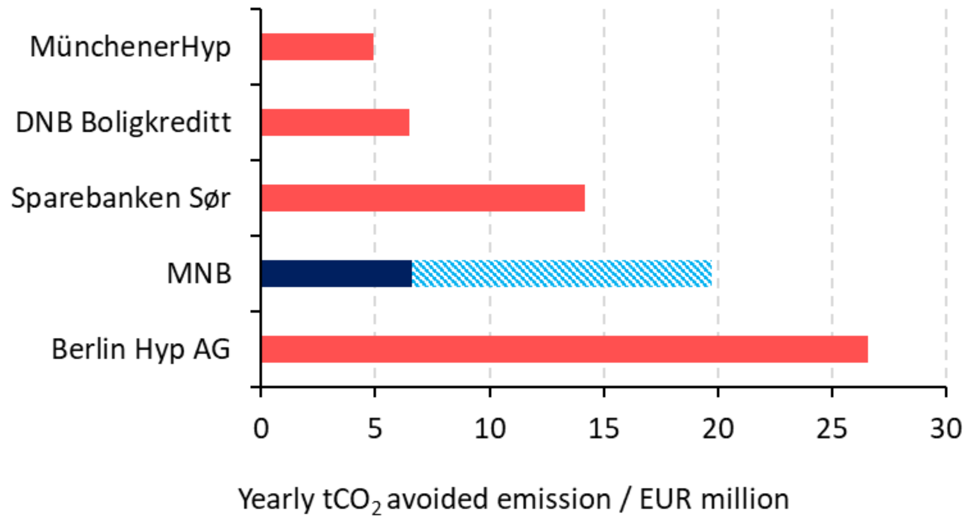


Figure 3: $CO_2$ emissions avoided per 1 million euro in tonnes per year for certain green bonds and the MNB's programme*

*Source: MünchenerHyp[10], DNB[11], Sparebanken Sør[12], Berlin Hyp AG[13], MNB*

*Note: The value reported regarding the MNB's programme is calculated using a different, specific estimation methodology and several uncertainty factors, so its comparison with the presented green mortgage bonds should be treated cautiously.

It can be seen that the MNB programme achieves a relatively high overall reduction in emissions per million euros. This may be partly because the Hungarian real estate stock is starting from a more outdated situation. Moreover, Hungarian real estate is relatively cheaper. Thus the amount of money invested may result in a larger reduction in emissions. It is also important to underline that different institutions may have different loan targets and property types behind their mortgage loans, with different criteria, which also affect the presented results. Finally, we would like to draw attention again to the model's uncertainties and assumptions. The comparison is an attempt to estimate the scale of the results of the MNB programme.

## 7. Summary

In our article, we attempted to estimate the environmental impact of the Magyar Nemzeti Bank's Mortgage bond purchase programme. After a brief introduction, we have attempted to review the relatively limited relevant literature available on the environmental impact of securities. We then presented the MNB Mortgage bond purchase programme, which was the subject of our analysis, and aimed to estimate its environmental impact. Our methodology was based on the changes in the composition of the Hungarian housing stock, and the main assumption was that, while maintaining the floor area of the housing stock unchanged, the financing of housing would have a modernisation effect due to the tightening building energy requirements and the renewal of the housing stock, which will lead to a reduction in emissions. In the methodological section, we presented our sources alongside the logic of our model. The assumptions and simplifications used in our calculations were then explained. These factors can significantly impact the results, so the estimations can only be evaluated under these assumptions and simplifications. Thanks to the MNB's Mortgage bond purchase programme, we estimate that the Hungarian building stock can reduce its $CO_2$ emissions by 13-41 thousand tonnes per year.

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[10] https://www.muenchenerhyp.de/sites/default/files/downloads/2021-05/mhyp_Impact_Reporting_2020_en_02.pdf
[11] https://www.ir.dnb.no/sites/default/files/3Q19%20Green%20Covered%20Bond%20Impact%20Report.pdf
[12] https://www.sor.no/globalassets/organisasjon/2020-green-impact-report.pdf
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# Application of specific tools of the Theory of Constraints – a case study

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**Abstract**

The Theory of Constraints is a management tool for continuously improving corporate performance. In the USA, it has been very successful, above all due to the contribution of a comprehensive assessment of the issues of managerial control. Its development has also been taking place in the Czech Republic. This paper aims to present the Theory of Constraints tools and then apply some of them to a specific enterprise in logistics activities. The findings in terms of detecting and widening the bottleneck afterwards should exert a positive impact on corporate performance. Current Reality Tree, Conflict Diagram and Future Reality Tree are applied in the paper to eliminate undesirable effects that prevent the enterprise from increasing its performance. Besides providing this specific enterprise with concrete solutions to identified issues, this study aims at depicting the procedure for implementing the methods of the Theory of Constraints, including specific results and benefits of the suggested solutions, along with the quantification of their costs, savings and throughput.

**Keywords**

Theory of Constraints, Current Reality Tree, Future Reality Tree, Conflict Diagram, streamlining, undesirable effects, desirable effects

## 1. Introduction

The benefit of the Theory of Constraints is a new perspective on enterprise management. Companies are established to generate profit, which is precisely what the Theory of Constraints is oriented towards, both from the point of view of the present and the future. Indicators other than profit are not considered significant within the Theory of Constraints, which focuses on a measurable enterprise indicator: the throughput. Revenue from the sale of a product or service, from which the invested funds are deducted, is considered a throughput. In the Theory of Constraints sphere, it makes no sense for an enterprise to perform activities that do not increase throughput.

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It is essential to understand the Theory of Constraints in today's business environment, which is characterised by intense competition and unstable conditions, both on the part of potential customers and suppliers and often even employees. A strong competitive environment encourages enterprises to improve continuously, directly related to a prompt response to market changes and prompt decision-making. A fundamental prerequisite for the success of an enterprise is its ability to adapt to changing market conditions. Top-quality management is undoubtedly essential for bringing an enterprise to its success. Ensuring the prosperity of an enterprise is a task that requires more and more effort, thorough analysis, planning, solving problems that have already arisen, and preventing problems. Enterprises can influence their success in the market by looking actively for the weaknesses that do not allow them to achieve higher productivity.

The founder of the entire concept of the Theory of Constraints (TOC) is *Eliyahu Moshe Goldratt (1990)*. He continues to develop the Theory of Constraints in cooperation with his colleagues and presents new findings in several successful books *(Goldratt, Cox, 1992), (Goldratt, Cox, 2016)*. Consulting companies also help enterprises apply the TOC tools in practice. Such an institute has also been operating in the Czech Republic since 1999. The basis of the TOC is a systemic analysis of an enterprise. An *enterprise* is understood as a complex of connected, interdependent processes. The purpose is to find a constraining element that does not allow higher system performance. TOC resolves the problem of limited system performance by finding a bottleneck and then expanding it. A correct solution to the key problem will ensure an increase in the performance of a given system. When a fundamental problem is eliminated, another bottleneck, a new system constraint, must be expanded to increase enterprise performance. Thus the improvement procedure based on TOC is a never-ending process.

This paper aims to present the Theory of Constraints tools and then apply some of them to a specific enterprise in logistics activities. The findings in terms of detecting and widening the bottleneck afterwards should exert a positive impact on corporate performance.

## 2. Literature review

This review mainly focuses on scientific articles that use individual techniques of the Theory of Constraints in the context of transport and logistics. *Simatupang et al. (2004)* deal with cooperation in a supply chain and discusses the benefits of cooperation in meeting customers' needs and applying the TOC approach in overcoming problems that may arise with cooperating parties in the supply chain. Meanwhile, *Gupta and Boyd (2008)* discuss that the Theory of Constraints can serve as a general theory in operations management. The paper first examines the links between TOC and core concepts/components of operations management and shows how the concepts can be integrated into TOC using examples from the published TOC literature. *Mabin and Balderston (2003)* present TOC as a multifaceted system methodology, offering breakthrough solutions, including their implementation, focusing on documented successful applications of TOC. *Kim et al. (2008)* provide an overview of TOC development from the point of view of the theory of knowledge, whereby they focus on thinking processes and analysing the nature of these processes. *Puche et al. (2016)* combine the application of Beer's Viable System Model (VSM; *Espejo, Harnden, 1989*) and Goldratt's Theory of Constraints (TOC). VSM defines the system structure of a supply chain and organises collaboration, while TOC implements system behaviour, i.e., integrates processes and defines performance measures. *Chronéer and Mirijamdotter (2009)* examine how supply chain management and the Viable System Model (VSM) can support and create effective use of information in product development and thus identify critical links in a supply chain. *Anderluh et al. (2020)* apply a model for the location selection of a midi-hub of a medium city centre in Vienna using an AHP (Analytic Hierarchy Process)-based decision-making support tool. For their research, it was also necessary to investigate the economic standpoint of the suggestions, which is documented by *Hlatká et al. (2017)*. This research implements the exact method in a specific manufacturing enterprise to optimise the distribution route and reduce operational transport costs. Like the previous ones, the study by Kauf et al. (2018) deals with a possible scenario for the desired supplier selection, but in this case, using the Analytical Hierarchy Process. *Hlatká et al. (2017)* apply a specific model for solving supplier shipment routing problems using one of the most widely used heuristic methods that solve vehicle routing tasks, namely the Clarke–Wright-algorithm. The European Journal of Social Sciences published by *Dinçer (2011)* focuses on the application of the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and WSA (Weighting Sum Approach) methods in terms of a multicriteria decision analysis of economic activity for the EU states and candidate countries evaluated by these two techniques. In this perspective, a system managed through decision-

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making is analysed by *Adetunji et al. (2018)*, where the authors introduce the criteria of an expert opinion into the methodology of managing system obsolescence using decision-making based on multiple criteria, precisely the TOPSIS method and the Monte Carlo simulation. The specific case study, carried out as part of their research work, was developed with the participation of military and civilian experts.

## 3. Methodology

### 3.1. Making up the Current Reality Tree (CRT)

Delineation of the area of analysis – determination of the area of the enterprise for which the research and tool application will take place. It is important to collect relevant information and enough of it so that the analysis has relevant, informative value.

Creating a list of entities – after determining the area to which the CRT will be applied, the undesirable effects that create various problems when trying to achieve better performance will be diagnosed. We refer to these entities as Undesirable Effects – UDEs.

A diagram of causes and consequences is created in which UDEs are connected according to Sufficiency Logic. A linear connection, specifically a V-connection, is created with multiple effects from one cause. UDEs are added gradually to a tree until all entities are included. 'Legitimacy reservations (if any) are also assigned to the entities.

Identification of the critical problem – the arrow that connects cause and effect does not lead to the primary causes, as they are input moments; at these points, a determination is made of up to which percentage it is responsible for each Undesirable Effect. A key problem is identified as the problem that causes at least 80% of undesirable effects. If the key problem is not found, common causes of input moments are sought. Once the key problem is found, it is expressed using the Conflict Diagram, with which the problem can be solved (*Guoping et al., 2006; Hua et al., 2006*).

### 3.2. Conflict Diagram Creation

The key problem is labelled D', the opposite of which is D. The Evaporating Cloud marks the change from 'what to change' to 'what to change it to'. Situation D and D' is the conflict. They cannot coexist. The application of the so-called Injections solves this discrepancy. The purpose of injections is to find a solution that achieves the objective without requiring the existence of D' or making D' invalid. When creating ideas on how to solve the situation, the creator must be uncompromising concerning the set objective. Whether an injection has been implemented correctly can be verified by checking that the conflict between D' and D has disappeared or that the simultaneous coexistence of these entities is possible (*Huang et al., 2012*).

### 3.3. Future Reality Tree (FRT)

The purpose of this diagram is to display the future situation of an enterprise and to check whether the injections have been implemented correctly, whether they have been sufficient and whether other undesirable effects have occurred. Some entities may appear, while others may disappear. The realisation of the Future Reality Tree consists of creating a basis for the tree, describing relationships using a sufficient cause and improving the quality of the tree (*Lowalekar and Rawi, 2017*)

## 4. Case study

The basis for creating the Current Reality Tree is to determine the analysis area, create a list of entities, and identify undesirable states. After these steps, the CRT can be processed.

Delineation of the area of analysis –where a survey and the application of the Theory of Constraints tools will take place is the area of textile waste collection. The survey will include routes, employees, owner access, collection points, textile handling, working hours, storage methods, loading and unloading to a replaceable truck body, and all the activities and conditions that affect the textile waste collection area.

Creating a list of entities –to create a list of entities, the enterprise owner, the logistics manager and also the employees and drivers, in this case, were interviewed. First of all, the issue of what problems the owner registers in textile waste collection, what leads to frequent turnover of employees, was analysed. Undesirable effects, by which weaknesses and problems in the company are detected, will be referred to as UDEs. The author asked about the causes of the identified problems, what their consequences are, and what the connections there are between them (*Mahto and Kumar, 2008; Sarkar et al., 2021*)

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Identified undesirable conditions (UDEs):

(1) **C**omplaints are made if the textile is damaged by moisture or is delivered contaminated to the contractual partner. In this case, the contractual partner will not pay for a part of the textile that is not in the required condition.

(2) **Increasing costs of servicing trucks** – long driving distances make it necessary to service vehicles more frequently.

(3) **Employee turnover** – employees in driver positions often leave. It is difficult for the owner to find new employees who can manage physically demanding work in the long term because drivers are also responsible for loading textiles, so they also fulfil the function of assistant drivers.

(4) **Time-consuming loading into the truck body** is time-consuming, related to its physical demands and the lack of handling equipment.

(5) **Work performed poorly by employees** – the owner has experience with employees who have stolen textiles or insufficiently sorted wet and dirty textiles, which can lead to the deterioration of a significant part of textile waste.

(6) **Long driving distances to the cities where the collection takes place –** the routes are not optimised in any way, and a driver does not have an exact determination of where a route should lead. The number of kilometres travelled is high (*Malhotra and Khandelwal, 2022*).

Based on the identified undesirable conditions, a diagram of the Current Reality Tree was created using the mentioned procedure (Figure 1):

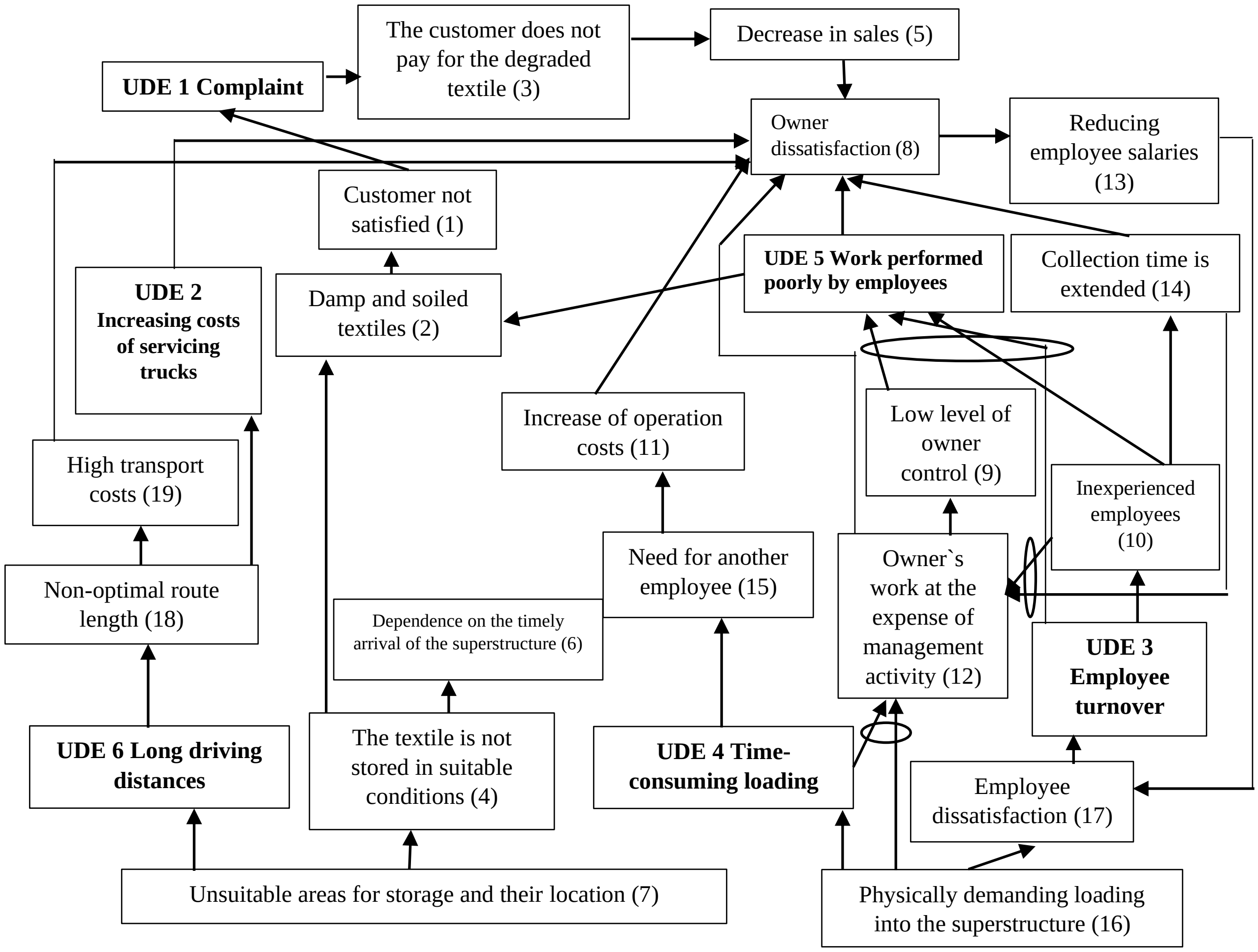


Figure 1: Current Reality Tree (CRT) diagram

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Identification of key problems

The procedure specified in the methodology has been used to identify any key problems. After the creation of the CRT, a check was made to see if there were any redundant branches in the tree, and all the inputs recorded in the diagram were marked. Two key problems were identified– unsuitable storage spaces and their location and physically demanding loading into the truck body. These problems cause the most undesirable effects.

The output of the Current Reality Tree is detailed in Table 1. The results arising from this diagram are summarised after that.

Table 1: Evaluation of the CRT

| No. | Cause | Consequence | Description of the situation |
|---|---|---|---|
| UDE 1 | 1 | 3 | If textile waste has deteriorated, the customer is unsatisfied and makes a complaint and does not pay for the deteriorated part. |
| 1 | 2 | UDE 1 | The customer reclaims dirtied and wet textiles. |
| 2 | 4 | 1 | When textiles are not stored in suitable conditions, they can get wet and dirty, leading to customer dissatisfaction. |
| 3 | UDE 1 | 5 | If a complaint is made, the customer will not pay for a part of the textiles that do not meet the quality the customer requires; therefore, the sales for the given month will decrease. |
| 4 | 7 | 2,6 | Textiles are not stored in suitable conditions since the enterprise's owner has not provided spaces corresponding to the requirements for storing textile waste. This fact results in dependence on the timely arrival of the truck. Otherwise, textiles are stored inappropriately, and their deterioration is risky. |
| 5 | 3 | 8 | The reason for the decrease in sales is that the customer does not pay for deteriorated textiles, which results in the owner's dissatisfaction. |
| UDE 5 | 9,10, UDE 3 | 8 | The employees do poorly work for several reasons; their frequent turnover means that the employees are inexperienced and make mistakes, and checking their work by the owner is low. |
| 6 | 4 | | As it is necessary to deliver textiles to the customer in the required condition and the storage spaces are not suitable, there is a specific dependence on the timely arrival of the truck. The existing warehouse cannot hold more than 1 ton of textile waste. |
| 7 | | 4, UDE6 | Due to inappropriate warehouses, textiles are stored in inappropriate conditions. |
| UDE 6 | 7 | 18 | Driving distances are long because the warehouse and the replaceable truck body are not located based on any logical determination; the warehouse and the truck body were located automatically in the city where the company is headquartered. It results in non-optimal routes. |
| 8 | 5, UDE 2, 11, 12, UDE 5,14 | 13 | As some employees do not complete their work, the owner has to help with collection or loading, which means that he often has to work overtime in order to be able to fulfil his managerial duties. Because of rising costs and work poorly done by his employees, he resorts to salary reductions. |
| 9 | 12 | UDE 5 | The owner does not have time to check the work of the employees, which is one of the reasons for poorly done work. |
| 10 | UDE 3 | 14, UDE 5 | The employees are inexperienced, do not know the routes well and cannot evaluate which textiles need to be dried before putting them in bags, the collection time is prolonged, and the work is done poorly. |
| 11 | 15 | 8 | Operating costs increase because loading onto the bodywork is time-consuming, and the driver often has to be assigned another worker to help him. These employees are then paid overtime. This fact causes the owner’s dissatisfaction. |
| UDE 4 | 16 | 12, 15 | Loading into the truck body is time-consuming, so additional employees or the owner must help. |
| 12 | UDE 4, 16, 14 | 8,9, 10 | The owner has to help with collections because loading is physically demanding and time-consuming, and the employees are inexperienced. These facts cause the owner’s dissatisfaction and the impossibility of carrying out checks, as he is swamped. If he helps with the collection, he has to catch up with his managerial duties in the following days. |
| 13 | 8 | 17 | Employees’ payments are reduced because the owner is dissatisfied with their work, which simultaneously leads to employee dissatisfaction. |
| 14 | 10 | 8 | As the employees are inexperienced, the collection time is prolonged, and the owner is dissatisfied. |
| 15 | UDE 4 11 | | An additional employee during loading is needed if loading is time-consuming, which results in increased operating costs. |
| 16 | | UDE 4, 12, 17 | Loading into the truck body is physically demanding, as the employees do not have any handling equipment. The consequences of physically demanding loading into the truck body result in tired and dissatisfied employees. The owner often has to be involved in helping out, and the physical demands also cause the loading into the truck body to be prolonged. |
| 17 | 13,16 | UDE 3 | The employees are dissatisfied due to salary reductions and physically demanding work, leading to a turnover. |

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Table 1: Evaluation of the CRT (continued)

| No. | Cause | Consequence | Description of the situation |
|---|---|---|---|
| UDE 2 | 19 | 8 | Vehicle servicing costs are increasing because the routes are not determined rationally; therefore, the number of kilometres driven is high. The enterprise is small, so it uses no software to optimise the routes. The drivers drive at their discretion. Increasing costs lead to the owner's dissatisfaction. |
| 18 | UDE 6 | UDE 2, 19 | Long driving distances are the cause of sub-optimal route length, which results in increasing vehicle servicing and transport costs. Since the employees do not have an exact procedure for the collection (in which city they should start and where they should end) and the enterprise does not use any software, the length of the routes is not determined frugally. |
| 19 | 18 | 8 | As the routes are not determined frugally, there are unnecessary transport costs, resulting in the owner's dissatisfaction with the current state. |

**Conflict Diagram (Evaporating Cloud)**

The solution of the key problems will be determined using the Conflict Diagram, based on which injections will be designed and implemented (*Richnák, 2022*).

**Injection 1 – Unsuitable spaces for storage and their location**

The key problem of an unsuitable warehouse lies in its insufficient capacity. The warehouse now only holds three tons of textile waste. The problem arises when the truck body is replaced a week later. At that moment, approximately 9.6 tons of textile waste need to be stored until the truck body arrives. This delay happens relatively often, and there is no place to store textile waste afterwards. Figure 2 presents the solution through the Conflict Diagram.

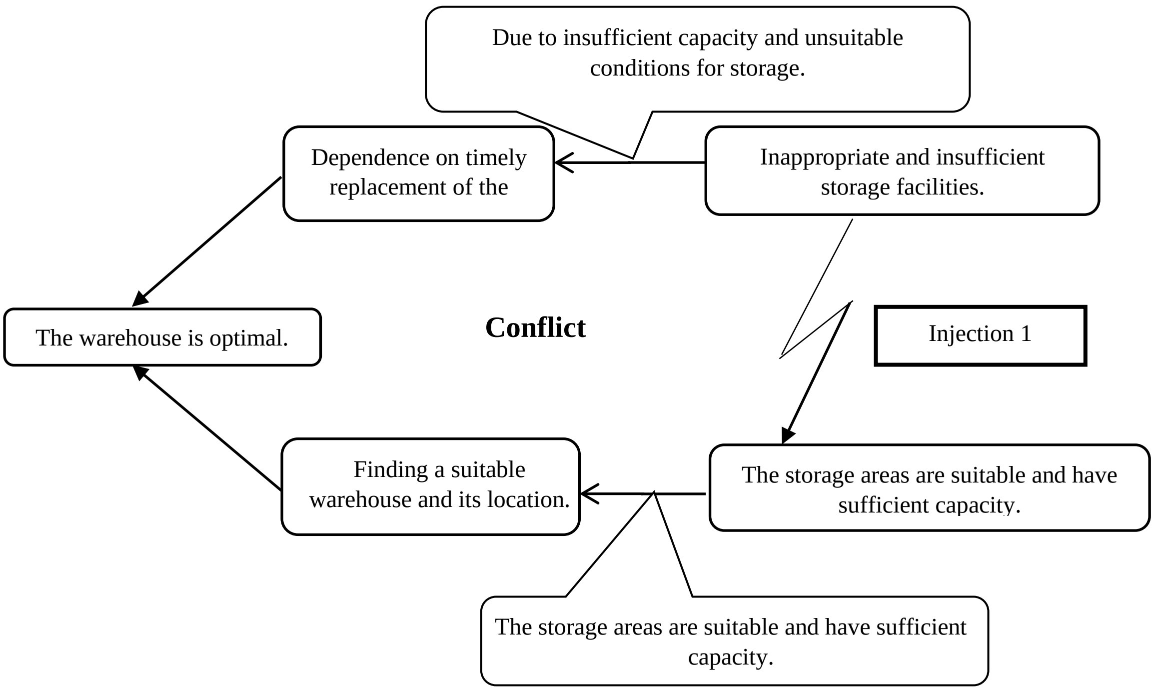


Figure 2: Injection 1

The problem will be solved by renting a new warehouse, the capacity of which will correspond to the amount of textile waste. The minimum amount of textiles that need to be stored in the event of delayed arrival of a new truck body is 9.6 tons – it would be advisable to find a warehouse where the capacity reserve would be at least half a ton. In order to make maximum

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use of this constraint, in addition to finding a new place for the warehouse in terms of space, a place will also be searched for in terms of a rational location about the cities in which the collection takes place and the driving distances to these cities. For this purpose, the centre-of-gravity method will be used. Afterwards, routes to the new warehouse will be determined, where the replaceable truck body will be driven.

