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Crude oil and refined products transportation from the Caspian region to the European Union

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Abstract: This article provides in-depth description of the situation with crude oil and refined products transportation from the Caspian Region to the European Union. It describes demand and supply, main transportation routes and modes of transport. The article then addresses existing and potential issues and discusses the ways to resolve them. There are two knowledge gaps associated with the topic of this article: (i) transportation of crude oil and refined products from the Caspian region to the European Union receives limited attention of researchers, and (ii) the majority of related scientific publications consider mainly the aspects of geopolitics and the European energy security, but not the transportation itself. The author attempts to partially close these gaps.

Keywords: Caspian region; European Union; transportation; crude oil; refined products

1. Introduction

As rightly mentioned [1] „The economy of Europe depends on energy imports, while the economy of the Caspian region depends on energy exports.” Though relatively close geographically, these two regions are still distant from each other. This determines the importance of transportation.

The Caspian region is represented by Azerbaijan, Iran, Kazakhstan, Russia and Turkmenistan. These countries have similar logistics performance indices (LPIs), significantly lower compared to the LPIs of more developed countries. Please see Table 1 below.

Table 1. LPIs of the Caspian countries and selected sample countries [2]

	Caspian countries						Sample countries		
	AZ	GE	IR	KZ	RU	TM	CN	DE	HU
2007	2.29	-	2.51	2.12	2.37	-	3.32	4.1	3.15
2010	2.64	2.61	2.57	2.83	2.61	2.49	3.49	4.11	2.99
2012	2.48	2.77	2.49	2.69	2.58	-	3.52	4.03	3.17
2014	2.45	2.51	-	2.7	2.69	2.3	3.53	4.12	3.46
2016	-	2.35	2.6	2.75	2.57	2.21	3.66	4.23	3.43
2018	-	2.44	2.85	2.81	2.76	2.41	3.61	4.2	3.42

AZ - Azerbaijan, GE – Georgia, IR – Iran, KZ – Kazakhstan, RU – Russia, DE – Germany, CN – China, HU – Hungary

Considering crude oil and refined products deliveries from this region to the European Union, we need to take into consideration the following:

- The Caspian region is one of the closest to Europe major producers of hydrocarbons;
- It has been and will be one of the main suppliers of hydrocarbons to the European market. Three out of five Caspian countries (Azerbaijan, Kazakhstan and Russia) are the largest suppliers of crude oil and refined products to the European Union. At the same time, most of the Russian crude oil production originated from the regions other than Caspian;
- The regional infrastructure for transportation of crude oil and refined products is well developed and is mainly aimed at supplies to Europe.

The points above define the crucial role of the transport corridors for supplying crude oil and refined products to Europe.

It is important to have a comprehensive picture of the situation. This is why the article looks at it from different angles considering demand, supply, transportation and different other factors.

2. Literature review

The topic of transportation of crude oil and refined products from the Caspian region to the European Union has received limited attention of researchers in comparison with deliveries from the Gulf area. Another circumstance, which complicates this research further, is that the majority of existing scientific publications, i.e. [3-5] and many others, consider mainly the aspects of geopolitics and the European energy security. These two circumstances constitute two major knowledge gaps and this article attempts to partially close them.

The number of scientific works addressing the transportation from the region is not substantial, but such works exist and are considered in this Literature review. For example, [6] discusses the EU's leading role in developing the Caspian - Black Sea - Europe energy bridge to „ensure that at the very least Eastern European states diversify their energy sources and develop transit infrastructure." In his view „Europe needs to employ generally pro-active policies toward the Black Sea/Caspian region, which should