**Injection 2 – Loading into the truck body is physically demanding and time-consuming**

Physical demands result in employee turnover and are related directly to the time required for loading. There is a problem with the lack of handling equipment that would make the work easier. The following injection in Figure 3 describes how to eliminate the key problem (Šimek et al., 2021).

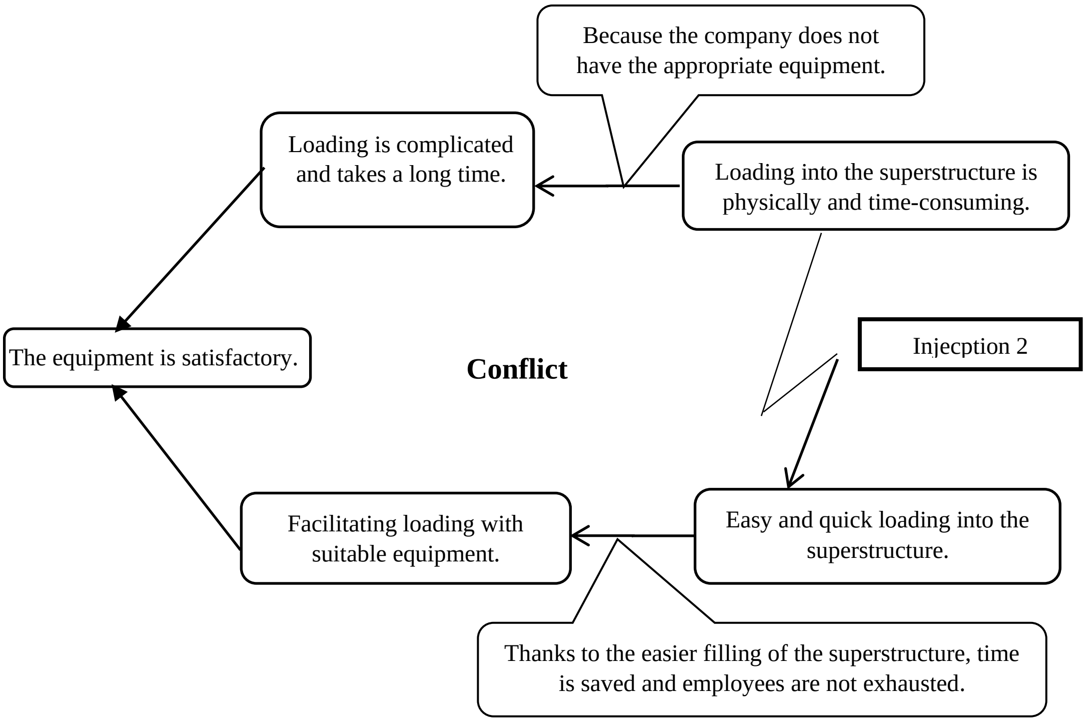


Figure 3: Injection 2 (source: authors)

The solution to eliminating the problem of physically demanding loading is to purchase a belt conveyor. A belt conveyor makes work easier for the employees and reduces the time spent on handling bags of textiles. Implementing Injection 2 will increase performance, although an investment in a belt conveyor will be required.

**Summary of injections**

Breaking down TOC and the methods used to make changes, TOC is based on two types of logical thinking. According to this logic, the key problem of unsuitable storage space must be solved so that the new space is sufficient in terms of space and conditions for storing textile waste and, at the same time, is optimally located. A necessary condition for removing restrictions is to ensure a warehouse with optimal parameters and is rationally located. It is necessary to think not only about the warehouse space but also about its location. The problem of physically demanding loading into the truck body can be characterised by insufficient handling equipment, i.e. insufficient resources. In order to facilitate and speed up the employees' work, it would be advisable, in consultation with the enterprise's owner, to purchase a belt conveyor for transporting bags of textiles to the replaceable truck body. Whether all the problems have been removed will be checked by the Future Reality Tree (*Skrúcaný et al., 2021; Poliak et al., 2022*).

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**The output of implementing Injection 1**

The implementation of Injection 1 solved several problems. The main problem was the insufficient warehouse and its inappropriate location. Using the centre-of-gravity method, it was determined that the town of Týn nad Vltavou is a logical place for the location of the warehouse. In connection with this change, new routes have been laid out. The total distance driven has been shortened by 111 km per week. Resolving undesirable effects through this change will be entered into the Future Reality Tree (FRT) (*Kubanova et al., 2022; Baric and Zeljko, 2021*).

**Injection 2 – Suggestion of a belt conveyor for loading into the replaceable truck body**

In order to load bags of textile waste into the replaceable truck body to facilitate the work, an inclined belt conveyor with a traction element is needed. The weight of a bag is 20 to 30 kilograms, and the maximum dimensions of the bags used are 700 × 1100 mm. The upper edge of the replaceable truck body is 4.85 cm high. 85 cm are the legs on which the truck body is placed. The required length of the belt conveyor is 6 meters – based on consultation with a specialised company. The width of the conveyor, according to the dimensions of the bags, must be at least 80 cm. A suitable conveyor is an inclined belt conveyor that can be permanently located in outdoor conditions. The price of such a conveyor is around 150,000 CZK. The best and most comfortable variants of belt conveyors for the needs of the enterprise cost around half a million CZK. The purchase prices of new belt conveyors are significantly higher than second-hand ones. The price of second-hand belt conveyors that meet the enterprise's needs is around 40,000 CZK.

The average weight of a bag of textiles is 25 kilograms. The quantity of bags that are transported on individual routes is recorded in the following Table 2.

Table 2: Time required for loading into the truck body with a belt conveyor

| | Number of bags | Time to transport bags by belt conveyor to the truck body | Time to arrange bags in truck body | Total time for loading bags into one truck body |
|---|---|---|---|---|
| Route 1 | 136 | 34 min. | 45 min. | 1 hour 19 min. |
| Route 2 | 126 | 31.5 min. | 42 min. | 1 hour 13.5 min. |
| Route 3 | 123 | 31 min. | 41 min. | 1 hour 12 min. |
| Total | 392 | 1 hour 36.5 min. | 131 min. | 3 hour 44.5 min. |

The time to load the bags of textile waste into the replaceable truck body was measured and recorded on each route. A specialised company recommended a belt conveyor with a speed of 1 meter in 3 seconds, and the driver could load about four bags on it per minute. The method of loading bags in the truck body is specific, and the bags must be trampled in. After every 30 bags, the belt conveyor should stop, and the bags should be levelled and trampled in. A worked manages to do this operation in 10 minutes. A comparison of the original time spent loading into the truck body with the time when using a belt conveyor is shown for individual routes in the following Table 2. The comparison is made with data for newly designed routes with a new location of the warehouse, i.e. with data from Table 3:

Table 3: Time savings using a belt conveyor

| | Loading time into the truck body | | |
|---|---|---|---|
| | Without belt conveyor | With belt conveyor | Savings |
| Route 1 | 2 hours 33 min. | 1 hour 19 min. | 1 hour 14 min. |
| Route 2 | 2 hours 22 min. | 1 hour 14 min. | 1 hour 8 min. |
| Route 3 | 2 hours 19 min. | 1 hour 12 min. | 1 hour 7 min. |
| Total | 7 hours 14 min. | 3 hours 45 min. | 3 hours 29 min. |

Source: own creation

With a belt conveyor, there would be a significant reduction in the time required for loading. More than an hour would be saved on collection day.

**The output of implementing Injection 2**

The second key problem was insufficient handling equipment for loading into the truck body. In the current situation, drivers have to load the entire volume of textiles manually, which is demanding both physically and in terms of time. This

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problem can be solved with suitable handling equipment. A belt conveyor would make work easier and, at the same time, reduce loading time. A reduction in employee turnover is expected, as most employees justify leaving their job positions due to physical demands and length of working hours (*Salamakhina et al., 2021*).

**Evaluating the Future Reality Tree (FRT) diagram**

In order to show the condition after the implementation of the injections and also to check whether the injections have solved the given problems found in the Current Reality Tree, the Future Reality Tree was created (Figure 4):

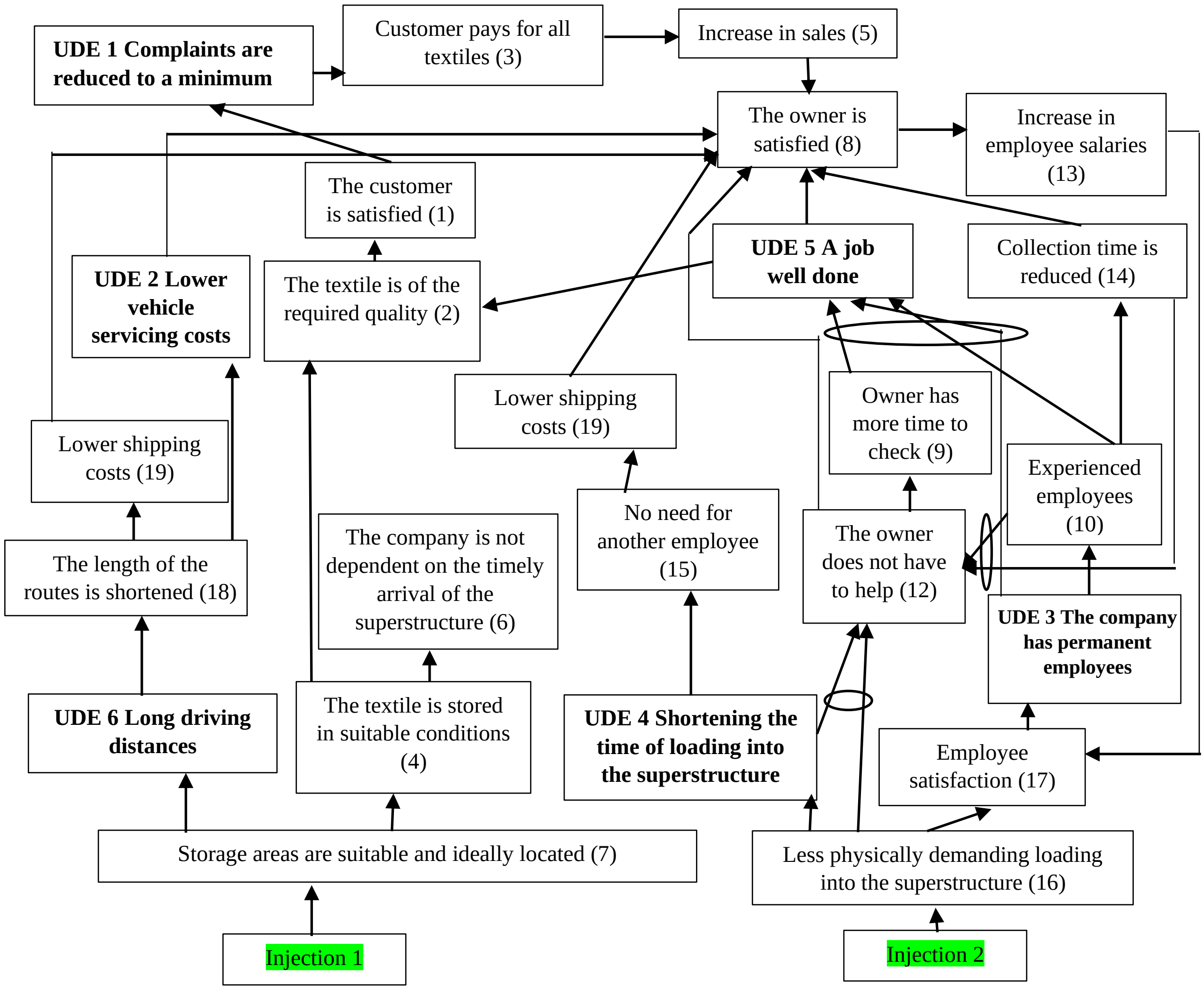


Figure 4: FRT

The Future Reality Tree expresses the desired condition, the condition after the implementation of the injections.

Desirable effects (DEs): 1 Complaint are reduced to a minimum. 2 Lower vehicle servicing costs. 3 Reduced employee turnover. 4 The time required for loading into the truck body is reduced. 5 The employees will do their work well, and the damage caused by them is minimal. 6 The driving distances to collection cities are shortened (*Klapita, 2022*).

**Evaluation of the FRT**

**Injection 1** has solved the key problem of the inappropriate warehouse, including its irrational location. This problem was followed by undesirable entities, of which there were 15. A suitable location for a new warehouse was determined using the centre-of-gravity method, and a warehouse in a specific town of Týn nad Vltavou was also suggested, including its size and the specific premises where the warehouse with the required parameters located.

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A new location for the warehouse was determined using the centre-of-gravity method, which directly related to streamlining the routes. Thus the continuity of the individual cities on the routes must be determined, leading to more efficient service for the given cities. The saving in kilometres stems primarily from the change in the location of the central warehouse.

**Injection 2** has been implemented to eliminate the problem of physically demanding the loading of textile waste into the replaceable truck body. The solution to this injection is the acquisition of a belt conveyor, which will significantly facilitate the work during loading, thereby eliminating a significant part of the undesirable effects. The course of the Future Reality Tree is detailed in the following Table 4:

Table 4: Course of the FRT

| No. | Cause | Consequence | Description of the situation |
|---|---|---|---|
| Injection 1 | | 7 | A new warehouse is rented at an ideal location. |
| Injection 2 | | 16 | A belt conveyor makes loading more straightforward and faster. |
| 1 | 2 | UDE 1 | The customer is satisfied because their requirements are met, |
| 2 | 4 | 1 | Textiles arrive at the contractual partner in the condition they require. |
| UDE 1 | 1 | 3 | Complaints are reduced. |
| 3 | UDE 1 | 5 | The contractual partner accepts the entire delivery of textile waste. |
| 4 | 7 | 2,6 | A sufficient and suitable warehouse relieves the enterprise of the problem of dependence on the timely arrival of the truck body, and the goods go to the customer in the required quality. |
| 5 | 3 | 8 | There is an increase in sales. |
| 6 | 4 | | The storage spaces allow the storage of all textiles if the truck body's replacement does not occur on the agreed day. |
| 7 | | UDE 6, 4 | The new warehouse location will shorten distances and improve textile storage conditions. |
| 8 | UDE 2, 5, UDE 5 11,12, 14, 19 | 13 | As costs are eliminated, and the employees work well, the owner is satisfied and willing to increase their salaries. |
| UDE 5 | UDE 3, 9, 10 | 8 | Work is done well. |
| 9 | 12 | UDE 5 | The owner has more time to check the employees' work. |
| UDE 3 | 17 | UDE5, 10 | Employee turnover is low. |
| 10 | UDE3 | UDE 5, 12, 14 | The employees are experienced. |
| 11 | | | Reduction of operating costs. |
| UDE 4 | 16 | 12, 15 | Loading time is reduced. |
| 12 | UDE 4, 16 | 8,9 | The owner does not have to help out for employees and has enough time to manage the enterprise. |
| 13 | 8 | 17 | Increasing the salary of the employees increases their satisfaction. |
| 14 | 10 | 8,12 | The collection time is reduced. |
| 15 | UDE 4 | 11 | The employee does not need to hire another assistant driver or pay overtime to another employee for help with loading. |
| 16 | | UDE 4, 12, 17 | Loading into the truck body is facilitated, loading time is reduced, the owner has more time to manage the enterprise, and the employees are more satisfied. |
| 17 | 16 | UDE 3 | The employees are satisfied because loading into the truck body is not so physically demanding. |
| UDE 6 | 7 | 18 | The route is shorter compared to the original condition. |
| 18 | UDE 6 | 19, UDE 2 | Thanks to the reduced number of kilometres driven, the transport costs and servicing of the vehicles are lower. |
| UDE 2 | 18 | 8 | Low vehicle service costs are a positive indicator, which leads to the owner's satisfaction. |
| 19 | 18 | 8 | Lower costs lead to an improvement in the enterprise's financial situation, which makes the owner satisfied. |

## 5. Conclusion

The objective of the paper was to analyse an enterprise's current situation in logistics activities to apply the tools of the Theory of Constraints to increase performance in the given area of business.

The success or failure of the enterprise is in the hands of the enterprise's management. The management's effort is to make the best possible use of the invested capital, for which various management tools can be used. Unlike other management methods, the Theory of Constraints focuses on the bottleneck, which is the limiting element of the enterprise's throughput. Such a point can be found in every enterprise because its existence means a particular limitation of performance, which would be infinite without the bottleneck.

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At first the Current Reality Tree was first created. It was used to identify key issues. These issues were analysed by applying the Conflict Diagram. Specific practical solutions were then suggested to eliminate and maximise the use of these problems. The centre-of-gravity method was used to solve the problems, after which the specific required warehouse size was designed for textile waste storage needs. Based on the new location of the warehouse, ideal routes to serve the cities were recommended. Another key problem was eliminated by suggesting a belt conveyor, which will facilitate the employees' work and reduce the loading time. Whether all the undesirable entities were solved or not was ascertained and confirmed by the Future Reality Tree, which presents the ideal state of the given system after implementing the required changes.

The following suggestions are the greatest benefit of applying specific tools of the Theory of Constraints for the enterprise.

- The new location of the warehouse brought mileage savings and helped significantly to increase the throughput.
- A new storage space, thanks to which the enterprise will not have complications associated with insufficient storage space in the event of a late arrival of an empty replaceable truck body, and the risk of textile deterioration will be eliminated, and the number of complaints will be reduced.
- The purchase of a belt conveyor will ensure an improvement in conditions for the employees, a reduction in the physical demands of loading into the replaceable truck body, and thus a reduction in employee turnover and inexpertly performed work is likely. Last but not least, this suggestion will reduce the time required for loading, leading to lower costs for employee overtime.

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# The economic effects of climate change on Budapest

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**Abstract**
Cities – the engines of the world economy – are on the front line of climate change. As a major city, Budapest is threatened by many of these risks, especially in connection with transport, the construction industry and improving the standard of living. The study investigates the possible challenges and policy solutions related to climate change in Budapest. By reviewing the experiences of the economic effects of climate change on big cities and their practices to mitigate, nevertheless, by mapping the climate-related status of the Hungarian Capitol, the analysis creates the opportunity for recommendations. The review resulted in a projection of global warming effects on the metropolitan economies. Besides, a collection of best practices was composed about the actions made by cities to mitigate these effects. The results created the opportunity to conclude the needful actions in Budapest to prepare its construction industry, transportation system, waste management and labour market for adaptation by financial, R&D and long-term planning solutions.
**Keywords**
climate change, city, economy

## 1. Introduction

Dealing with the effects of climate change on cities presents several challenges to decision-makers (both at the city and state levels). Cities are the world's and national economies' engines, so they deserve special attention. The adverse economic effects of climate change make cities and even entire countries vulnerable. It is necessary to decide on the strategies and developments that will significantly determine the fate of cities and the global economy in the coming decades. The most pressing questions related to the topic include the following: What parameters will allow cities to be climate-proof in order to be able to maintain their role and value? Which cities will be the winners of the competition between cities? The key issues are the climate resistance of cities and the preservation of their role and value.

The study's research question is what policy actions should be taken at the municipal government level in Budapest to mitigate the impact of climate change? The aim is to uncover best practices in metropolitan governance. To conclude policy recommendations, first, the paper determines the range of economic effects on big cities caused by global warming. Then the international examples of city actions for mitigation are collected. It is followed by an overview of Budapest-specific economic challenges and impacts potentially caused by climate change. Finally, municipal policy actions are recommended on infrastructural (construction, transportation, waste management) systems, labour market, innovation and financial planning.

## 2. The economic effects of climate change on large cities

When analysing the effects of climate change on cities, three important points must be addressed: the topics of sustainability, global and local population movement, and the pursuit of balance and circular economy techniques. In terms of sustainability, the primary impact of climate change on cities is that the previously stable environment is disrupted, while the need to adapt requires the use of resources, which may be limited. In addition, climate change affects the habitat and causes global and local population movement. For example, when the inner city heats up, it will make people move out to the outer parts of the agglomeration. In addition, water and food shortages may occur in certain cities, leading to international migration. Pursuing balance and circular and blue economy techniques form a separate group. In connection with these, another question arises: what kind of effect does the amazing power of absorption and emission of cities have on their natural environment? In other words, in exchange for a high GDP, are there areas on the verge of destruction and which, if they were not in decline, would have a role in maintaining the environmental balance – if they did not need to adapt?

The problems air pollution poses in cities do not only include the high $CO_2$ concentration, nor is it the most dangerous effect. There are many other directly dangerous toxic substances, such as arsenic, whose concentration has increased to a much more threatening extent than carbon dioxide due to the industrial revolution. The doughnut model represents the visual framework of sustainable development in the shape of a doughnut, which combines the concept of planetary boundaries with the definition of social boundaries. The middle part of the model represents the proportion of people who do not have access to basic needs (such as healthcare and education), while the crust represents ecological ceilings (the Earth's limits), i.e. the factors on which life depends and which must not be exceeded. The chart was published by Oxford University economist Kate Raworth in 2012 and detailed in her 2017 book. The framework proposed to evaluate the economy's performance according to the extent to which people's needs are met without exceeding the Earth's ecological ceiling. The main goal of the new model is to reframe economic problems and set new goals. In this model, an economy is prosperous if all twelve social foundations are met without exceeding nine ecological ceilings. This situation is represented by the area between the two rings, which its creator sees as a safe and just space for humanity (*Raworth, 2012; Monbiot, 2017*).

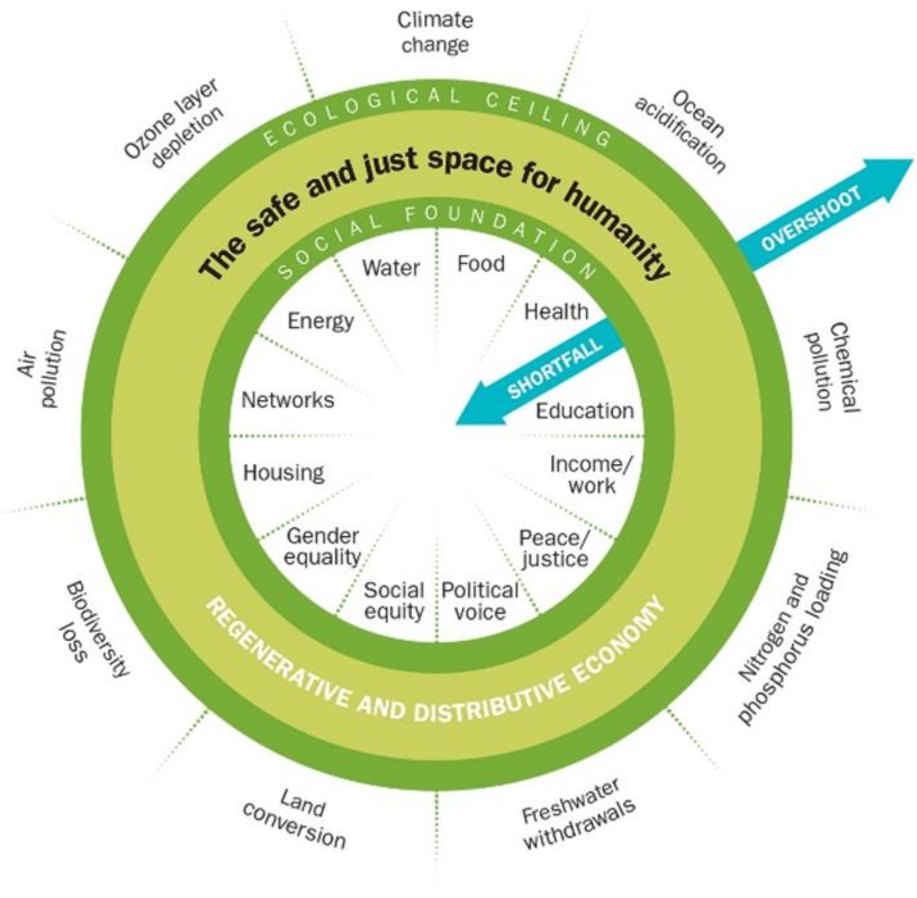


Figure 1: Doughnut model

*(source: Nugent, 2021)*

Cities are on the front lines of climate change. Although they occupy only about 1-2% of the world's land area, they account for 2/3 of the world's total energy consumption. In most cases, the energy sources for cities come from long distances, which presupposes maintaining infrastructure and logistics of a certain quality. However, they are the engines of economies worldwide, producing more than 80% of the global GDP. (*World Bank, 2021*) The World Bank works in cooperation with the UN to make cities and all other settlements more resilient, safer

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and more sustainable and mitigate climate change's adverse effects on settlements. Thanks to projects like those in Tanzania, Mozambique, Belize, Turkey, and many more states, protection systems against floods and destructive storms and infrastructure have been developed. (*World Bank, 2021*) From the percentage of the world's global GDP, it can be concluded that if the cities around the world are unable to properly perform the important tasks associated with them as the engines of the world economy due to the adverse effects of climate change, then there will be a massive decline in the economy on a global level (*World Bank, 2021*):

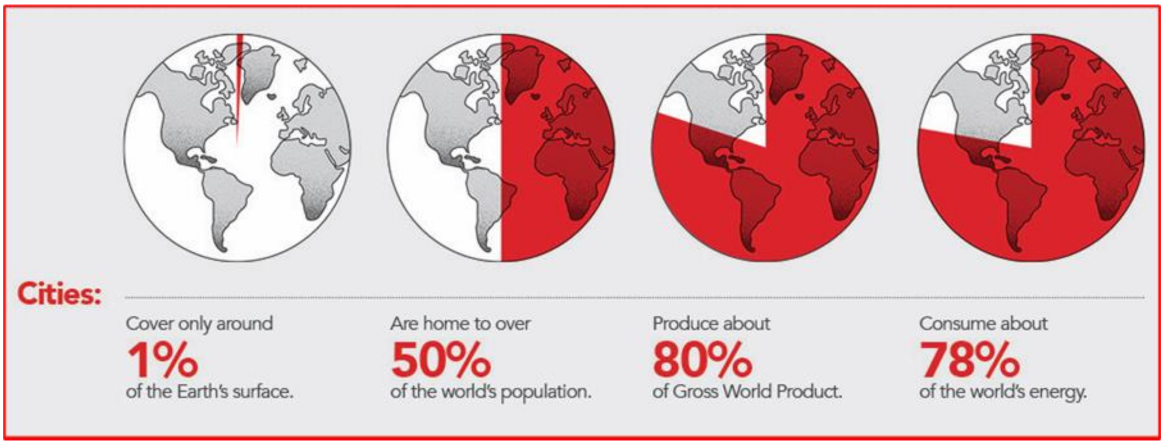


Figure 2: Important figures and ratios related to the cities of the world

*(source: Cities Alliance, 2020)*

In 2018, nearly 60% of the world's cities (major cities with more than 300,000 inhabitants) were exposed to the risk of at least one major natural disaster (cyclone, flood, drought, earthquake, landslide or volcanic eruption) due to the effects of climate change. These disasters and their risk also make most cities – 88.9% – economically vulnerable (*Gu, 2019*). Other types of damage can also occur due to climate change or the resulting human activity. These include the gradual lowering of the groundwater level, the loss of potable surface water, increasing levels of air pollution, an ever-increasing number of days with heat-warning and decreases in agricultural land productivity. The problems listed above are not disasters but disaster-like effects that burden the performance capacity of the cities' infrastructure not on a case-by-case basis but continuously. This damage is mainly caused by human activity.

Table 1. Natural disasters threaten the risk to the world's cities

| | Number of cities (Total: 1860) | Percentage rate (Total: 100%) |
|---|---|---|
| No risk | 105 | 5.6 |
| Low risk | 20 | 1.1 |
| Medium risk | 82 | 4.4 |
| High risk | 1653 | 88.9 |

*(source: Gu, 2019)*

As already noted, climate change harms GDP all over the world. According to *Stanford's (2015)* study, climate change will reduce GDP by more than 20%, and this downward trend will also be permanent. (*Stanford, 2015, referred by Kimberley, 2021*) *Swiss Re Group (2021)* report presents similar numbers, predicting that the world's economies will suffer a 10% decrease in GDP over the next 30 years. In addition, people living in cities are exposed to increasing financial burdens due to climate change and natural disasters – for example, insurance premiums are increasing. However, not only the cost of insurance but also the level of energy prices will increase significantly. In addition to these, natural disasters also pose a threat to security. All over the world, many military bases are located in cities, which are also at risk – and in the event of natural disasters, it would cost hundreds of billions of dollars to restore them (*Wade, 2016*).

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According to a 2015 study conducted at Columbia University (*UNFCCC, 2015*), due to the effects of climate change, cities will have to double the amounts they spend on infrastructure development by 2025, which will amount to more than $20 billion in total—the global costs of floods caused by climate change amount to approximately 1 billion dollars worldwide each year. However, cities alone cannot finance the costs of climate change. Globally, the costs related to climate change range between 80–100 billion dollars per year, more than 80% of which are borne by cities (*UNFCCC, 2015; UNFCCC, 2021*).

According to the "World Employment and Social Outlook 2018" report, 1.2 billion jobs directly depend on climate change and its effects – most jobs are in cities. (*ILO, 2018:7; referred by Kimberly, (2021)* In the United States of America, 150,000 people lost their jobs due to Hurricane Sandy in 2012, with more than 11,000 in New Jersey alone. Cyclone Sidr destroyed thousands of small businesses in Bangladesh and threatened more than 567,000 jobs in 2007. Typhoon Haiyan adversely affected more than 800,000 workers in the Philippines in 2013. In addition, these natural disasters negatively impacted multinational companies, not only the settlements affected by the disaster but also workers working in other countries. (*Evans, 2015*)

According to *ILO (2019*) report, heat from climate change will reduce working hours by more than 2% worldwide, and more than 43 million jobs will be lost due to rising temperatures. Among the most affected sectors of the economy are winemaking, tourism, agriculture, fishing, the food industry and the energy sector. 60% of the global working hours in agriculture will be lost due to heat waves by 2030. *ILO (2019)* In tourism, the impact on winter sports will result in a loss of 20 billion dollars in the United States of America – and this will also negatively affect the surrounding accommodation and hotels. In addition, due to the melting of the snow caps, many ski areas will no longer be useable in the foreseeable future. Due to the rising water levels, many beaches will be flooded, adversely affecting the local workers. Many people have already lost their jobs in fishing due to climate change: in the USA, 16% of jobs related to fishing disappeared between 1996 and 2017 due to climate change on the New England coast. The global fishing sector will suffer losses of around $2 trillion by 2100. The food industry is also severely affected by climate change. The Fresh Del Monte company lost more than $2.5 million due to drought in Brazil in 2016, while Coca-Cola and Pepsi lost more than 1 million retailers in the Tamil Nadu region of India due to drought in 2017. More than 17,000 jobs have already been lost in wine production worldwide due to the adverse effects of climate change (*FileUnemployment.org, 2021*).

It is also worth looking at the 2016 report of the European Environment Agency. Based on this report, between 1980 and 2013, the economic losses of the European Environmental Protection Agency member countries due to natural disasters might be related to climate change amounted to more than 400 billion euros. (Storms, floods, landslides, drought, forest fires, heat waves) However, it is essential to highlight that more than 70% of losses were caused by 3% of extreme events (*European Environment Agency, 2017*).

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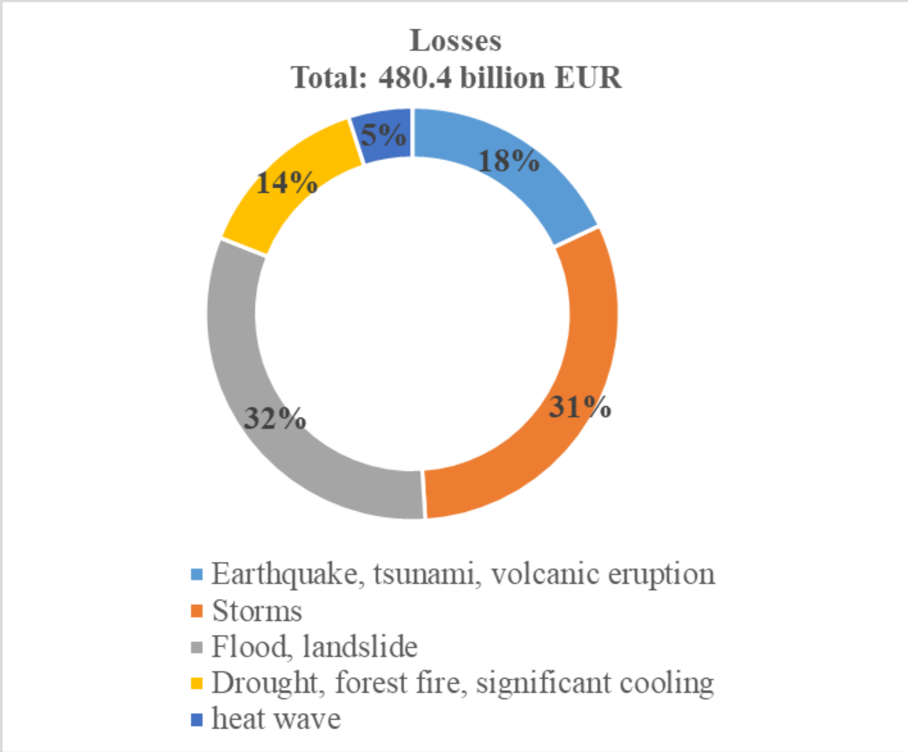


Figure 3. Losses of the member countries of the European Environment Agency between 1980 and 2013 by natural disasters

*(Source: own editing based on the 2016 report of the European Environment Agency)*

One of the adverse economic effects of climate change is that many people may lose their jobs. However, jobs may also be created in response to these effects, especially in the construction sector. Buildings that are more energy efficient and more resistant to the effects of climate change must be constructed, and these investments will create many new jobs (*Gouldson et al., 2018*). More expertise will be required at all sector levels, including the planning, implementation and operation phases.

One of the adverse economic effects of climate change is that companies may withdraw from a particular city completely. It is, therefore, necessary to pay special attention to these businesses and encourage industries and businesses to stay and invest locally (*Lee, Erickson, 2014*).

Based on what has been described, the following questions may also arise: Which factors will render cities climate-proof in order to be able to maintain their role and value? Which cities will be the winners of the competition between cities? Will it be those that can moderate the projected GDP fall? Will it be the 'techno cities' that generate a continuous flow of resources and gradually strengthen their technological structure based on permanent innovation, raising productivity and GDP? Or will it be the 'passive cities' based on flow and circulation – based on physical laws and ecological values that result in seeking harmony with natural resources?

## 3. Metropolitan responses to the economic effects of climate change

Climate change is a global problem that cannot be addressed exclusively globally, but solutions should also appear locally – including in cities. Since there is no clear global action strategy for finding appropriate and practical solutions, it is left to local communities to deal with the adverse economic effects of climate change. As a result, city-level action plans need to be created to deal with the adverse economic effects of specific impacts, such as heat waves. The management of these effects is also essential because the employment rate, economic growth, the amount of investment and output of many cities around the world, as well as the personal income of their residents, depending on how these settlements respond to such effects (*NASA, 2014; United States Environmental Protection Agency, 2016*).

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Worldwide, several examples can be found of cities successfully coping with the adverse economic effects of climate change. In 1974, victims of a devastating flood in Tulsa, Oklahoma, began to pressure the city in the aftermath of the natural disaster to begin developing a strategy that would significantly reduce the damage from subsequent floods. Thanks to this pressure, the city started planning and implementing technological developments and organised the institutional and financial framework for flood protection. Construction in the floodplain was prohibited, and most of the buildings that were already there were moved to other parts of the settlement. Another major flood occurred in 1984, when, thanks to this strategy, significant damage was almost entirely avoided, and the city's residents did not lose their homes and jobs, thus minimising possible economic losses (*Rasmussen, 2014*).

Another example can also be cited from Central America: San Salvador was often hit by floods and storms. Landslides were also a frequent phenomenon due to the heavy rains in the region. However, in 2016, based on a *UNU (2020)*[1] study, more than 25 adaptation measures to mitigate the adverse economic effects of climate change were introduced. (*Souvignet, 2020*) First, a kind of "danger map" was created for the city based on the available older data. The value of the endangered area's homes, schools, and hospitals had to be assessed, and the number of people living there had to be determined precisely. Based on the information gathered, a table demonstrates how effectively various adaptation measures can protect a given area from the adverse effects of climate change. Such measures include, for example, urban planning, encouraging household water-saving practices, the use of permeable pavements, the lining of canal pipes (to reduce water leakage), the use of a modular water retention system, the establishment of emergency/overflow canals, and the improvement of the drainage system. However, the city could not have implemented these costly developments with its scarce financial resources, so the projects were realised with the co-financing of the German Development Bank (*KFW Development Bank, 2020*). The example of San Salvador demonstrates that cities that do not have the financial means to mitigate the adverse economic effects of climate change may still, with foreign help and support, implement mitigation measures. Using the ECA method, San Salvador also solved the city's water supply problems in the event of a drought, so this phenomenon no longer threatens the city's economy (*Souvignet, 2020*).

According to a World Bank publication, one possible response to the adverse economic effects of climate change would be for cities to consider levying a real estate tax on their agenda. Tax incentives and subsidies could also be applied, along with a real estate tax in areas classified as higher risk and differentiated insurance. Internally generated revenues (taxes) are very important as they can be used for investments and infrastructure developments that mitigate the adverse economic effects of climate change. A property tax would incentivise residents to buy and rent apartments away from more vulnerable areas. Separate area taxes could also be applied, which would be higher if the given apartment is closer to the endangered area (*The World Bank Group, 2011*).

With the ever-increasing occurrence of threats related to the adverse effects of climate change, cities must invest in increasing their resilience and minimising damage. In New York, Hurricane Sandy in 2012 caused about 19 billion dollars in damage, left 2 million residents without electricity, and flooded approximately 90,000 buildings. (*Global Commission on the Economy and Climate, 2014*) However, proper urban planning and urban management can contribute to reducing such losses. Transport infrastructure, canals and utility systems must be strengthened and well-maintained. These measures both increase the city's future resilience and create jobs. As a result of the introduction of these measures, cities can operate more efficiently in terms of energy and resources, their resilience increases, and they can lure residents from the areas most exposed to dangers to safer parts of the city (*Global Commission on the Economy and Climate, 2014*).

Milan is a large city with several rivers and canals. As a result, the city faces the risk of floods during heavy rains and storms. The city's government is committed to significantly increasing the resilience of the settlement. A climate adaptation plan and a flood protection map of the city have also been created. The local authorities also

[1]ECA is a decision support tool that integrates climate change vulnerability and risk assessment with economic and sustainability impact studies to determine optimal adaptation measures for various risks. ECA supports decision-makers in choosing the most appropriate investments that are consistent with the impacts and consequences of current and expected future climate conditions and increase resilience to them.

aim to increase energy efficiency. In order to achieve the goals, the city actively cooperates with the private sector, has established a car-sharing program and, as part of the development of the city's public lighting, the existing legacy streetlights are being replaced with LED lamps (*CDP, 2017a*). In Rio De Janeiro, the residents are threatened by significant heat waves.

For this reason, the local government has commissioned the development of an application that informs registered users about extreme weather conditions (*CDP, 2017b*). Taipei is an example of a big city in which the economy is driven by high-tech services (which are based in office buildings). Accordingly, the city aims to create "green" buildings. Many green walls and roofs have been created, permeable pavements are used on the streets to reduce the effects of heat, and many solar panels have been installed (*CDP, n.d.*).

The leaders of Chinese cities have also realised that to eliminate the adverse effects of economic growth and climate change. Cities must be developed accordingly. Traffic jams and high levels of air pollution are the main problems in Chinese cities. Because of these problems, a national urbanisation conference was held in China in 2013, where it was determined that the level of environmental pollution should be reduced. A national urbanisation plan was drawn up for 2014–2020 to reform cities to address the effects of climate change. The various conferences and forums where the problems of cities can be discussed are, in many cases, a very good starting point for solving those problems (*Global Commission on the Economy and Climate, 2014*).

Houston, located in the United States of America, is one of the world's most sprawling, low-density cities with a high level of car usage and ownership – and where spatial planning and development policies are lacking. By 2035, Houston residents will spend 145% more time in their cars than in 2014. The city administration is trying to control the city's expansion and implement sustainable investments. It launched a programme offering investors up to $15,000 to build more single-family homes in the city centre. An urban light rail system has also been launched. A significant proportion of the bus fleet is now made up of hybrid vehicles, and a car-sharing system has also been established involving cars owned by municipalities. The city and the private sector have contributed hundreds of millions of dollars to an initiative that has created more than 150 miles of new hiking and biking trails (*Global Commission on the Economy and Climate, 2014*).

The urban development strategies that cities can pursue to mitigate the negative economic impacts of climate change vary from city to city. Key determinants include carbon dioxide emissions, electricity supply and population density. The development path may therefore be different for cities as various as Denver, Toronto, Rio de Janeiro or Beijing. In cities experiencing rapid growth and a corresponding increase in the demand for electricity supply, the expected future greenhouse gas emissions from electricity supply must be considered.

An initiative aimed at the development of the "clean technology" sector was created in Singapore. This sector has created thousands of new jobs and generated billions of dollars in profits. The essence of this initiative is that international companies can apply for support and use the city as a test site for developing sustainable technologies and as a way of making them known as widely as possible. For example, one company built the city's first "green" business park with an intelligent electrical grid. (*Flater, Rode, 2014*). Stockholm also sees opportunities for development in clean technologies. The city has created so-called eco-districts in its former industrial areas, where clean and low-carbon technologies are also developed. (*Flater, Rode, 2014*). Baoding in China's Hebei Province is a major hub for renewable energy production. Traditionally known as a manufacturing centre, this city's main fields of expertise are textiles and automobiles. Using more than 200 renewable and energy-efficient technologies, the Baoding manufacturer created more than 20,000 jobs in 2009 and generated a turnover of more than 1 billion dollars. The Chinese government has designated the city as a High-Tech Development Zone, imitating the industrial model of California's Silicon Valley (*Flater, Rode, 2014*).

In this analysis based on data from 60 world cities, researchers found that switching from coal-based energy production to renewable energy sources would create more than 1 million new jobs. In addition, the number of premature deaths would also decrease, fewer residents would have to be cared for in the health sector, and the time off work due to illness would also decrease – which would also have a very positive effect on the labour market (*C40 Cities Climate Leadership Group; 2021*).

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According to some experts, the world's largest cities should develop a model in the next 10-20 years to help them positively influence the future of urbanisation. This model should include smart infrastructure (such as LED street lights and electric buses), the creation of low-carbon districts (with the development of bus and bicycle infrastructure), and the introduction of various energy efficiency measures. An analysis of five cities at different levels of development (Leeds, Kolkata, Lima, Johor Bahru and Palembang) suggests a considerable potential to improve energy efficiency in the transport sector, the energy sector and the construction industry (*C40 Cities, 2021*).

Strategies that contribute to mitigating the adverse effects of climate change can involve additional costs and require significant investment on the part of cities. Since city governments worldwide do not all have the necessary level of resources, the involvement of the private sector and/or international cooperation in their development is often essential. Maintaining the developed "intelligent" new infrastructures also entails higher city costs. Within the framework of international cooperation, cities can share their development ideas, techniques, and policies. International players can help cities improve their creditworthiness and mobilise significant funds on the domestic and international financial markets. Uganda, for example, managed to increase its revenues by 86% within a year. International collaborative initiatives have emerged to help more cities mobilise private finance, such as the World Bank-led Creditworthiness Initiative and the Cities Climate Finance Leadership Alliance (launched at the 2014 Climate Summit to accelerate additional capital flows to cities) (*Gouldson et al., 2015*).

Floods and inundations are other adverse effects of climate change, resulting from which cities suffer enormous economic damage. In order to mitigate these damages, in the framework of a project called MOSE, mobile gates were created in Venice to protect the city from large sea waves and floods. These gates "close" the lagoon at high tide, thus preventing seawater from rushing into the city. (*CDP, 2017c*)

Medellin struggled with the adverse effects of heat waves for many years. However, a solution to the situation was found within the framework of a project implemented in recent years. Thirty-six green corridors – running throughout the city – were created from various plants. These contributed to a decrease in the temperature of the air and the surrounding surfaces, keeping the surrounding areas in the shade, significantly reducing the exposure of the city and its inhabitants to extreme heat and have had a very positive effect on the health and well-being of the residents. The positive economic effects of the measure/project include job creation and increased labour productivity (*C40 Cities, 2019*).

As clients of the World Bank, cities can benefit from a financial program, support and analysis services that are much larger and more significant than in other countries. São Paulo, Jakarta, Mexico City and Cairo are also clients and partners of the World Bank. Various international climate funds have benefitted many large cities, including Mexico City, Bangkok and Cairo. In the last decade, a large-scale urban development took place in Bangkok, which was realised based on the investments of the Clean Technology Fund approved in 2009 (for example, energy-efficient buildings were created within the program's framework). The carbon financing unit of the World Bank launched a city-wide carbon financing methodology called Carbon Expo in 2009. The first version of the program was implemented in Amman, Jordan. The World Bank is working to increase the number of cities participating in the project and to make the methodology even more effective. In 2010, a program aimed at mitigating climate change was launched in Tokyo (*World Bank, 2010*).

Another promising approach is that of so-called smart cities. These settlements prepare and implement their integrated settlement development strategy using the smart city methodology. This involves a process, a path of continuous development, in which the smart city methodology is the Smart City Development Model (*Lechner Tudásközpont, 2017*). In these settlements, sustainability is applied, and efficiency and broad participation are prioritised. The strategy of these cities focuses on four main areas: improving the quality and efficiency of services; more economical use of energy and other resources; involving citizens and improving their quality of life; and the creation of economically self-sustaining systems (*Lechner Tudásközpont, 2017*).

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## 4. The effects of climate change on Budapest

As in other cities, the economic effects of climate change can be felt in various aspects in Budapest. These include the development of transport, the construction industry and the standard of living. As Budapest is the capital city of Hungary, it has been the subject of most analyses and specialist literature on the topic in the country.

*Révész and Zalai (2012)* use two types of models to analyse the economic effects of climate change on Hungary. Their computable equilibrium model, HUMUSGE, divided production and consumption into 25 sectors. They examined several scenarios using a model of the impact of climate change on tourism. "According to the third simulation, labour productivity in agriculture deteriorates by 3% and material services by 2%. These are the sectors most exposed to climate change. This productivity loss causes approximately HUF 43 billion in additional wage costs if the production level unchanged should remain unchanged. Due to deteriorating labour productivity, GDP will decrease by 0.65%" (*Révész and Zalai, 2012*). The projection puts the challenge of food and resources supply based on geographically long supply chains in the spotlight. Resource seeking in the city's vicinity can be a solution, like livestock herding in the agglomeration's green areas or using local energy sources, e.g. geothermal heating. The city governance is recommended to focus on demographics of the agglomeration labour market, organisation of supply chains by city management and city diplomacy. The local government should find a way to promote investment toward more productive food manufacturing and energy-supplying firms to settle them in the agglomeration.

The SOCIOLINE model examines natural, social and financial sustainability, for which it depicts the degree and consequences of external and internal indebtedness (risk premiums). Alongside productive and financial assets, the model treats infrastructure, the environment, the workforce and social capital as forms of capital (*Révész and Zalai, 2012*).

*Farsang et al. (2015)* present climate change's expected economic effects. In Budapest, energy efficiency can increase significantly by renovating its legacy prefabricated concrete tower blocks, the so-called "panel apartments". In the 3rd district, the ambitious reconstruction programme of one of Hungary's largest apartment complexes completed in 2009 generated more than 50% of energy savings. There is room for extensions of energy-saving renovation of buildings, green roofs for lower tempering by tax and subsidies incentives, like carrot and stick.

In the welfare times, the protection of historical monuments has a high priority for cityscape and tourism purposes, though the protection and renovation of century-old buildings in the non-tourist areas are against the energy efficiency of a modern city. The role and weight of the protection of historical monuments can be reconsidered. The city's structure and stock of buildings are recommended for more concentrated residential areas and tower buildings to concentrate the population. This can reduce the length of citizens' daily routes of personal mobility by settling the individual needs close to them.

In 2021, Budapest Capital City Planning Ltd. published an action plan for climate change in the capital city. This analysis identified the problems threatening the capital linked to climate change and proposed solutions. These include, for example, improving the energy efficiency of the capital's transport infrastructures. $CO_2$ emissions from elements of the transport sector totalled 1.7 million tons in 2015. To determine the $CO_2$ emissions related to transport, the $CO_2$ emissions of the vehicles of local government institutions and companies, the capital's public transport system, and private and commercial transport were calculated using the SECAP methodology (*Tatai et al., 2021*).

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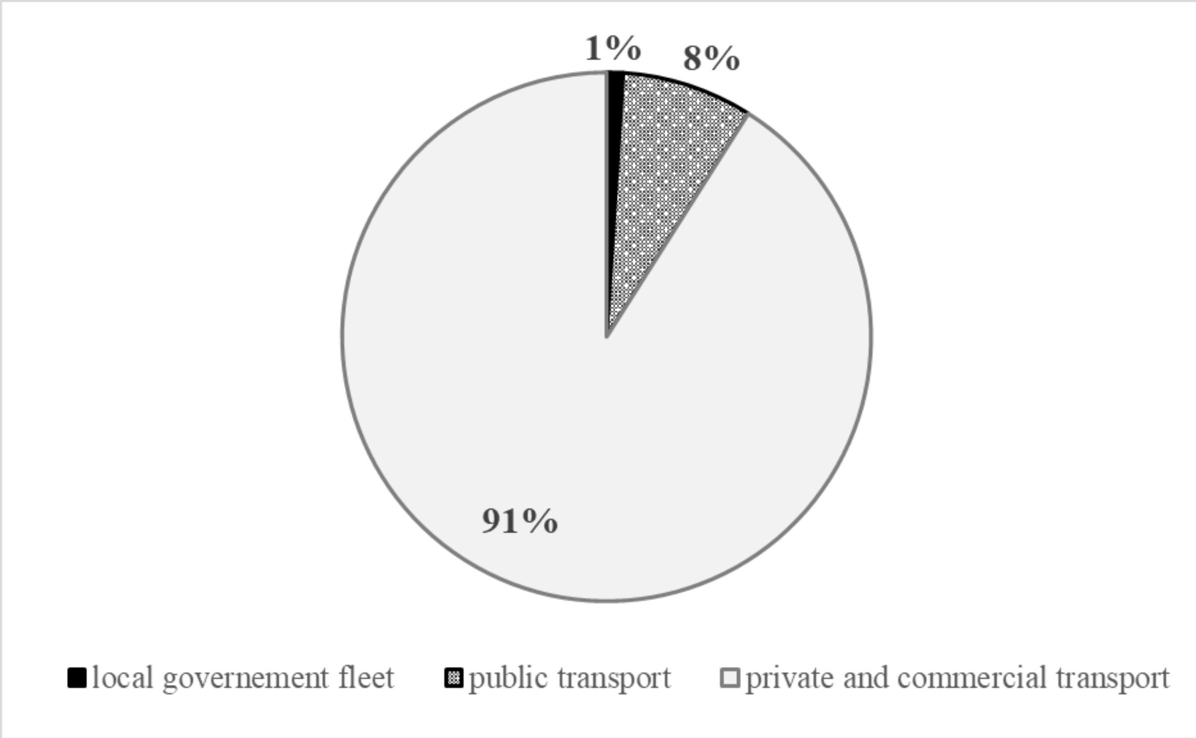


Figure 4. Distribution of transport $CO_2$ emissions in Budapest
*(Source: Budapest Capital Municipality, 2021)*

Transport emitted the most carbon dioxide in the European Union between 1990 and 2016, followed by the energy sector, agriculture, households, and industry. In 2019, however, the energy sector was the largest greenhouse gas (GHG) emitter. (*European Parliamen*, *2021*) Figure 5 demonstrates the distribution of $CO_2$ emissions from transport. Based on the data, 91% of transport $CO_2$ emissions can be attributed to private and commercial road transport. (*Tatai et al., 2021*)

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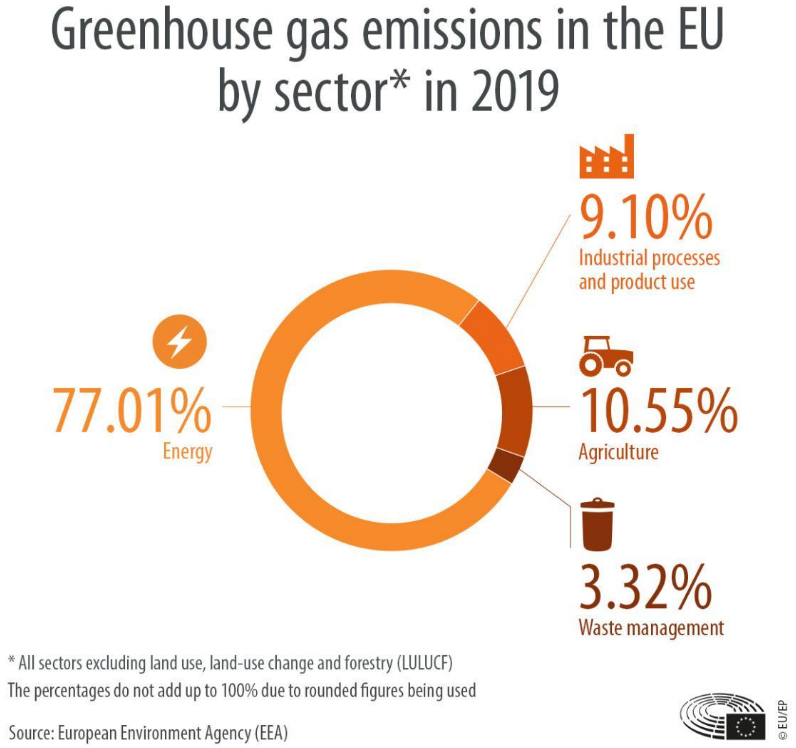


Figure 5. Greenhouse gas emissions in the EU by sector in 2019.
*(Source: European Parliament, 2021)*

Based on the conclusions about the sources of GHG emission, the city-level energy policy should turn toward the local green sources in the energy sector, just as geothermal, solar and biomass technologies. Besides, the city's policymakers should divert freight and passenger transportation toward emission-free vehicle technologies. Moreover, passenger transport is recommended to use fixed track and electrified public transportation, which shall be the focus of the public transport development strategy. The zero-emission vehicles should be combined with renewable charging energy sources. The carbon emission can be reduced if the supply chains get shorter in transportation. This highlights, again, the importance of local energy sources.

According to a study by *Baranyai and Varjú (2017)*, the relationship to climate change can vary by county and settlement. They claim that social status significantly affects the attitude towards climate change. In the counties classified as having a favourable social composition and in Budapest, the proportion of low-status persons was at most 18%, and the proportion of high-status persons was at least 20%. In counties with an unfavourable social composition, the proportion of low-status people exceeded 25%, and that of high-status people did not reach 15%. In Budapest, they found that the inhabitants are less sensitive to changes in the climate than people living in villages. According to the authors, due to climate change, the desire to emigrate may also increase in parallel *(Baranyai and Varjú, 2017)*.

For efficient mitigation, the city government needs the cooperation of the local citizens. Not merely policy actions but policy communication is a part of the instruments, too. Communication campaigns can raise the citizens' climate conscientiousness. Additionally, tax, cost and subsidy incentives can guide the local society and businesses to join climate-neutral networks and systems.

An article by *Buzási, Pálvölgyi and Szalmáné Csete (2021)* deals with the economic effects of climate change. Hungarian cities face significant challenges due to the impacts of the changing climate. For this reason, the authors advocate the development of a climate-oriented evaluation methodology to assess the performance of urban development interventions (*Buzási et al., 2021*).

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Among the various indicators related to the climate and cities, special attention should be paid to Sustainable Development Goals (*UNIS Vienna, n.d.*). These include, for example, promoting sustainable industrialisation and innovation, ensuring sustainable, modern energy, making cities more sustainable and increasing their adaptability, and taking action to mitigate the adverse effects of climate change. A similar indicator can be found among the goals of the Sendai disaster risk reduction framework, which the document related to the UN Framework Convention on Climate Change also calls essential (*United Nations Statistics Division, 2021; UNDRR, n.d.*)

## 5. Conclusions

Cities are significantly affected by climate change. According to *Gu (2019)*, nearly 60% of the world's big cities (cities with a population of at least 300,000) have already been exposed to the risk of at least one major natural disaster caused by climate change. These risks also make cities economically vulnerable. This vulnerability affects, among other key areas, the labour market, the construction industry, the energy sector, infrastructure, and transportation.

In terms of sustainability, the impact of climate change on cities is that the previously stable environment is disrupted, while the need to adapt requires the use of resources, which may be limited. Climate change transforms human habitats; and, therefore, causes global and local population movement. For example, as the inner city heats up, people move to the outskirts or surrounding settlements. In addition to these challenges, water and food shortages may occur in certain cities, thus accelerating international migration.

Climate change might reduce cities' GDP by 10-20% in the coming decades, according to *Stanford (2015)* and *Swiss Re Group (2021)*. This is a high risk because cities are the engines of the world economy and generate more than 80% of the global GDP. Labour productivity deteriorates (due to heat waves, for example), many people lose their jobs, and infrastructure development also involves enormous costs. The high concentration of carbon dioxide and increased incidence of air pollution place greater burdens on the health sector, so the operation of the health care system also entails higher costs.

The following economic impacts are expected in Budapest related to climate change. Higher temperatures can deteriorate the productivity of workers. Air pollution and warming can lead to illnesses and increase health care costs, leaving less income for other purposes. The mitigation demands infrastructural investment in public transportation and building stock for energy efficiency.

As a result of climate change, economic effects can be felt in Budapest, particularly in the transport and construction industry. Most of the properties in the city need to be modernised in terms of energy use and energy efficiency, which imposes significant additional costs on the city. Public transport must also be developed to achieve the lowest possible carbon dioxide emissions.

This literature highlights that Budapest has broad room for carbon reduction in the energy and transportation sectors. The city management should strive to extend local renewable energy and carbon-free transportation via investment, development and incentives toward the private sector. Besides, the city's structure and stock of buildings should be rationalised to concentrate the population, reduce the route lengths in transportation, and settle the individual needs close to the citizens. Nevertheless, citizens can be incentivised by taxes, costs and subsidies, moreover, convinced by appropriate communication.

The development of cities is also essential for the development of national economies. Cities must continuously work against the adverse economic effects of climate change. Based on all of these challenges, the following recommendations can be formulated for city administrations to be climate-proof and to combat the adverse economic effects:

- Construction industry: Energy-efficient buildings must be constructed while existing buildings must be modernised in terms of energy efficiency. Buildings that are sustainable in the long term should be preferred, and developments should be based on business models that are also functional in the long term. The construction materials used should be selected based on their impact on the environment, and the planning of their lifespan should also be emphasised.

- Transport: Public transport should be developed, and residents should be encouraged to walk more and use bicycles more often. Self-powered devices should be preferred over energy-consuming convenience devices (i.e. a healthy lifestyle should be preferred instead of comfort).
- Waste management: Recycling waste and transitioning to waste management with lower carbon dioxide emissions is necessary.
- Energy sector: The so-called clean energies should be increasingly used, i.e. the shorter supply chain, the local use of renewable (solar) and green (geothermal) energy, and the creation of energy communities should also be advocated.
- International examples: It is worth analysing and adopting the best practices of foreign cities. Importantly, these examples should only be followed closely in certain specific cases. However, their adoption usually involves adapting the system created abroad, even though every settlement is unique. Instead of entirely adopting strategies, focusing on the analysis and appropriate exploitation of local resources would be more worthwhile. In this way, cities could become much more innovative.
- Infrastructure: Developing an intelligent urban infrastructure and using new technologies is necessary.
- Financing: In addition to the cities' resources, state resources and the private sector's contribution may also be needed to carry out the necessary developments. Self-sustaining models should be preferred in this regard.
- Workforce: Investments to develop cities must be encouraged because many new jobs will be created this way.
- Research and development: Indicators and metrics must be developed to accurately indicate the effect of the measures implemented in the city. The state must support research and development activities, e.g. innovations that can make the existing infrastructure work more efficiently, i.e. at a lower cost.
- Planning: It is necessary to identify the areas within the city where the most investment and development are required. Developing urbanisation strategies is also useful (*Gouldson et al., 2018*; *Global Commission on the Economy and Climate, 2014*).

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# Driver alertness monitoring system in the context of safety increasing and sustainable energy use

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**Abstract**
Road transport is an important factor in carbon dioxide emissions. These emissions can be reduced by improving propulsion sources and traffic flow (avoiding traffic jams due to accidents). This article presents a system for monitoring and warning the driver to prevent a possible accident involving material damage, injury, or loss of life. The system performs video monitoring of the driver in order to determine his state (tired or attentive). By reducing traffic incidents and traffic jams, the energy consumed will not be wasted; thus, more sustainable transport energy use can be achieved.
**Keywords**
Driver monitoring, sustainable energy use, drowsy driving, $CO_2$ emissions.

## 1. Introduction

Road transport is one of the most energy-intensive sectors compared to other modes of transport: air, rail and water. However, in some situations, car transport is a safe way to move goods and passengers. According to Statista (2023), *Figure 1* shows the percentage by category of $CO_2$ (carbon dioxide) emissions from all means of transport in 2020.

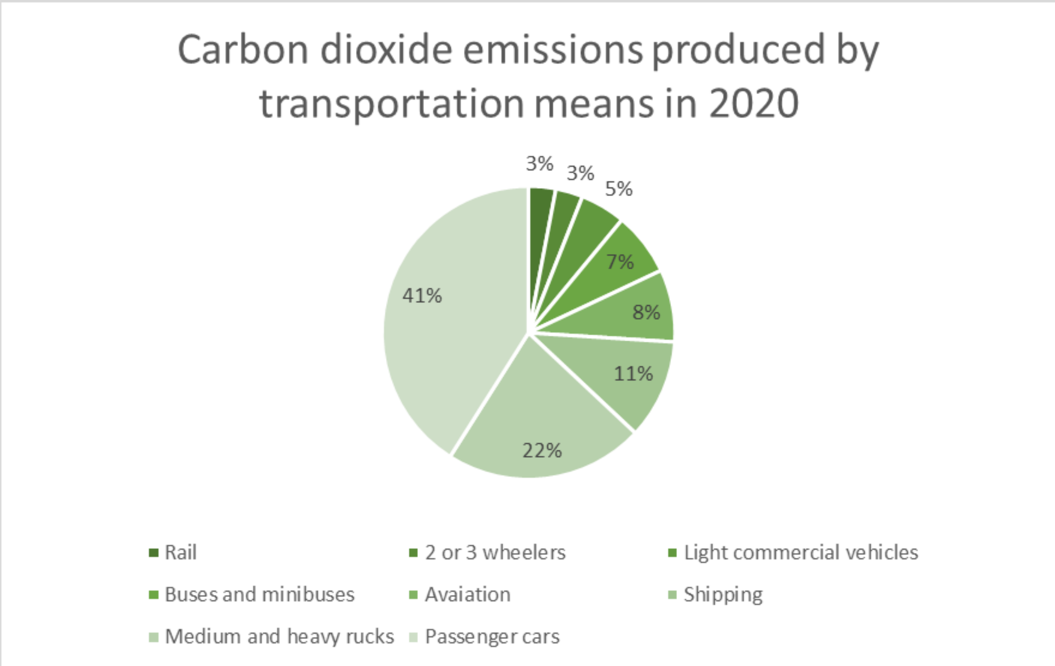


Figure 1 Carbon dioxide emissions produced by transportation means in 2020
(*source: Statista, 2023*)

Although 2020 was the year of the Covid-19 pandemic's onset, industries worldwide reduced their production capacities and the transport sector was directly affected. This did not significantly reduce $CO_2$ emissions. According to *Statista (2023)*, the approximate total amount of $CO_2$ emissions due to transport was 7.3 billion metric tons. Population growth in recent

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decades has also increased the number of cars on the road. However, the road and motorway network has not been able to develop so quickly, which causes traffic jams on some roads. Traffic jams in big cities and on motorways are major contributors to transport energy consumption. In this case, we have to consider both the energy gained from fossil fuels in internal combustion engines and electrical energy (stored in the batteries of electrically powered vehicles). Because in these congestions, there is a need for energy consumption which is used both for maintaining passenger comfort (air conditioning + entertainment) and for maintaining the transport conditions of perishable goods. All this energy is practically not used sustainably. It is wasted.

Considering all the losses caused by traffic jams in a single country, more precisely in the European country with the most developed road infrastructure, according to (zf.com), the annual losses to Germany's economy are 80 billion euros. The factors that can generate traffic jams are diverse and numerous (infrastructure maintenance works, traffic light malfunctions, busy road junctions, weather conditions, and accidents). This article will consider traffic jams generated by accidents, particularly accidents due to driver fatigue. It is well known that driver fatigue and falling asleep while driving are relatively common occurrences that result in severe and even fatal accidents.

Several statistics highlight the consequences of driving in a state of severe fatigue. According to NHTSA (National Highway Traffic Safety Administration) statistics, based on police reports, 91,000 crashes were involved or resulted from fatigued drivers in 2017. As a result of these crashes, there were 50,000 injuries and nearly 800 fatalities (*NHTSA, n.d.*). In the following years, the number of fatal accidents due to drowsiness decreased: in 2019, there were 697, and in 2020 there were 633 deaths. According to a study by the Centers for Disease Control and Prevention (CDC), 1 in 25 drivers admitted to falling asleep/sleeping while driving at least once in the past month (*CDC, 2022*). The National Safety Council (*NCS, n.d.*) presents some aspects of fatigued driving. For example, it was found that driving after 20 hours of sleep deprivation would make the driver's actions similar to a driver with a blood alcohol concentration of 0.08%. This can be associated with decreased attention and delayed driving reactions/activities. An Explanatory memorandum (EU, 2021) estimates that between 10 to 25% of all accidents in Europe are due to driver fatigue. Over time it has been observed that fatigue often occurs when driving activities are monotonous. This is most commonly found on motorways and expressways between cities. That is why researchers have been trying to develop different systems to monitor drivers' drowsiness. The solutions investigated have been quite varied, but most have focused on the use of the following sensors: ECG (Electrocardiogram), EEG (Electroencephalogram), EOG (Electrooculography), EMG (Electromyography) and even PPG (PhotoPlethysmoGraphy), which are used in various combinations. Video recorders were also used in most cases. The simple use of these sensors is not enough, so a system is also needed to process all the signals from the sensors so that a decision can be generated on whether the driver is alert or drowsy. To process this data, specific deep learning algorithms (e.g. Fuzzy algorithms) are often used together with ANN (artificial neural networks - (*Liu et al., 2022*).

The main aim of these research projects was to reduce accidents, especially the number of casualties, and to avoid waste due to material damage. In addition to these losses occurring to the vehicles directly involved in the incident, secondary losses generated by the incident must also be considered. A relatively frequent consequence of these accidents is the occurrence of traffic jams which lead to a waste of fuel but can also represent a new accident hazard if they occur on motorways or expressways. Some authors have investigated several variants of complex systems to determine whether the driver is tired. In the following paragraphs, some of these studies will be briefly presented.

In the literature (*Vesselenyi et al., 2009, 2016, 2017, 2019a, 2019b; Nagy et al., 2017, 2018*), several system variants were presented, among which one of the systems was based on the use of EEG, EOG and ECG sensors. These sensors have a good enough accuracy, but a rather inconvenient problem exists. This disadvantage refers to the fact that the sensors must be positioned on the driver's scalp to be as accurate as possible. This was inconvenient and required device calibration for each person, as biological signals can differ from person to person. The system's operation was satisfactory regarding results, but drawbacks arose when mounting the system in the vehicle regarding ergonomics and inconvenience for the driver. Therefore, a video camera was also used, whose images were processed using neural networks based on algorithms. Using the video camera was much easier and less intrusive for the driver, leading to further experiments.

In order to correlate driver monitoring systems developed by different manufacturers or researchers, a common scale with nine levels of attention is usually used. This scale is known as the Karolinska sleepiness scale (KSS) and is presented in Table 1. Of course, just monitoring the driver is not enough. That is why it is also necessary to warn the driver to increase

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his attention. Usually, the warning is done by the following methods: audible, visual and possibly tactile (physical). The warning modes should be correlated with the driver's inactivity, so if the system identifies intense drowsiness, the warning signal will be very strong.

Table 1 Karolinska sleepiness scale

| Scale/level: | Description |
|---|---|
| 1 | Extremely alert |
| 2 | Very alert |
| 3 | Alert |
| 4 | Fairly alert |
| 5 | Neither alert nor sleepy |
| 6 | Some signs of sleepiness |
| 7 | Sleepy, but no effort to keep alert |
| 8 | Sleepy, some effort to keep alert |
| 9 | Very sleepy, great effort to keep alert |

*(source: Putilov, Donskaya, 2013)*

In order to contribute to traffic safety and reduce energy waste due to accidents caused by driver fatigue, this paper presents a way to process images from the video camera that monitors the driver's actions, especially the driver's face and eye area. In the following sections, some of the research will be described.

## 2. Data and methods

The algorithm used for face detection is based on the Viola–Jones algorithm (*Viola and Jones, 2001*), which was implemented in MATLAB software. The bounding box is shown in *Figure 2a*. After the bounding box is detected, feature points are selected using a minimum eigenvalue algorithm developed by (*Jianbo and Tomasi, 1994*) (*Figure 2b*):

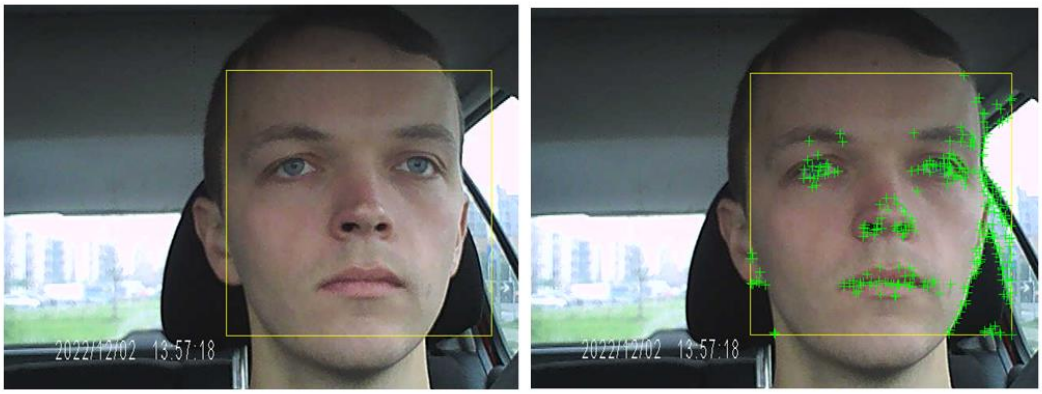


Figure 2a Face detection using bounding box (yellow); b Detected characteristic points (green +).

After detecting the feature points, a tracker algorithm can be applied, such as the Kanade–Lucas–Tomasi (KLT) algorithm (*Tomasi and Kanade, 1991*). The point tracker can be used in a larger program when more detections are needed.

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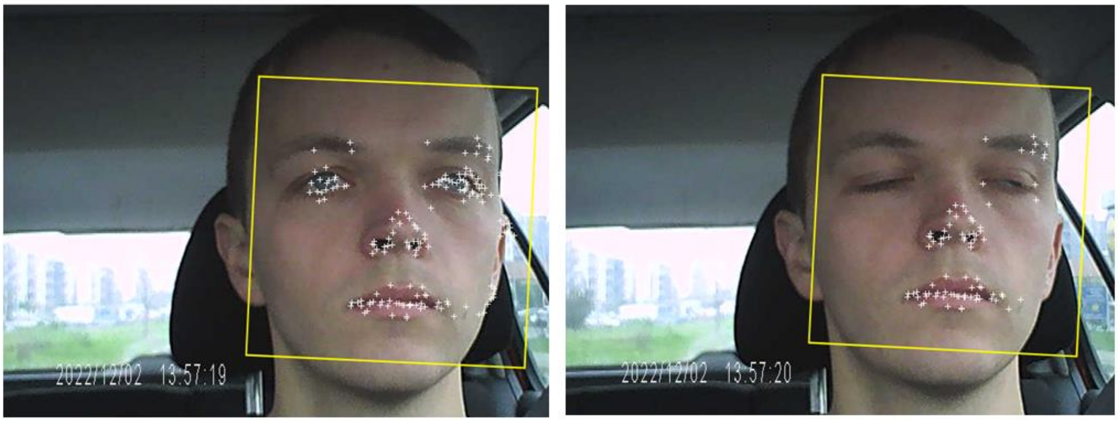


Figure 3a Feature points before blinking; b Loss of feature points after blinking.

Due to lost points, successive acquirements of feature points must be made. This can be observed in Figure 3, where in *Figure 3a*, a large set of points are lost after the driver has blinked (*Figure 3b*). The applied face-tracking algorithm is sufficiently robust to work even in extreme cases (*Figure 4*):

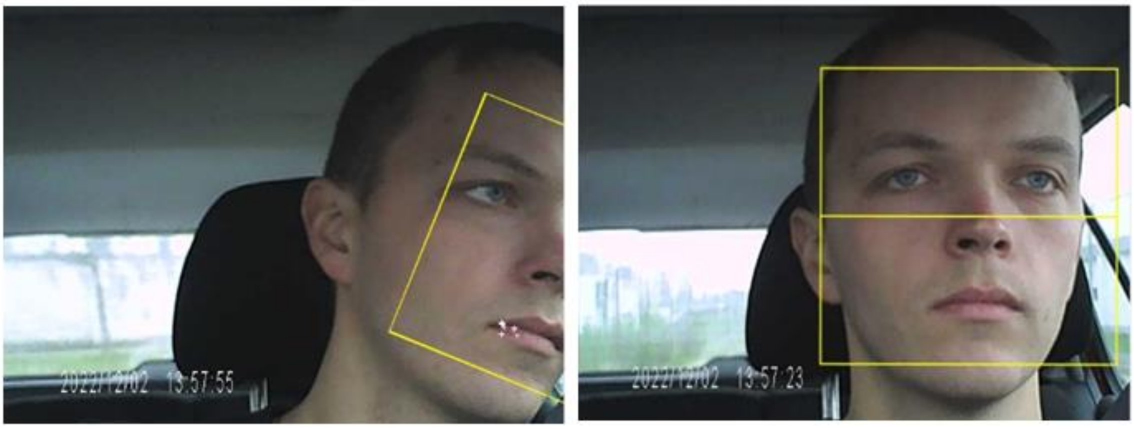


Figure 4a Extreme position of driver's face still detected by the algorithm; b Upper half of the face detection box.

We can use deep learning ANN for eye state detection, like, for example, CNN (Convolutional Neural Network - Kumari, Chakravarthy, 2022). For this study, we used a CNN algorithm which is available in the Deep Learning Toolbox of the Matlab software. The network has been set up with the following structure. The input layer width is computed from the size of the image (in this case, 416× 416 DPI). This is followed by five kernels, each consisting of four layers: convolution, batch normalization, ReLU (Rectified Linear Unit) and max pooling. The Convolution layers have 5 × 5 filters which are growing in numbers from 1 to 64, and the batch normalization units are also growing from 4 to 64 channels. These are succeeded by the last convolution layer 5 × 5 × 64, batch normalization with 128 channels, and ReLU, without a max pooling layer. Instead, the last layers form one fully connected layer, one softmax layer and a Classification Output layer with classes ‘0’ for images with closed and ‘1’ with open eyes. The training set consisted of 100 images for opened and 100 for closed eyes. A sample of 20 images used for training and validation is given in Figure 5:

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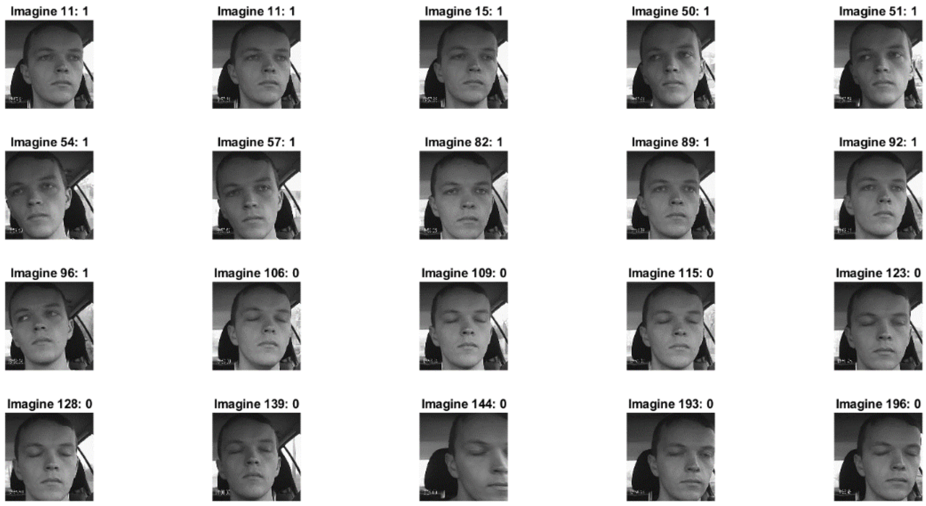


Figure 5 The samples of whole face images used for training and validation.

## 3. Results and discussion

The results of the training process are given in *Figure 6.* After repeated training sessions, we obtained a maximum classification accuracy of 87.5%.

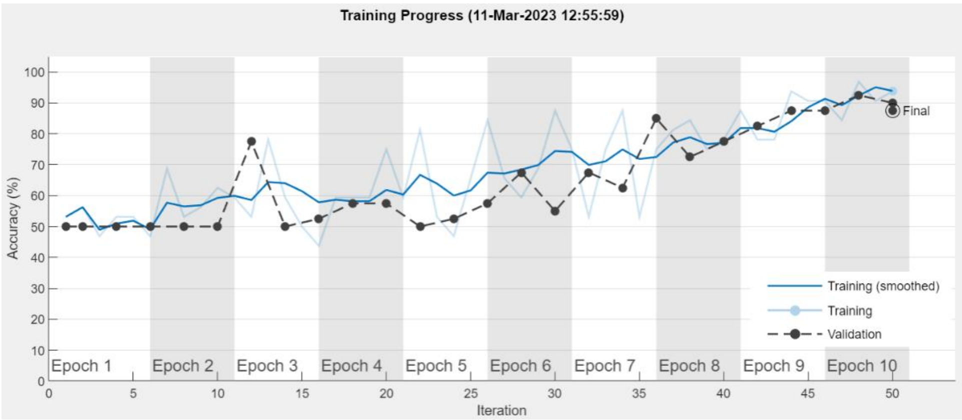


Figure 6. Evolution of accuracy over training epochs for the entire face detection.

In order to improve the accuracy of the classification, we used as input images only the upper half of the previously used whole-face images and trained the same network. We constantly obtained accuracy levels between 97.5 and 100% for successive training sessions. A sample of 20 randomly chosen images is depicted in *Figure 7*, and the evolution of accuracy as the training progresses shown in *Figure 8*.

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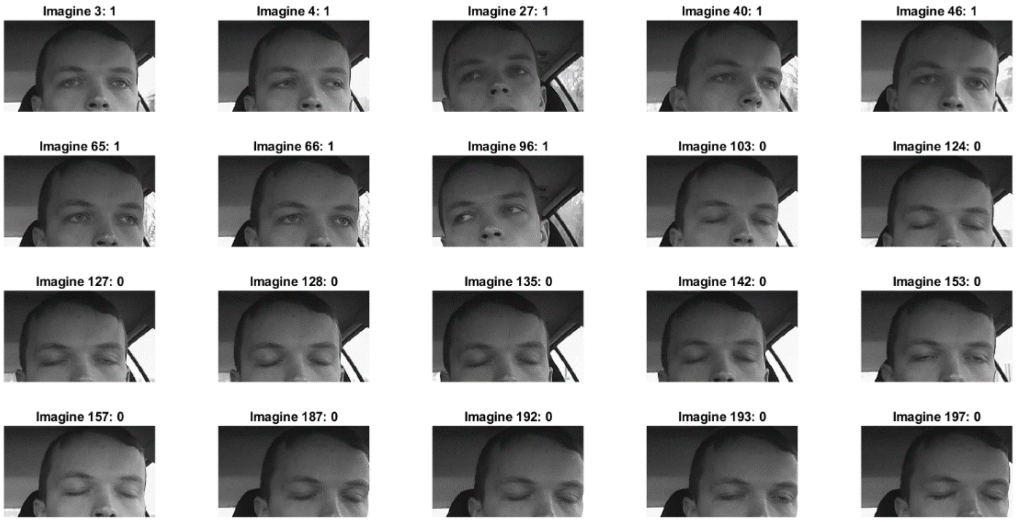


Figure 7. 20 samples of upper half face images used for training and validation.

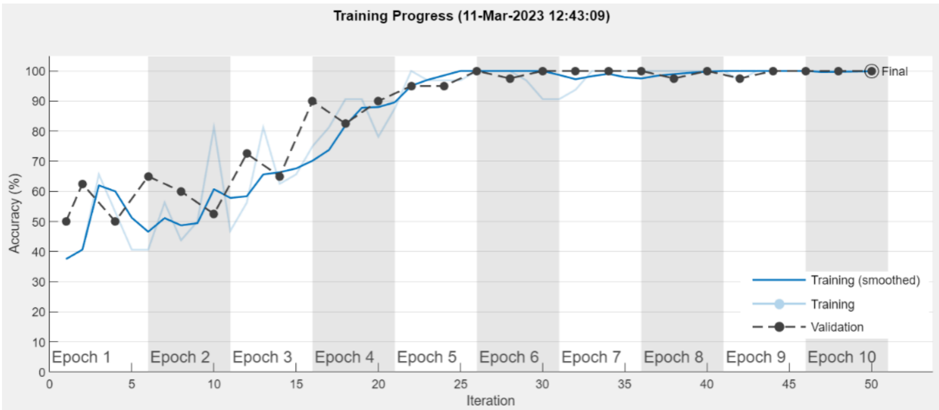


Figure 8. Evolution of accuracy over learning epochs for the upper half face detection.

It could be observed that under optimal brightness conditions and if the neural network has a large enough database for training and learning, the system has increased accuracy in detecting the driver's state. Even if this system, based on video monitoring of the driver's activity, is perhaps the most comfortable, it must have a backup solution in case of malfunctions, which often refers to sensors that must be in contact with the driver. Albadawi et al. (2022) present such hybrid fatigue monitoring systems.

While great strides have been made in autonomous driving, the technology is not sufficiently developed to be relied upon in every driving situation. Considering the levels of autonomy defined by SAE International (*Shuttleworth, 2019*), driver monitoring would be beneficial up to SAE level 3. Thus, implementing such systems to monitor driver fatigue would bring an important benefit to road safety.

For the same reason, several institutes have started to take action on this issue to reduce the number of accidents due to driver fatigue and avoid generating traffic jams and wasting resources. A EURO NCAP document of July 2022 also refers to driver (fatigue) monitoring systems. Moreover, according to Regulation *(EU) 2019/2144* of the European Parliament and the Council, car manufacturers must introduce driver fatigue monitoring systems from 7 July 2024 for all new motor vehicles. The Explanatory Memorandum (*EU, 2021*) sets out much of the technical detail that car manufacturers must consider.

## 4. Conclusion

In conclusion, the mandatory implementation of fatigue monitoring systems on new vehicles will initially influence the development and implementation costs, increasing the vehicles' production costs. However, the main attributes of such a system will only become apparent after its widespread in vehicle construction. The major expected benefit would be to reduce the high number of accidents (fatalities + material damage) due to driver fatigue or reduce the severity of accidents. Even if the number of accidents were to decrease by only a few percent, it would still be a significant benefit, considering the secondary costs arising from road accidents.

A possible future research direction on this topic would be to test neural network functionalities when brightness conditions are greatly impaired by either strong sunlight or poor cabin illumination.

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# Ranking of four dual loop EGR modes

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**Abstract**
Modern Diesel engines contain sophisticated control systems to keep their environmental impact low for sustainable road transport. One of these systems is the dual loop exhaust gas recirculation, which can change combustion properties in several ways. This article presents an engine dyno measurement based on analyzing the duel loop EGR with a medium-duty Diesel engine. Intake throttles and exhaust brakes for the highest freedom in the air-fuel ratio setting support the EGR systems. The EGR modes are compared from fuel consumption, $NO_x$ emission, and exhaust gas opacity in steady and transient operations. There are expected results, for instance, in the HP EGR's faster reaction time or the LP EGR's boost pressure holding property. Unexpected results are also presented. Contrary to theory, LP EGR generally provides a fuel consumption advantage in many operation points due to its higher boost pressure. Typically, HP EGR can provide lower fuel consumption at higher engine power. In the emission results, LP EGR is favourable both in $NO_x$ emission and exhaust gas opacity, whereas the intake throttle-supported HP EGR usually shows the highest emission. Besides, with high EGR rates at lower engine loads, LP EGR can realize low-temperature combustion, where both emissions decrease. No difference can be detected between the LP EGR's support valves' results. HP EGR was faster in the transient operation, with about half the reaction time. The results can be utilized for dual-loop EGR layout and control design.

**Keywords**
Diesel engines, dual loop exhaust gas recirculation, exhaust brakes, nitrogen-oxide emission, exhaust gas opacity.

## 1. Introduction

Today's Diesel engines are one of the most complex engineering products ever made (Guzella and Onder, 2010). Besides the automated driving functions, internal combustion engine control is probably the most sophisticated system in road vehicles. They can work reliably when several science disciplines' achievements and experiments are designed into their complex systems. However, their operation principle cannot be changed: imperfect combustion processes produce undesirable, harmful emissions. The changes for sustainable road transport impose new requirements, and new technologies are applied. Due to the electrification of road transport, research in the field of internal combustion engines is in decline. The future of these engines depends on emission regulation and green or synthetic fuels *(Rajkumar and Thangaraja, 2019, Virt and Arnold, 2022*), but even with these, engines cannot reach zero harmful emissions (*Zöldy et al., 2022*). The change will be more difficult with commercial vehicles. Probably, Diesel engines will remain in this segment for a longer term (Sinay et al., 2018).

Before the alternative fuel research, Diesel engines were developed with more precise control systems (*Wang, 2008; Bárdos et al., 2016; Castillo Buenaventura et al., 2015*). There can be several control aims: low fuel consumption, low emission, better performance, etc. One of them is to minimize nitrogen oxide ($NO_x$) and particulate matter (PM) emissions altogether. Their formation during combustion is counterproductive (*Abián et al., 2018*). However, optimums can be found with the control of the combustion (*Divekar et al., 2015; Luján et al., 2015*). Furthermore, cooperation with the exhaust after-treatment system can also determine the rate aims of forming these harmful emissions (*Mao, 2015*).

Exhaust gas recirculation (EGR) is a commonly used solution to reduce $NO_x$ emissions. EGR can be realized with the valvetrain (internal EGR) and an additional pipe system between the exhaust and the intake side (external EGR). In a turbocharged engine, the latter can be realized in two ways: on the low and high-pressure sides of the turbocharger (Grondin et al., 2009). Based on this, low-pressure exhaust gas recirculation systems (LP EGR) and high-pressure exhaust gas recirculation systems (HP EGR) can operate in a given engine. Their common name is the dual-loop EGR system. Several articles discuss these systems' properties (*Millo et al., 2012; Reifarth, 2014*). A summary presents them in Table 1:

Table 1. Advantages and disadvantages of HP and LP EGR *(Nyerges and Németh, 2014)*

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| HP EGR | LP EGR |
|---|---|
| fast response, favourable in transient cycles | slower response, higher boost pressure because all exhaust gas runs through the turbine, favourable in stationary cycles |
| the time for gas mixing is shorter | longer time for mixing, but the condensed water can damage the compressor |
| it increases fuel consumption, but in high power demand operations, it can provide lower BSFC | it increases the BSFC less than the HP EGR because of the higher boost pressure |
| Using both systems on the same engine has the advantage of optimization | |

In external EGR systems, the EGR valve controls the mass flow rate of the recirculated exhaust gas. The pressure difference between the exhaust and intake sides determines this configuration's maximum EGR mass flow rate. Diesel engines sometimes require more EGR than this limit in low-load operation. Support valves can be utilized to increase further EGR mass flow rate: an intake throttle (THR) can reduce fresh air intake, or an exhaust brake (EB) can reduce the exhaust gases that leave the air-path system (*Nyerges and Zöldy, 2020a*). These valves give intake oxygen rate control a significant degree of freedom (*Bárdos and Németh, 2017*). Even rich combustion can be set too. These valves can realize four EGR modes: HP or LP EGR with intake throttle or exhaust brake support.

Traditionally, engine performance and emission can be influenced in two ways: changing the combustion or changing the charge exchange processes. The former can be achieved by combustion timing or with different injection strategies (Vass and Zöldy, 2020). The latter method also changes the combustion indirectly by the pressure, temperature, or composition of the intake charge (Nyerges and Zöldy, 2020b). The EGR plays a role in the second method. In summary, the effects of EGR on engine operation are composed of the following.

- The oxygen concentration of the intake charge and the air-fuel ratio of the combustion decreases.
- The higher ratio of burnt gases slows down the combustion processes.
- The higher intake charge temperature decreases volumetric efficiency.
- With HP EGR, the turbine mass flow rate decreases, i.e., the engine-turbocharger cooperation changes.
- With HP EGR, the engine's pumping loss may decrease, i.e., the volumetric efficiency can be improved.
- Due to these, brake efficiency and fuel consumption change generally increase. Higher fuel consumption causes higher exhaust gas enthalpy, which may improve the engine-turbocharger cooperation.
- Consequently, the emission map changes (generally, $NO_x$ emission decreases, and PM emission increases).
- Due to the slower combustion, the in-cylinder pressure characteristics are also changed, and the engine's run becomes smoother and more silent.

Several articles compare the HP and LP EGR systems (*Zamboni and Capobianco, 2012; Cornolti et al., 2013; Mao et al., 2016*), and some analyze the effect of high EGR rates (*Nyerges and Zöldy, 2020c*). However, no article exists where these four EGR modes are analyzed and compared. This paper aims to analyze the properties of the different EGR modes. The measurements were done using a medium-duty Diesel engine (MDD) dyno. The paper will compare the EGR modes from the following aspects: $NO_x$ and soot emission, fuel consumption and efficiency, air path system's $O_2$ concentrations, and pressures, both in steady state and transient operation. The paper aims to offer advice on optimal air path system layout.

## 2. Measurement considerations

### 2.1. Engine dyno

Our research group has an engine dyno with an MDD engine. It has been used in several research projects in the last decades, primarily for engine modelling (*Nyerges and Zöldy, 2020a*), control (*Bárdos et al., 2016*), and injection and combustion analysis (*Virt et al., 2021*). The general parameters of the engine are shown in Table 2. The low speed and high torque range with relatively high boost pressure is important properties. The boost pressure control is conventional, wastegate type. Initially, it did not have any EGR systems. They have been designed and mounted onto the engine in the last few years.

Table 2. Engine parameters (*Bárdos and Németh, 2013*)

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| | |
|---|---|
| Type | turbocharged Diesel, in-line, four-cylinder |
| Maximum power | 125 kW (2500 1/min) |
| Maximum torque | 600 Nm (1200-1600 1/min) |
| Displacement | 3.9 l |
| Stroke/bore ratio | 1.176 |
| Compression ratio | 17.3 |
| Injection system | direct injection, common rail |
| Maximum boost pressure | 2.5 bar |

The air path system of the engine is depicted in Figure 1. It has two EGR systems and four support valves. The LP intake throttle is mounted upstream of the LP EGR mixer; therefore, it can increase the LP EGR rate. Similarly, the HP intake throttle can also increase the HP EGR rate. It is mounted between the compressor and the HP EGR mixer.

The placement of the exhaust brakes is slightly different. The short air path of the exhaust manifold is important for efficient turbocharger operation, i.e. the first exhaust brake (EB1) cannot be mounted upstream of the turbine. Instead, it supports the HP EGR system downstream of the turbine at low pressure. The second exhaust brake (EB2) is placed at the end of the air path system. All of the six valves are controlled electronically.

For comparison, several measurement opportunities are available. Besides the usual operation properties (speed, torque, fuel consumption), the $O_2$ and $NO_x$ concentrations in the air-path system can be measured by Lambda and UniNOx sensors (*Nyerges and Zöldy, 2020c*), an opacimeter can measure the opacity of the exhaust gas, and the boost pressure and the intake fresh air mass flow rate are also measurable.

The engine operation, basically the injection strategy, is controlled by the engine's own ECU:

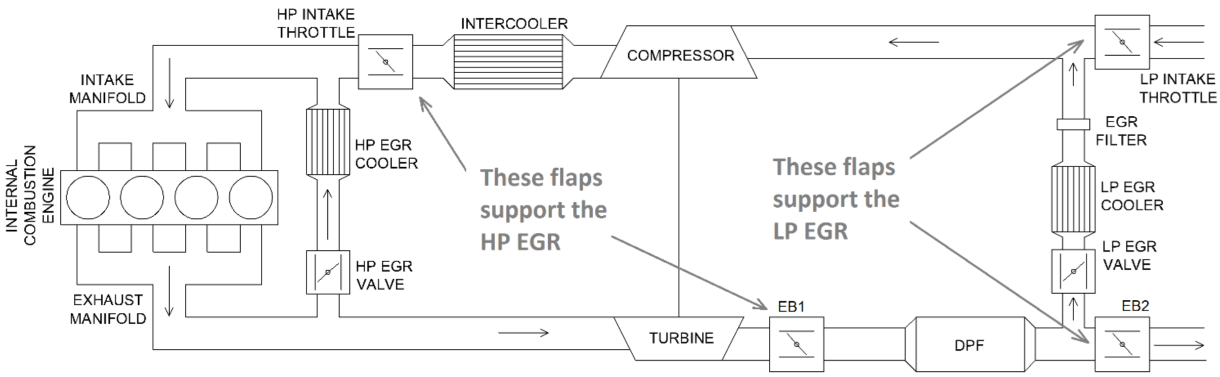


Figure 1. The air path system of the engine dyno (*Nyerges and Németh, 2014 p3.*)

### 2.2. Measured operation points and experiences

Conventional Diesel engines always run with a lean air-fuel ratio (AFR). Lower AFR results in progressively increasing PM emissions. Therefore, the PM emission classically determines the lowest AFR limit and, indirectly, the engine's maximum torque (*Huang et al., 2014*). As the load is reduced, the AFR also gets leaner. Since the EGR decreases the AFR, EGR can be applied only at lower loads. The steady-state operation point selection considered these for the EGR mode comparison. The selected operation points are shown in Figure 2:

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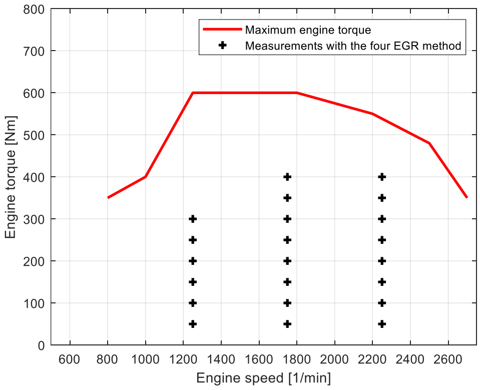


Figure 2. The measured and analyzed operation points

Three-speed levels are selected evenly from the engine's speed range. There are two main differences between these speed levels. Due to the engine's original emission standard, the injection strategy (by the ECU) on lower speeds does not have pre-injection: this causes high NOx and low PM emissions. Due to the significant pre-injection, the emission map changes to lower $NO_x$ and higher PM emission at higher speeds. The other difference between the speed levels is the turbocharger operation. At 1250 1/min, the boost pressure is not significant. At 1750 1/min, the boost pressure changes show its effect from low loads to higher ones.

Moreover, finally, at 2250 1/min, the boost pressure is significant even at a low load. The torque demand steps are selected at 50 Nm intervals. Altogether 22 operation points were analyzed. On the highest applied torques, the AFR is low even without EGR.

It can be stated that the support valves can only be applied on very low loads. The comparison between the intake and exhaust support valves cannot be predicted. The exhaust brakes can provide better fuel consumption (*Nyerges and Zöldy, 2018*), but this research was based only on simulation results. The pressure drop through the HP EGR system is more significant (due to the turbocharging) than in the LP EGR systems. The LP EGR system's pressure levels are always close to ambient pressure. This is why LP EGR is more sensitive to the EGR valve position (*Zamboni et al., 2017*).

### 2.3. Measurement challenges

The measurements presented some unexpected challenges. To ensure the reproducibility of the measured characteristics, the four EGR modes were measured one after another on the same speed and torque level but always in changing order. The aim was to avoid the EGR modes' consistent effect on each other.

The EGR mode's measurement always started without EGR. Then in the first phase, the EGR valve (HP or LP) was opened step by step. When the EGR valve was fully opened, the selected support valve (intake throttle or exhaust brake) was closed step by step again in the second phase. The support valve closes until the combustion becomes unstable – typically in the rich AFR zone. Conventionally, the stoichiometric and rich AFR in road vehicles' Diesel engines is not utilized due to the high PM emission (*Zeng and Wang, 2014*). However, the present paper also aims to analyze the effects of the unusually high EGR rates where even alternative Diesel combustion can be realized. Typically an EGR mode measurement resulted in 10-15 steady-state operation points on the same speed and torque level.

It was important to consider the transient effects on the results. There were fast transient changes after the valve position changes: the pressures, mass flow rates and charge compositions. The decay of these transients typically requires 5–15 seconds.

Eliminating the slower transients from the results was the more difficult challenge. These are typically temperature changes. During the measurements, the temperature of the engine dyno's cooling system slightly changes, as well as the temperature of fresh air intake. As shown above, this effect is eliminated by order of the operation points and the EGR modes. Due to the EGR mass flow rate changes, the wall temperatures of the air path system also changed with slightly slow transients. These changes were slower than those mentioned above, 5–15 seconds, but their effect was about 5–20 ppm $NO_x$, which was finally neglected. In summary, the effects of the temperature changes were difficult to eliminate, but the extent of the effect is significantly slighter than the EGR modes' and changes' effects.

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The third property that can cause inaccuracy is the positioning of the valves. There is always some leakage with closed valves, and the realized valve position is not always the same as the position demand. The presentation of the results eliminates the effect of this issue: the different characteristics are always depicted in the function of the $O_2$ concentrations, the air-fuel equivalence ratio, or the EGR rate.

## 3. Measurement results

### 3.1. Experiences

The first challenge in creating the measurement strategy was how the different EGR methods could be compared. The aim is to select a parameter that can be the same in the different EGR mode operations. The following important parameters change due to EGR:

- Intake parameters: oxygen concentration, boost pressure, temperature.
- Exhaust parameters: oxygen concentration, turbine backpressure.
- In-cylinder: air-fuel ratio, combustion speed.
- The mass flow rate through the cylinders, EGR mass flow rates.

The selected parameter should characterize the EGR operation. It should provide an objective comparison of the different modes. Advantageous if the available engine sensors can measure it.

Usually, the first approach for the comparison is the EGR rate, which gives the ratio between the EGR's and the engine's mass flow rate. Due to the lean AFR operation, the exhaust gas of Diesel engines can contain a large amount of fresh air (i.e. oxygen). Therefore, the EGR rate does not reveal much important information about the engine's operation. Moreover, with the same EGR rate, all engine parameters can be different (*Park and Bae, 2014*).

EGR rate ($x_{EGR}$) can be estimated from the $O_2$ concentrations by (1), where AMB refers to the ambient conditions, IM refers to the intake manifold, and EM refers to the exhaust manifold (*Guzella and Onder, 2010*).

$$x_{EGR} = \frac{x_{AMB} - x_{IM}}{x_{AMB} - x_{EM}} \qquad (1)$$

Without EGR, the intake charge has the ambient oxygen concentration. With the increasing EGR rate, the intake $O_2$ concentration decreases. The lowest level depends on the engine's $O_2$ consumption. On the exhaust side, the change is similar to an "$O_2$ concentration offset". Without EGR, the exhaust side $O_2$ concentration depends on the engine load, but it is equal to the difference between the ambient $O_2$ concentration and the $O_2$ consumption. With the increasing EGR rate, the exhaust side $O_2$ concentration also decreases until the combustion process becomes unstable, typically with rich AFR.

The air-fuel equivalence ratio can be estimated from the measurements by (2) from the fresh air and fuel mass flow rates ($\sigma_{air}$ and $\sigma_{fuel}$) or by the $O_2$ concentrations of the intake and exhaust manifold ($x_{O2,IM}$ and $x_{O2,EM}$). Due to accuracy issues, the mass flow rate-based equation was used (Jung et al., 2014). $K_{L0}$ is the stoichiometric air-fuel ratio.

$$\lambda = \frac{\sigma_{air}}{\sigma_{fuel} K_{L0}} \approx \frac{x_{O_2,IM}}{x_{O_2,IM} - x_{O_2,EM}} \qquad (2)$$

In summary, the advantages of the different aspects:

- The intake $O_2$ concentration shows the EGR's operation.
- The exhaust $O_2$ concentration shows the EGR potential.
- Moreover, the AFR shows an important parameter of combustion properties.

And the disadvantages:

- None of them contains the effects of boost pressure changes.
- The intake $O_2$ concentration does not show the EGR potential.
- The exhaust $O_2$ concentration does not show the intake properties.
- Moreover, while the $O_2$ concentrations are directly measurable, the AFR is just estimated, i.e. it can be inaccurate.

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Finally, intake $O_2$ concentration was selected for the basis of the comparison. This choice has several arguments: $O_2$ concentration provides understandable information about EGR and is easily measurable and controllable. Since it does not contain the mass flow rate changes, it highlights the turbocharger operation advantages of LP EGR. Consequently, in this paper, the EGR modes are comparable when they produce the same intake oxygen concentration.

The comparison of the different EGR presentation diagrams is shown in Figure 3 and Figure 4. The analyzed effect is the fuel consumption change with the four EGR modes. The explained properties significantly appear: the different presentations show different rankings for the EGR modes. In function of the intake $O_2$ concentration LP EGR provides lower fuel consumption characteristics in these operation points. Meanwhile, its advantage disappears in the function of the exhaust O2 concentration, air-fuel equivalence ratio, or even ranking turns.

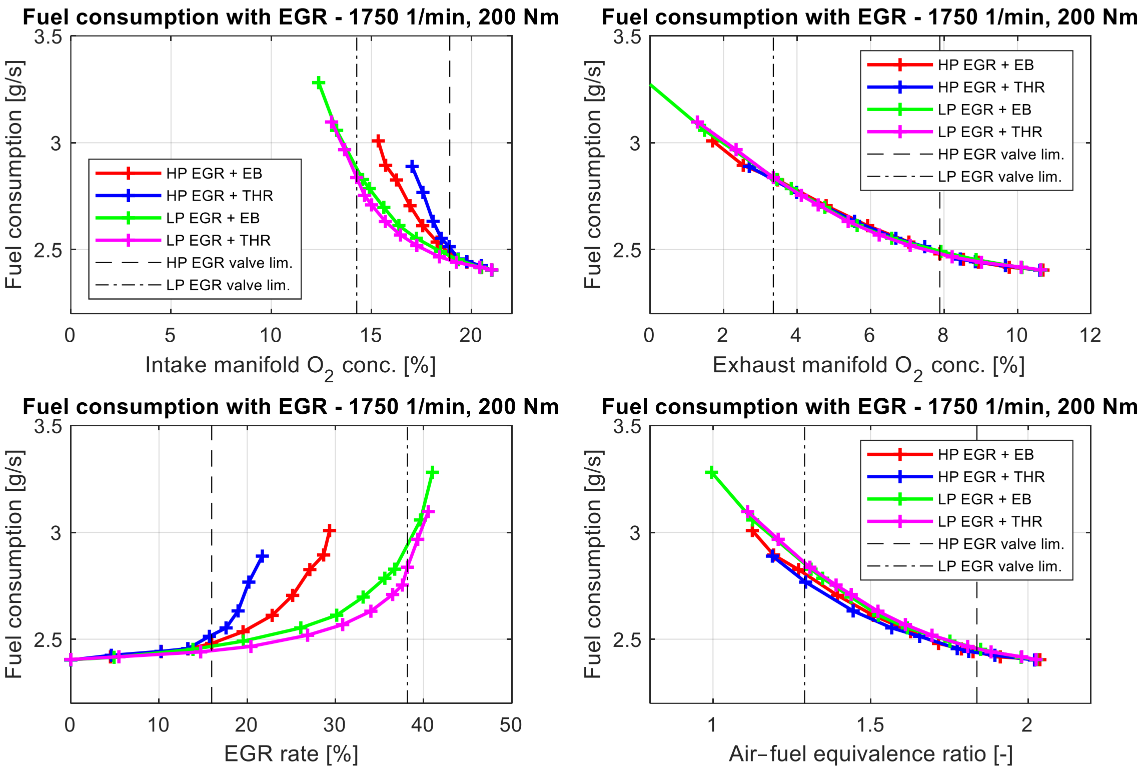


Figure 3. An example of the different EGR effect presentations at the same operation point (1750 1/min, 200 Nm)

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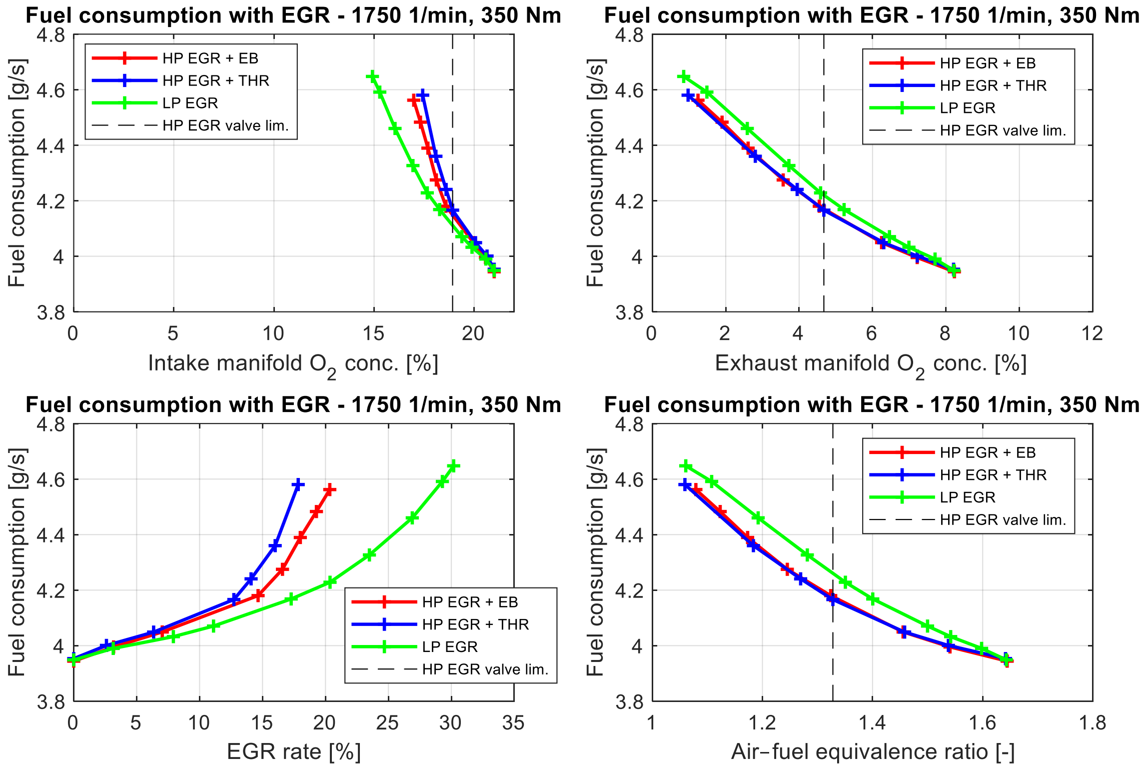


Figure 4. An example of the different EGR effect presentations at the same operation point (1750 1/min, 350 Nm)

As for the curve characteristics, the EGR modes' curves should start from the same point as in the case without EGR. If only the EGR valves set the mass flow rates, there should be only two curves (HP and LP EGR) because the support valves do not change in this phase. The figures in the results section will also show the limits of the EGR valves (without using the support valves). In this example, the LP EGR valve has a much higher EGR rate potential than the HP EGR – this property will be typical for all results. Finally, with high EGR rates, there can be four different curves due to the intake throttles and exhaust brakes – if there is any difference in the operation of these valves.

The presentation of all the measurement results would exceed the limits of this paper. The most representative ones are always selected for each type of test. Above average 200 Nm, the support valves are unnecessary to reach the stoichiometric AFR. Therefore, the lower load operation is preferred.

### 3.2. Steady state operation

In this section, the stationary measurement results will be presented. First, how the oxygen concentration changes in the air path system will be shown. These characteristics allow the EGR systems' operation to be understood more thoroughly. Next, the engine performance-related results will be analyzed: fuel consumption, engine efficiency, and boost pressure. Finally, the emission-related properties will be discussed: $NO_x$ and exhaust gas opacity.

#### 3.2.1. Oxygen concentrations

This section aims to analyze the operation of the EGR systems through the oxygen concentration changes in the air path system. Two operation points will be used: 1250 1/min with 100 Nm (small power, slight boost pressure), and 1750 1/min, 150 Nm (medium power, medium boost pressure). Figure 5 and Figure 6 depict the changes from several aspects.

As explained above, the intake side oxygen concentration shows the amount of the recirculated burnt gases. On the other "side", the exhaust gases' oxygen concentration indicates the combustion properties within the AFR. I.e., the exhaust side oxygen concentration is an EGR reserve: when it runs out, the combustion reaches the rich AFR zone.

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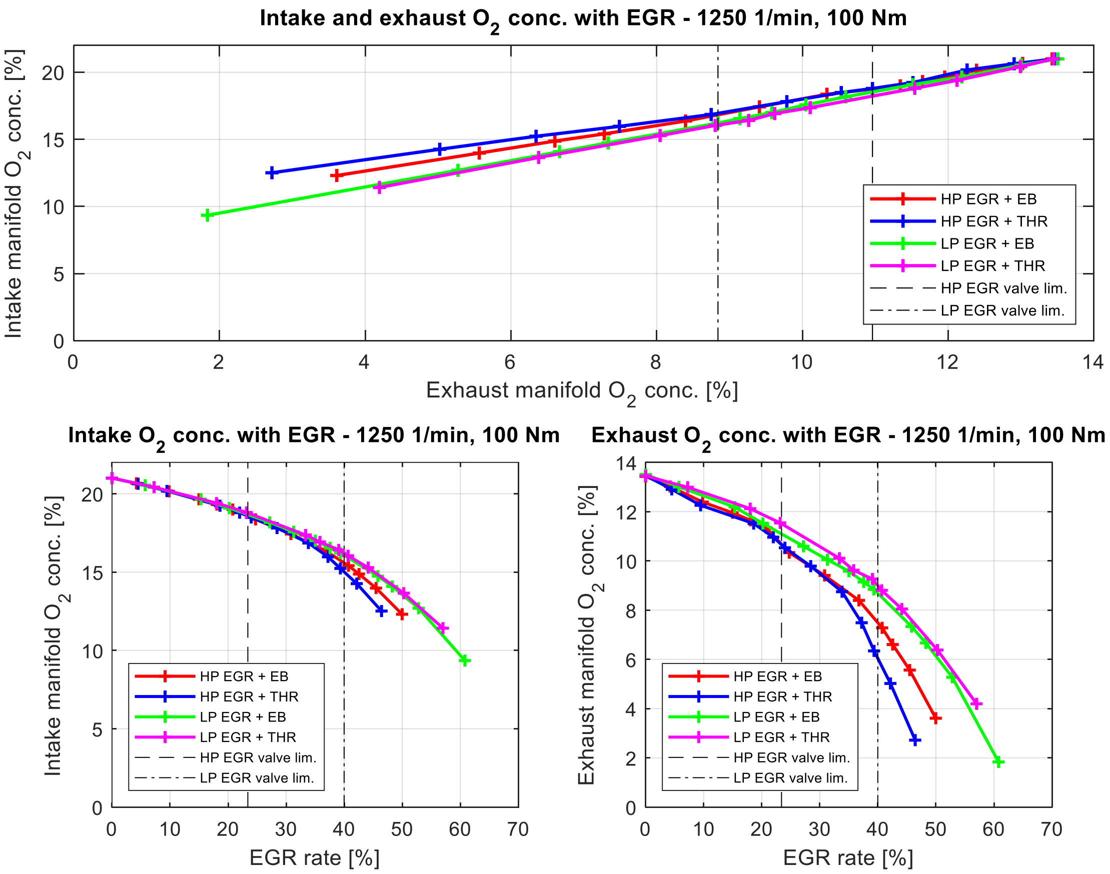


Figure 5. Intake and exhaust oxygen concentration changes (1250 1/min, 100 Nm)

Significant differences are shown between the HP and LP EGR; smaller differences are between the support valves if we compare the curves. The higher $O_2$ concentration change through the engine can signal either higher fuel consumption or lower mass flow rate through the engine (or generally both). Since the cylinders' mass flow rate significantly decreases with HP EGR, HP EGR's oxygen concentration change is usually higher.

The EGR rate-based diagrams also prove the engine mass flow rate changes: much higher EGR rates can be reached with LP EGR. The exhaust side O2 concentration is also higher, with a higher engine mass flow rate. Therefore, more exhaust gases can be mixed into the intake charge.

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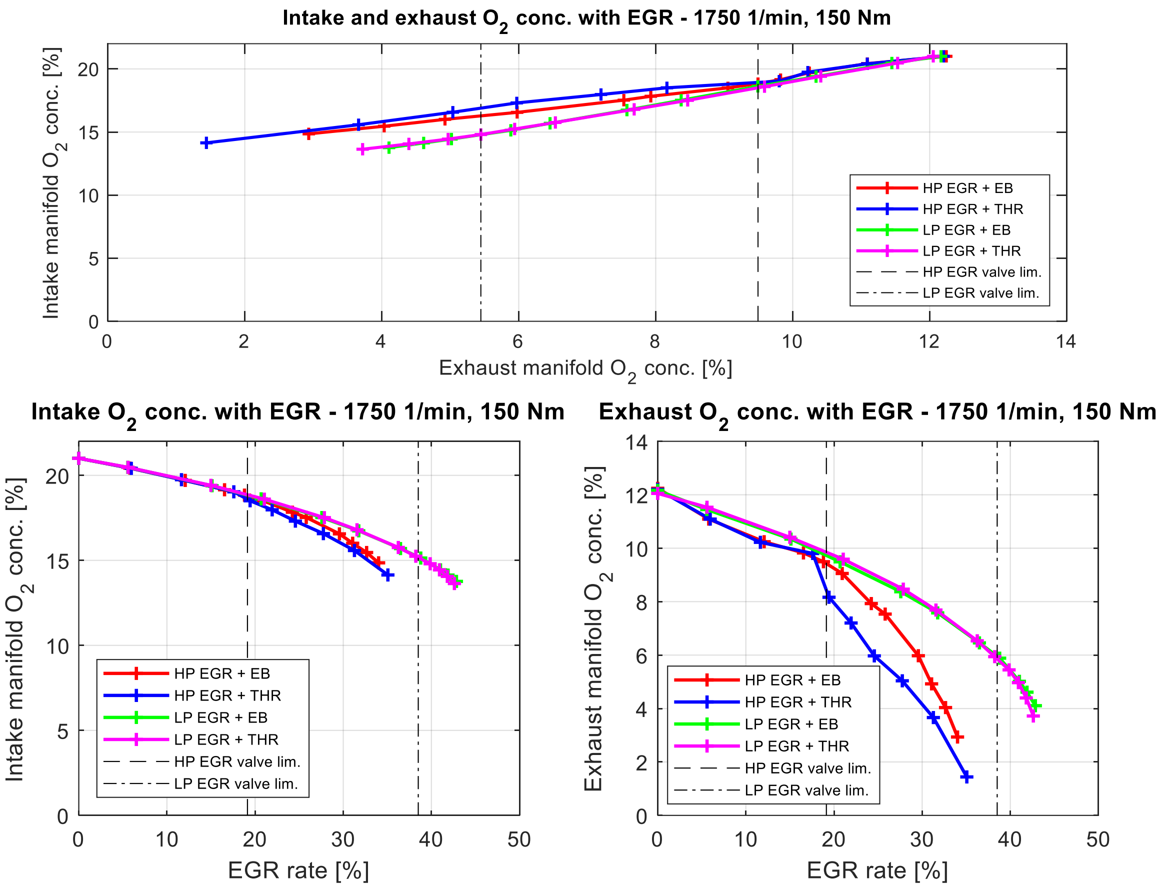

Figure 6. Intake and exhaust oxygen concentration changes (1750 1/min, 150 Nm)

Both in Figure 5 and Figure 6, there is a significant difference between the HP EGR's support valves: the exhaust brake provides higher $O_2$ concentrations. When the support valves take over the role, there is a break in the curves, which is more significant with higher boost pressures. This refers to engine-turbocharger cooperation changes.

With LP EGR, no definite difference can be discovered between the support valves, but in most cases, the intake throttle has slightly lower oxygen consumption. This difference is difficult to detect because the measurement inaccuracies have nearly the same scale. However, the intake throttle-supported HP EGR increases oxygen consumption in both cases.

### 3.2.2. Performance

For the evaluation of results on fuel consumption, three operation points were selected: a small power one (1250 1/min, 150 Nm), a medium power one (1750 1/min, 200 Nm), and a higher power one (2250 1/min, 200 Nm). In these operation points, all four support valves can be utilized. Below, two other operation points will also be presented where the LP EGR does not need support valves.

Figure 7 and Figure 8 show the tendencies at the medium power operation point. In Figure 6, the first diagram depicts the fundamental changes, while the second diagram's y-axis shows the critical interval for detecting the relative changes. In this operation point, fuel consumption increases with increasing EGR. The tendency is progressive. Higher EGR amounts cause higher fuel consumption increases. The overall fuel consumption increase is about 25%, but conventionally the highest EGR rates are not used in road vehicle engines. The fuel consumption differences between the different EGR modes are only significant when the HP EGR support valves take over the role. LP EGR provides lower fuel consumption (the difference can reach 7–10%), and the intake support valve has favourable results. In the case of HP EGR, the exhaust brake is the better choice, with around 3%. Brake-specific fuel consumption (BSFC) and brake efficiency are proportional to the fuel consumption, i.e., they provide similar information. These characteristics can be seen in Figure 8.

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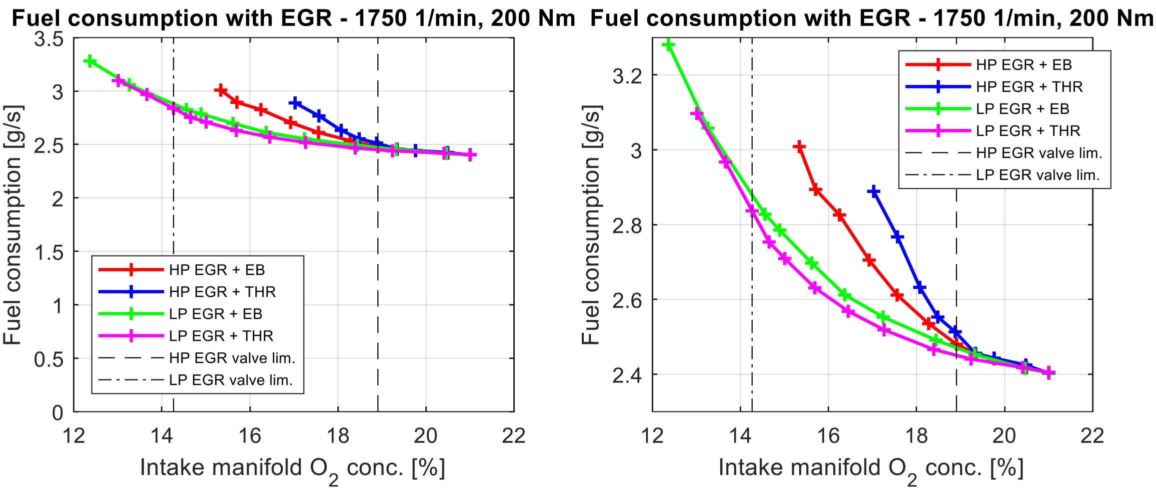


Figure 7. Fuel consumption changes with different EGR modes (1750 1/min, 200 Nm)

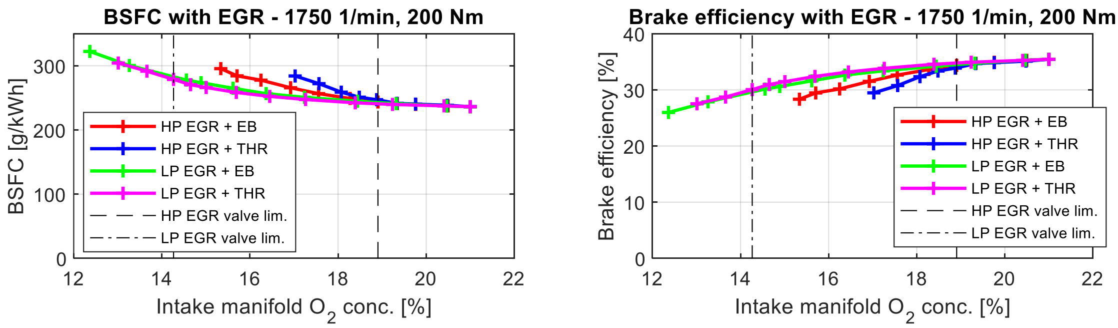


Figure 8. BSFC and brake efficiency changes with different EGR modes (1750 1/min, 200 Nm)

According to measurement experiences, the turbocharger operation highly influences the results. The ranking of the EGR modes can differ when the boost pressure is small (at the increasing phase) or when the boost pressure is high and the wastegate controls it. Considering the basic properties of dual loop EGR, the boost pressure change with LP EGR will be smaller because the turbine mass flow rate can remain similar—instead, the wastegate mass flow rate changes.

Figure 9 shows an example of low-power engine operation with small boost pressure. This operation's overall fuel consumption changes and the differences are smaller. At this operation point, the LP EGR provides lower fuel consumption. Within this example, the intake throttle support mode provides the lowest consumption. The differences are only significant with higher EGR amounts.

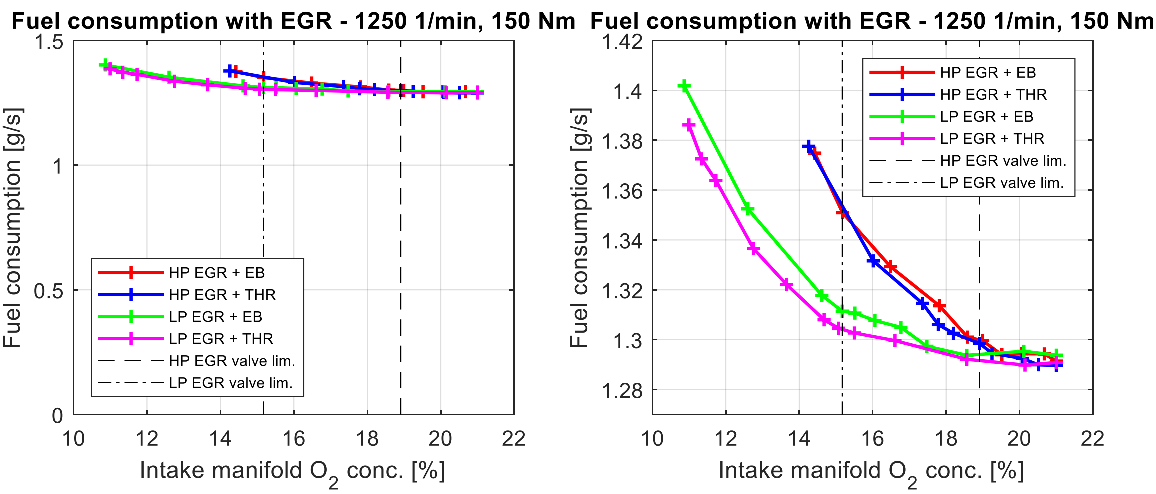


Figure 9. Fuel consumption changes with different EGR modes (1250 1/min, 150 Nm)

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Theoretically, the HP EGR may be able to decrease fuel consumption. If the turbine's backpressure is much higher than the boost pressure, the HP EGR can reduce this difference, i.e., the pumping loss of the engine. The operation with a higher power is represented in Figure 10. At this operation point, the theory is confirmed: the HP EGR system with lower EGR rates improves fuel consumption and increases with LP EGR. HP EGR's maximum fuel consumption advantage is about 2-3%. The ranking turns when the HP EGR support valves take over the role. After that, the LP EGR provides lower fuel consumption again.

The fuel consumption reduction is not notable with HP EGR, it is less than 1%, but it exists. The differences in the support valves are only significant with HP EGR: the exhaust brake lowers fuel consumption by around 7 %.

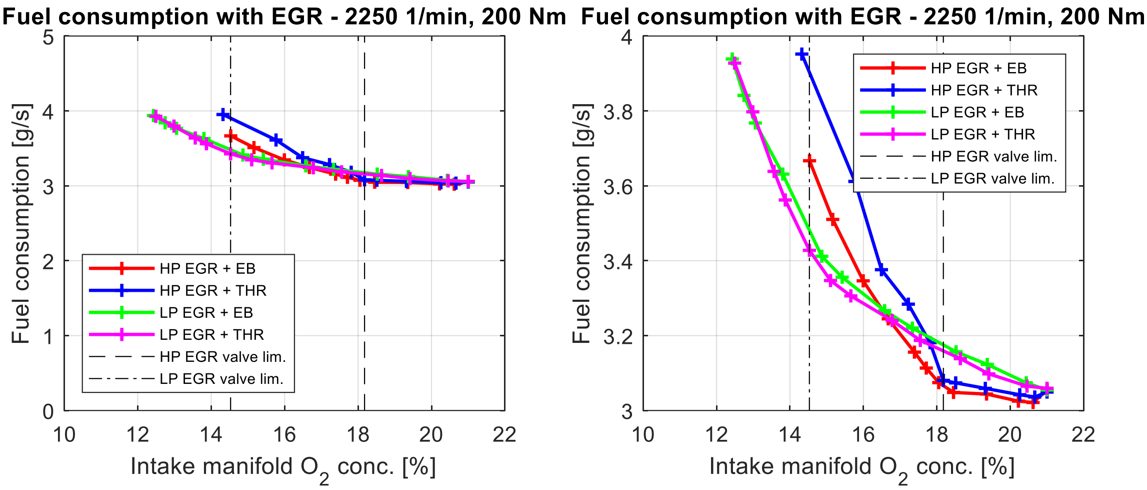


Figure 10. Fuel consumption changes with different EGR modes (2250 1/min, 200 Nm)

Figure 11 and Figure 12 show fuel consumption results with higher loads, where the LP EGR valve can reach the EGR limit, i.e., no support valve is necessary in these cases. The tendencies are similar. LP EGR provides lower fuel consumption at the lower engine speed (1250 1/min, 250 Nm). The difference is slight, barely 1-2% with low EGR amounts, but it can reach 6-7% with higher EGR amounts.

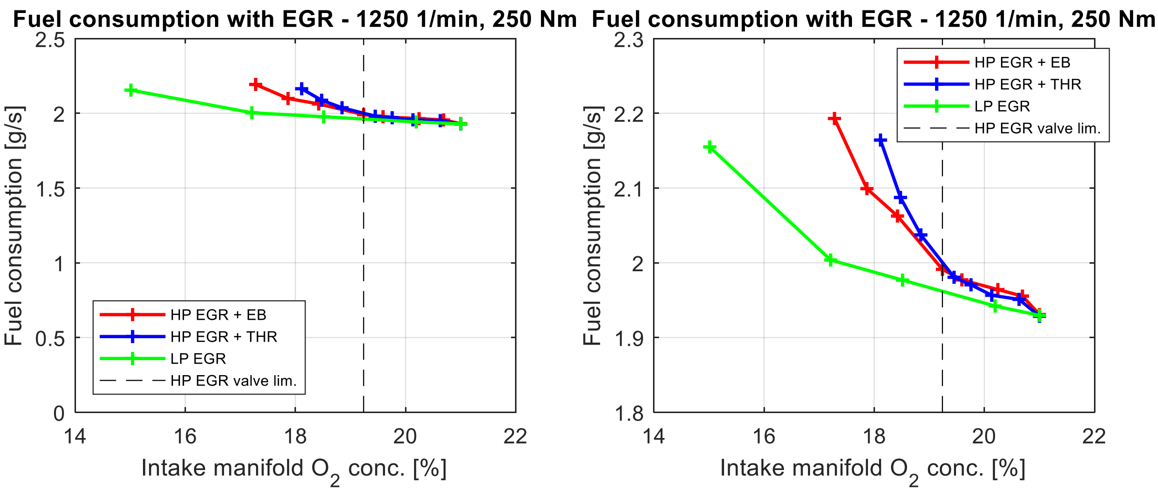


Figure 11. Fuel consumption changes with different EGR modes (1250 1/min, 250 Nm)

In Figure 12, with a higher engine speed (2250 1/min, 400Nm), the tendency turns again: HP EGR has more favourable fuel consumption in the full EGR range. In this case, the difference reaches 1-5%. Both in Figure 11 and Figure 12, the exhaust brake-supported HP EGR provides lower fuel consumption than the intake throttle. The difference is not significant.

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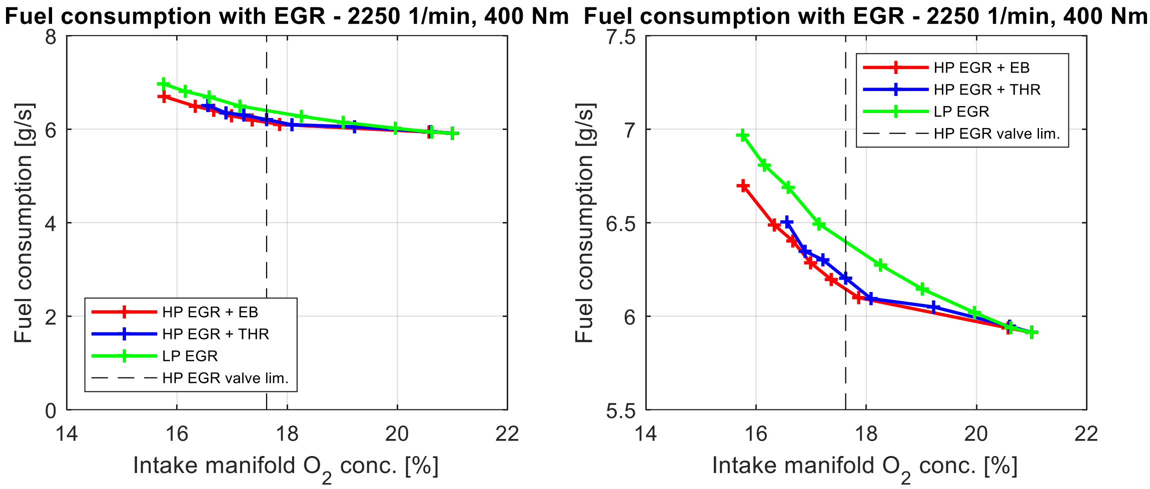


Figure 12. Fuel consumption changes with different EGR modes (2250 1/min, 400 Nm)

As discussed, the main reason for the HP and LP EGR operation differences is the turbocharger operation change. Figure 13 depicts the pressure changes in the intake side in a medium power operation point (1750 1/min, 150 Nm). This operation point has already been presented in Figure 6. Due to the high-pressure intake throttle, the characteristics are different downstream of the compressor and in the intake manifold. The left diagram shows the change in the turbocharger operation: while the HP EGR reduces the boost pressure, with LP EGR, it slightly increases. The boost pressure reduction is expected because the turbine's mass flow rate decreases with the opened HP EGR valve. The LP EGR's increasing boost pressure is caused by the deteriorating efficiency, i.e., the increasing fuel consumption results in higher turbine power.

The pressure in the intake manifold is slightly lower due to pressure losses through the intercooler. Moreover, the high-pressure throttle valve operates here. Therefore, the intake manifold pressure is significantly lower in this EGR mode, as seen in the right diagram in Figure 13. A detailed pumping loss analysis is not the aim of the present paper.

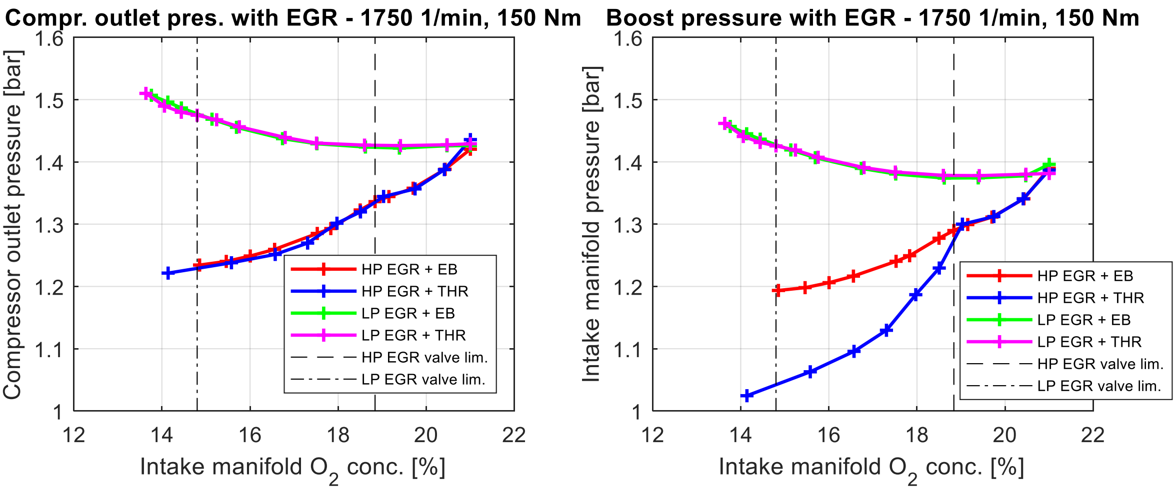


Figure 13. Intake side pressure changes with different EGR modes (1750 1/min, 150 Nm)

Another important aspect would be the detailed analysis of the cooler's effectiveness. The engine has three coolers in the air path system: the intercooler, the HP, and the LP coolers. The left diagram of Figure 14 shows a typical measurement result of the intake charge temperature characteristics. While with HP EGR, the intake temperature keeps its level, with LP EGR, it increases. The engine's LP EGR cooler and intercooler are undersized based on these. Since the compressor multiplies the LP EGR intake temperature, the LP EGR cooler's size would be expedient to redesign.

Figure 14 also presents the intake fresh air mass flow rate characteristics with the different EGR modes. As it is expected, with EGR, it slightly decreases. The comparison basis causes the differences: analyzed as a function of the EGR rate. There would not be such significant differences.

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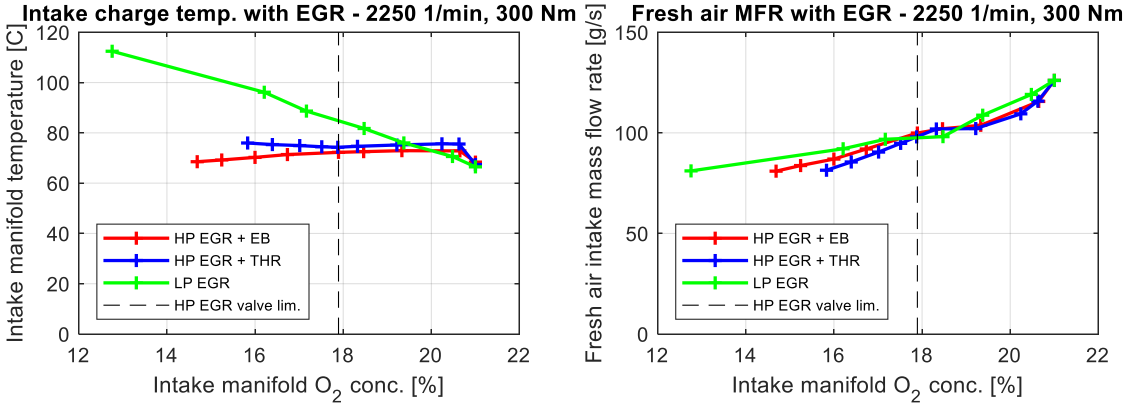


Figure 14. Intake charge temperature and intake fresh air mass flow rate changes with different EGR modes (2250 1/min, 300 Nm)

### 3.2.3. Emission

Since EGR aims to reduce emissions, the most exciting results are expected from this analysis. Diesel engines emit two crucial harmful materials: $NO_x$ and PM. Their elimination is expensive and complicated because their formation is counterproductive (Grondin et al., 2009). This paper does not consider the CO and HC emissions. They can be handled more effectively with catalysts.

Although the method does not give accurate information on the PM emission amount, the diagrams estimate PM emission based on the opacity of the exhaust gas. An opacimeter was available in our research.

The AFR of the combustion mainly influences the proportions of the emission components. Although the injection strategy has a strong effect, it does not change in this research. The engine's original ECU controls injection. This engine produces high $NO_x$ below 1400 1/min. Above this value, $NO_x$ emission is much lower, as shown in the figures below.

The emission characteristics show several different behaviours according to the engine operation points. Therefore, this section will present several engine speeds, and load (and power) levels, generally in ascending order.

First, the low-speed, small-load operation results are presented. Figure 15 shows the measurement results at 1250 1/min and 50 Nm. The $NO_x$ emission takes shape as expected: it strongly decreases with increasing EGR. According to Zamboni and Capobianco (2012), the decrease is exponential. LP EGR provides a lower amount with a medium EGR rate. The difference sometimes reaches 35%. Between the two HP EGR modes, the exhaust brake is significantly better. The difference is about 20-30%. Below and above, the difference is not so significant. There are not any observable differences between the LP EGR modes again. The shape of the opacity curve in Figure 15 offers exciting information. In the first phase, the opacities grow rapidly. The ranking is the opposite as it was with $NO_x$. The change occurs with a high EGR rate: the opacity with LP EGR decreases. Low-temperature combustion with low AFR is called low-temperature combustion (LTC) (Divekar et al., 2015). The opacity is lower with LP EGR all over the range.

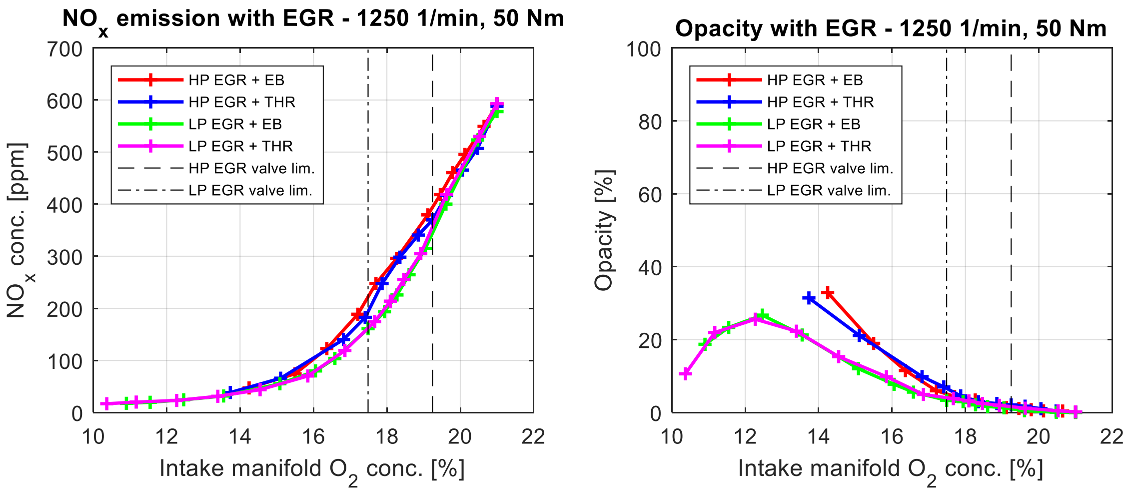


Figure 15. $NO_x$ emission and opacity of the exhaust gas with EGR (1250 1/min, 50 Nm)

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The amounts of harmful emissions are strongly increased with higher load. Figure 16 shows the results at 1250 1/min again, but at 200 Nm. The ranking of the EGR modes is the same, i.e., LP EGR's advantage is low for low $NO_x$ emission but much higher for low soot emission. The HP EGR with intake throttle is a slightly worse mode for $NO_x$ emission again. There is only a tiny difference between the intake throttles and exhaust brakes for better exhaust gas opacity.

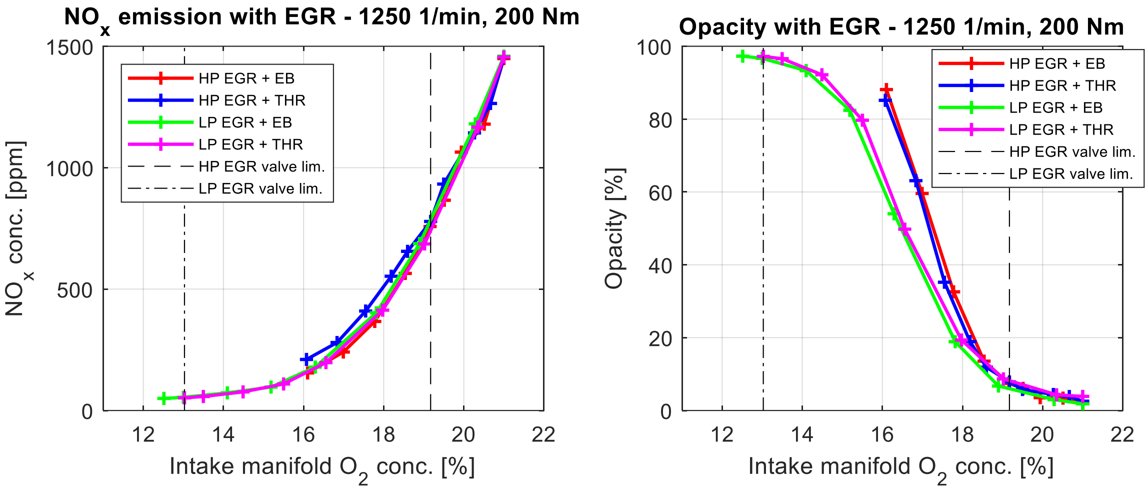


Figure 16. $NO_x$ emission and opacity of the exhaust gas with EGR (1250 1/min, 200 Nm)

In Figure 17 and Figure 18, the emission results can be seen at 1750 1/min. The load level of Figure 17 is 150 Nm. The tendencies are similar to those in Figure 15: with a high LP EGR amount, the opacity decreases again. LTC can be realized at a higher speed than at 1250 1/min. A strong difference can also be seen between the two HP EGR modes: the opacity with intake throttle in the first phase is the best, and then it becomes the worst. From the $NO_x$ aspect, the ranking is the same.

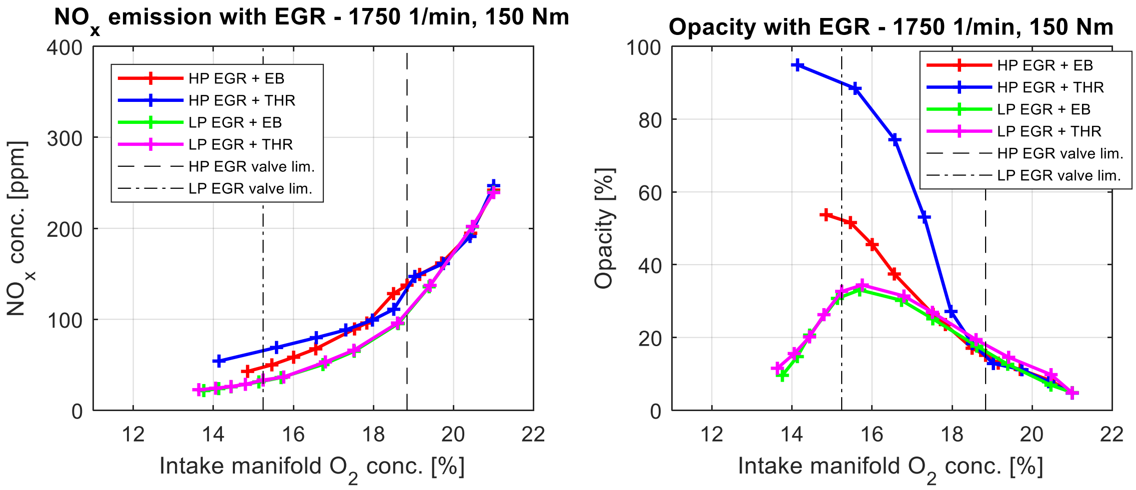


Figure 17. $NO_x$ emission and opacity of the exhaust gas with EGR (1750 1/min, 150 Nm)

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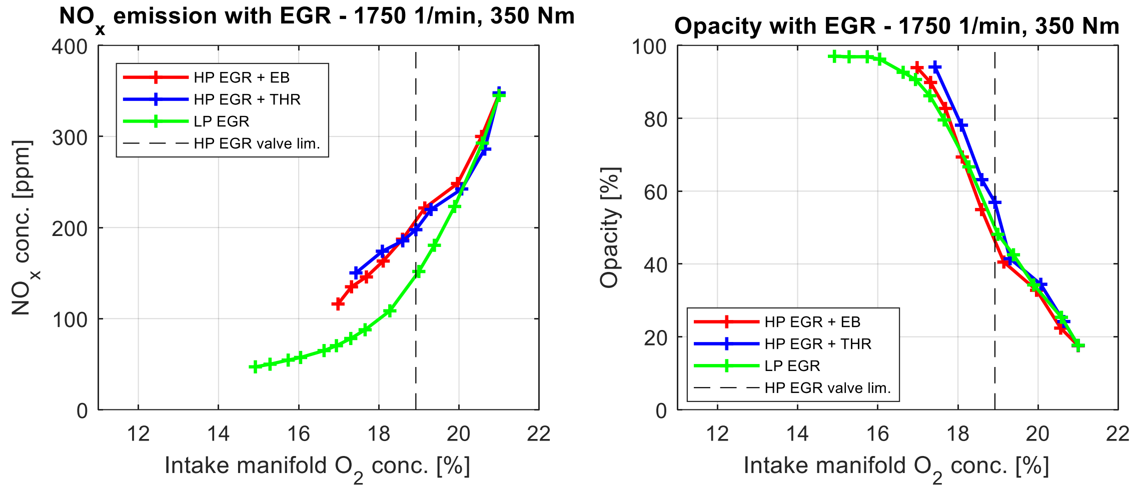


Figure 18. $NO_x$ emission and opacity of the exhaust gas with EGR (1750 1/min, 350 Nm)

In Figure 18, the engine torque is high: 350 Nm. With this load, the LP EGR support valves are not necessary. As in the former results, the differences between the EGR modes are only significant when the HP EGR support valves actuate. After that, the $NO_x$ emission is lower by around 25-30%. LP EGR's opacity advantage is disappeared. For supporting the HP EGR, the exhaust brake is a better choice again. However, the $NO_x$ decrease potential is less effective than with lower loads. The opacity increases very fast for effective $NO_x$ emission reduction.

The following four figures depict the measurement results at 2250 1/min with ascending load levels. The EGR modes show their four diverse faces at different load levels. The first level is 100 Nm in Figure 19. The $NO_x$ characteristics are the same as above: HP EGR with exhaust brake has lower $NO_x$ emission than with intake throttle, and overall, LP EGR provides lower $NO_x$ emission after the HP EGR valve limit (maximum with around 20-30%). The shape of the opacity curves is similar to Figure 17. With small EGR amounts, there is not any difference, but with high LP EGR rates, LTC is realized again. With higher EGR rates, intake throttle-supported HP EGR gets worse again.

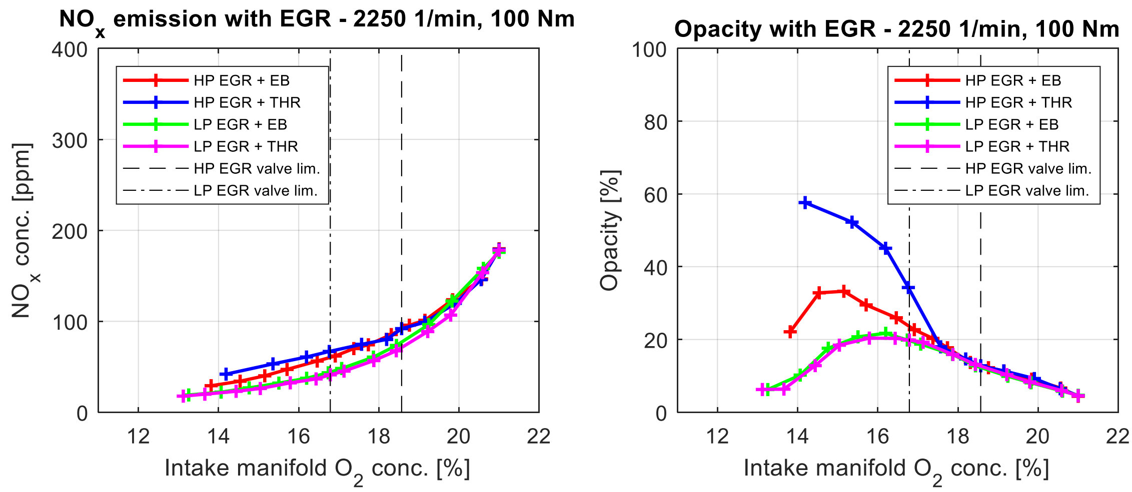


Figure 19. $NO_x$ emission and opacity of the exhaust gas with EGR (2250 1/min, 100 Nm)

The next load level is 150 Nm in Figure 20. Small torque change does not occur in significant changes: the curve shapes and the rankings are nearly identical, and the overall amounts are higher. However, the extremity of the intake throttle supported HP EGR has disappeared. The HP EGR shows a slight NOx advantage (5-10%) with low EGR amounts.

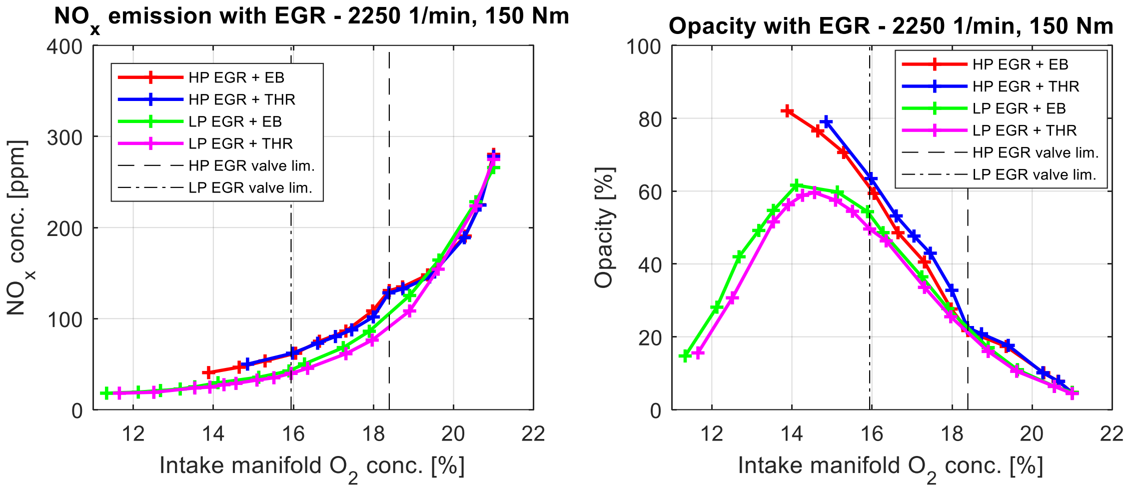


Figure 20. $NO_x$ emission and opacity of the exhaust gas with EGR (2250 1/min, 150 Nm)

The diagrams in Figure 21 show the following torque levels step: 200 Nm. These measurement results have smaller but significant changes again: LTC is no longer feasible. Moreover, HP EGR's $NO_x$ advantage with small EGR amounts slightly increases by around 7-15%. The LP EGR modes are the best, and HP EGR with intake throttle is the worst, as usual.

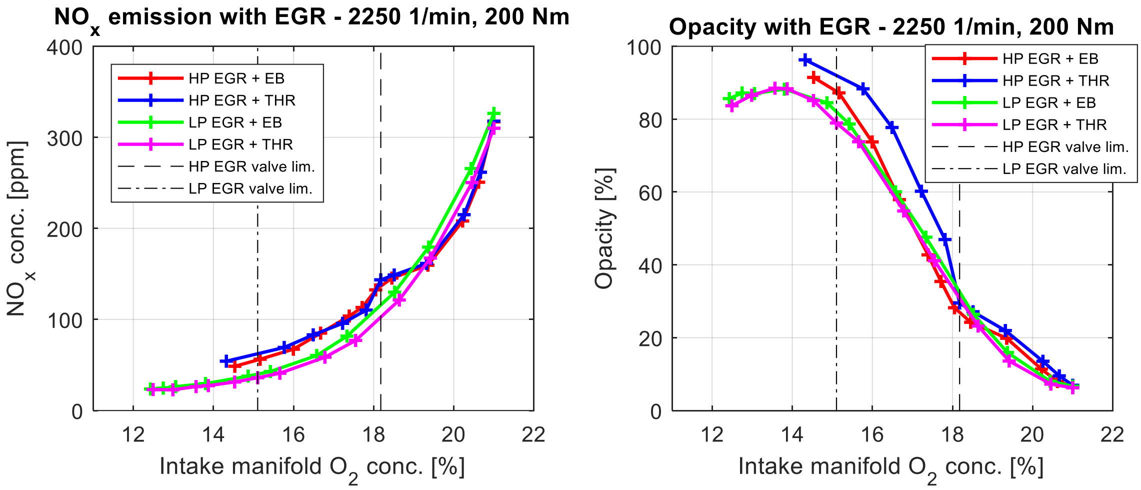


Figure 21. $NO_x$ emission and opacity of the exhaust gas with EGR (2250 1/min, 200 Nm)

The last torque level is 350 Nm, this section's highest power measurement point. Figure 22 depicts the results. Overall the differences become lower. The $NO_x$ advantage of HP EGR is disappeared with low EGR amounts. When the HP EGR support valves take over the role, the LP EGR's $NO_x$ emission decrease is nearly half of HP EGR's. In contrast, the opacity ranking is the opposite. With any intake oxygen rate, the HP EGR has the advantage.

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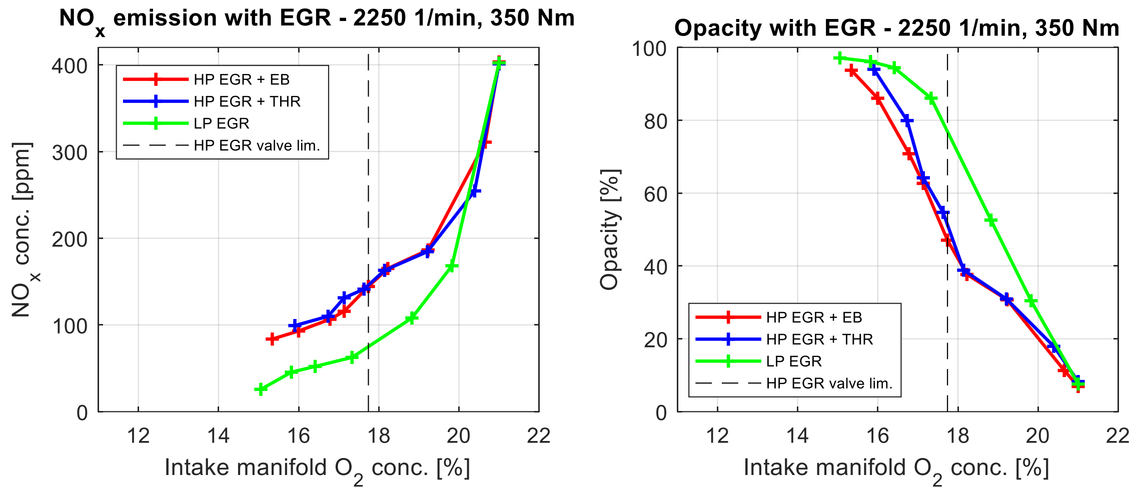


Figure 22. $NO_x$ emission and opacity of the exhaust gas with EGR (2250 1/min, 350 Nm)

### 3.3. Transient behaviour

As discussed in the introduction, the two EGR systems' behaviours in transient cycles differ. Due to the shorter loop, HP EGR is expected to be faster. In control-oriented dual loop EGR models, the reactions of EGR systems are usually modelled with time constants (*Nyerges and Zöldy, 2020a*). This section may help to understand the transient processes and to model their behaviour in a proper mathematical way.

Three operation points are selected for the transient behaviour representation: 1250 1/min with 200 Nm, 1750 1/min with 300 Nm, and 2250 1/min with 300 Nm. At the first phase of the transients, the engine runs in its steady state operation without EGR. The change starts with the EGR flap position change:

- HP EGR position change with exhaust brake support,
- LP EGR position change.

The target positions were calibrated manually. The aim was to achieve the same intake side $O_2$ concentration with both EGR systems (like in all the previous sections).

Figure 23 presents the oxygen concentration changes. At the end of the transient's decay, the intake side $O_2$ concentration is nearly the same – except at 2250 1/min at the late phase of the transient. Following the previous section's results, the exhaust side O2 concentrations are not converged to the same values.

Let us analyze the operation of EGR. Before the EGR valve opening, the intake pipes (volumes) are full of fresh air, while upstream of the EGR valve, the EGR pipes are full of exhaust gases. When the EGR valve opens, the exhaust gas mixing is started in the intake volumes. The mixed intake charge needs a short time to reach the cylinders. In this interval, the AFR in the cylinders does not change; consequently, neither does the exhaust side oxygen concentration. As soon as the recirculated exhaust gas arrives in the cylinders, the combustion process changes lower AFR, slower combustion, higher fuel consumption, and lower exhaust $O_2$ concentration. The new exhaust gas composition then results in a new intake mix in the later phase of the transient. Overall the reaction delay of the intake side $O_2$ change should be shorter than the exhaust side $O_2$ change.

According to the values in Figure 23, at 1250 1/min, the theory is proven. The intake side oxygen concentration change with HP EGR is nearly prompt, and the reaction time on the exhaust side is about 0.5s. The reaction delay of the LP EGR is 0.6 s on the intake side and nearly 1 s on the exhaust side. An important property of this operation point that its boost pressure is small. The total time of the transient decay is about 9 s.

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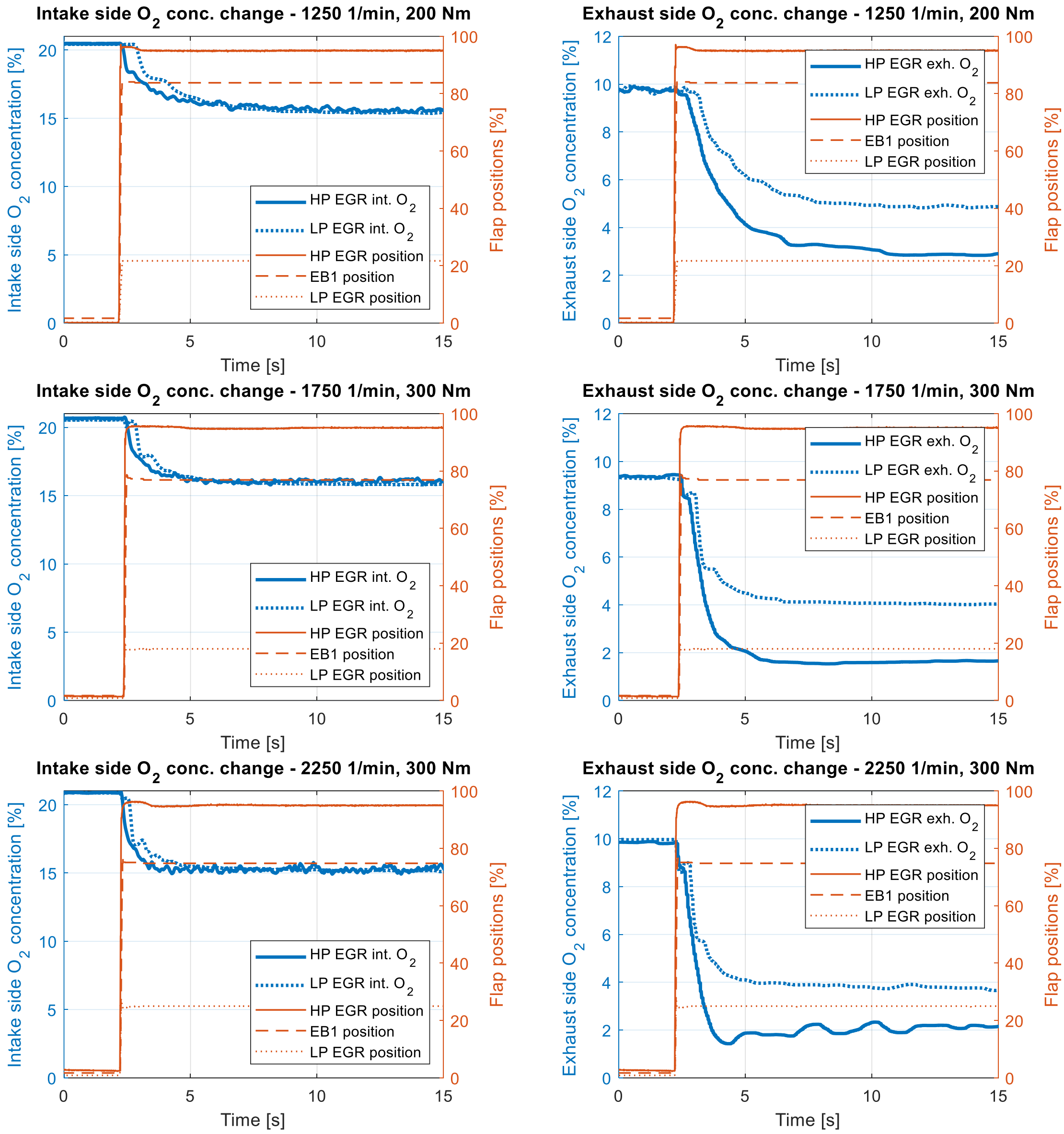

Figure 23. Intake and exhaust side oxygen concentrations in transient operation with HP and LP EGR

The reactions change at 1750 1/min and 2250 1/min due to the higher gas speeds and higher boost pressures. On the intake side, the HP EGR's change is prompt again, while the LP EGR's reaction delay decreases to 0.4 s and 0.3 s, respectively. The total time of the transient decay decreases to 5 s and 3 s, respectively. There is an oxygen concentration step on the exhaust side with both EGR systems, probably due to the turbocharger operation change. Consequently, the reaction delay is difficult to determine. However, the reaction delay difference is decreased between the two EGR systems.

Figure 24 depicts the $NO_x$ emission and the opacity change of the exhaust gas during the transient cycle at the three-speed levels. The reaction time of the emission changes is slower than that of the exhaust gas $O_2$ concentration (HP EGR: 0.8 s, LP EGR: 1.1 s). The overall transient decay is about 8 s.

The effect of higher engine speeds is similar to the above. The difference between the two EGR systems is greatly decreased again. The reaction times and the overall transient decays decrease at a similar rate.

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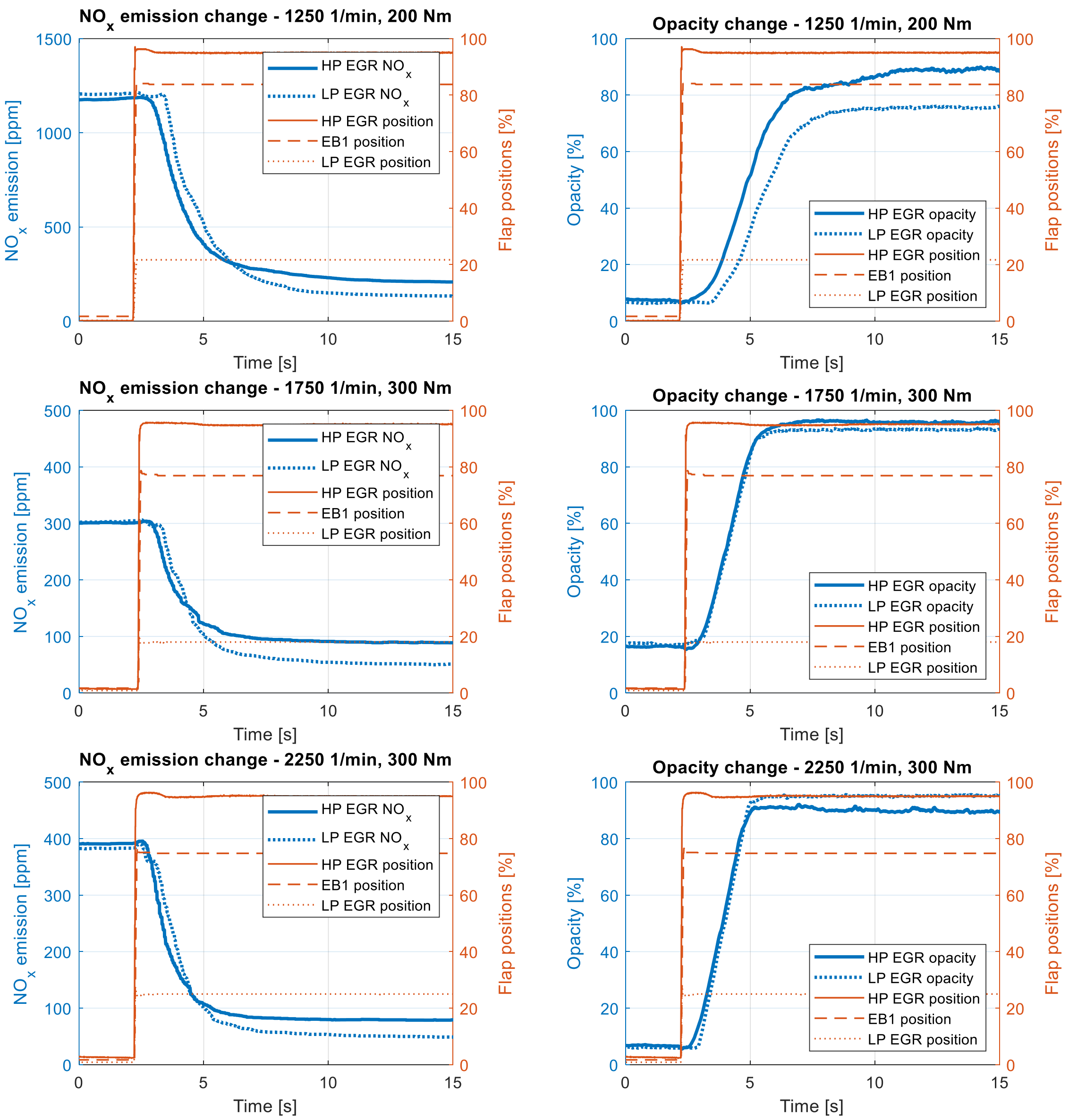

Figure 24. $NO_x$ emission and opacity in transient operation with HP and LP EGR

Finally, Figure 25 presents the boost pressure and fresh air consumption changes at 1250 1/min and 2250 1/min. The boost pressure decreases with HP EGR and slightly increases with LP EGR. While HP EGR simply falls to its convergence value, LP EGR's behaviour differs. At the first phase of the transient, the boost pressure slightly decreases, increasing the convergence value. The overall transient decays are not comparable between the two EGR systems due to their different behaviour. At 1250 1/min, they take about 3-6 s, while at 2250 1/min, they change to 2-3 s.

The fresh air consumption change has a similar duality. It decreases with both EGR systems, but with LP EGR, it has a significant overshot, which increases in function of the engine power.

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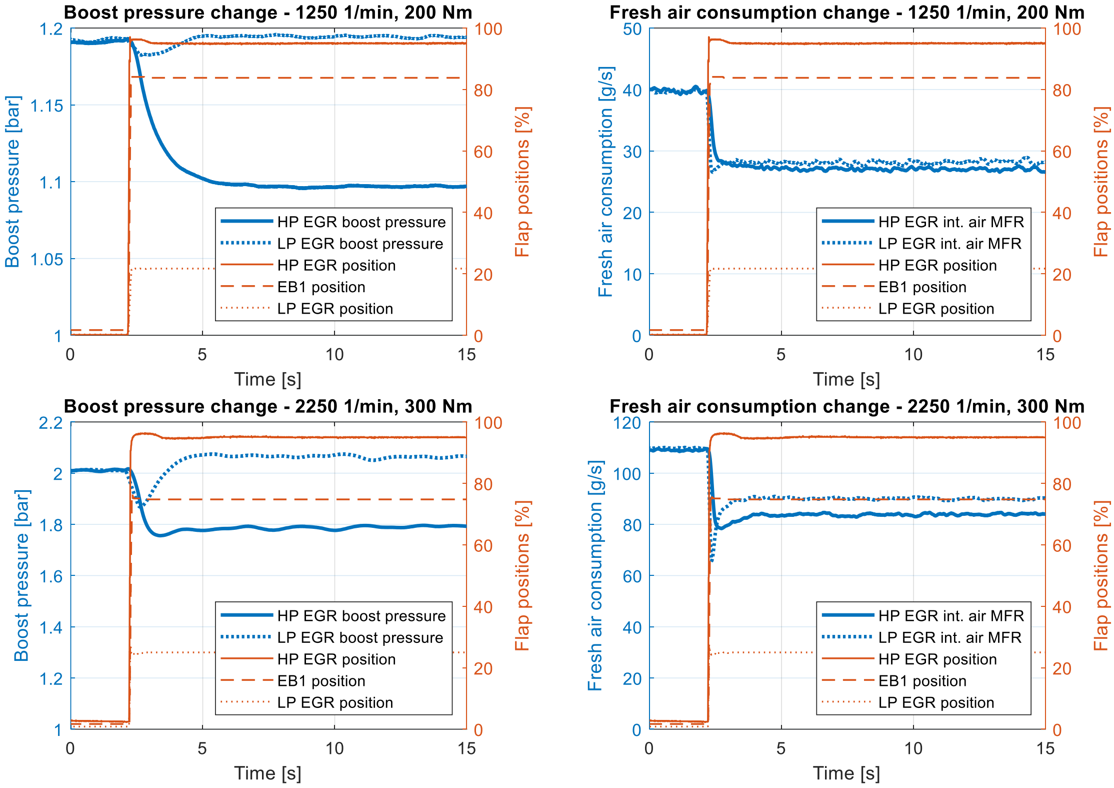

Figure 25. Boost pressure and fresh air consumption change in transient operation with HP and LP EGR

## 4. Conclusion

Modern Diesel engines have complex, creative control systems for low environmental impact and sustainable mobility. One of these complex elements is the exhaust gas recirculation system. In turbocharged Diesel engines, dual-loop EGR systems are sometimes implemented. However, the pressure differences determine the maximum EGR mass flow rate with only EGR valves. Intake throttles and exhaust brakes can support the EGR systems, providing the highest freedom to set any EGR rate. The present paper showed the differences between the four possible EGR modes from several aspects, for instance, fuel consumption, $NO_x$, and soot emission or boost pressure. The comparison is made both in steady state and in simplified transient operation. It is based on engine dyno measurements.

The result evaluation also explains the details of the EGR operation. EGR makes several changes in engine operation by changing the intake charge's composition, pressure (through its effect on the turbocharger's operation), and temperature. Indirectly, the combustion process changes, resulting in a different efficiency and fuel consumption map. The performance and emission changes were depicted as a function of the air-fuel equivalence ratio – because both the intake and exhaust oxygen concentrations change with EGR.

Concluding remarks according to the fuel consumption results:

1. EGR increases fuel consumption progressively. The increase is 10-15% with a lower EGR rate. Its maximum can reach 25%.
2. The ranking of the EGR modes strongly depends on the turbocharger's operation changes. Since the boost pressure mainly depends on the engine power, i.e., indirectly, the ranking depends on the engine power.
3. LP EGR provides lower fuel consumption in most operation points than HP EGR. The difference is about 1-10%. It increases with higher EGR rates. The difference is very small during the HP EGR support valve operation.
4. The exhaust brake-supported HP EGR always consumes less fuel than the intake throttle-supported one. The two LP EGR modes do not show significant differences.
5. With high engine powers and with high wastegate openings, the rankings are changed. Firstly the HP EGR provides lower fuel consumption until its support valves operate. With very high engine powers, HP EGR (and within that, the exhaust brake supported one) proved to be better. LP EGR provides up to 1-5% higher fuel consumption.

6. HP EGR can reduce fuel consumption with high boost pressure and a low EGR rate. The decrease is about 1%.

Concluding remarks according to the $NO_x$ and soot emission results:

1. It is well known that NOx and PM emission formation is counterproductive. I.e. generally, the EGR mode that is favourable to one is unfavourable to the other emission.
2. In most of the operation points, there are no emission differences between the two EGR systems until the HP EGR support valves operate. The exception is only with high engine powers.
3. LP EGR provides lower $NO_x$ emission and opacity when HP EGR support valves operate. The $NO_x$ difference is around 20-35%, except with high engine powers.
4. With high engine powers, HP EGR can have a slight $NO_x$ advantage while its support valves operate (7-10%). Moreover, HP EGR also can have a significant opacity advantage with up to 60% engine power.
5. HP EGR with exhaust brake provides lower $NO_x$ emission than with intake throttle. The difference is about 5-20%. The two LP EGR modes do not show significant differences.
6. With higher EGR rates, LP EGR can realize low-temperature combustion, where exhaust gas opacity decreases with increasing EGR. This property gradually disappears in the function of the engine power.

Concluding remarks according to the transient operation results:

1. The reaction times estimated by the oxygen concentration changes. As it was expected, HP EGR reacts faster. The maximum reaction time difference between the two EGR systems is about 0.5 s, gradually decreasing with the EGR rate. At high engine speeds, their difference is almost negligible.
2. The changes on the intake side are faster than on the exhaust side. On the intake side, HP EGR's reaction is prompt.
3. During the transient cycles, the emission changes show similar properties. Both the $NO_x$ and soot emission changes are faster with HP EGR. The overall reaction of the emission changes slightly slower than the $O_2$ concentration changes.

The present addressed EGR research from a broader perspective: it examined the high EGR rates and the effect of the support valves. At the same time, the article also advised on the dual loop EGR design and control.

The results presented here call for further research in several directions:

- Development of an optimal EGR strategy for low emission and fuel consumption.
- Analysis of the EGR cooling effects.
- Examination of the cooperation of injection strategies and dual loop EGR.
- Dual loop EGR measurements with green fuels.

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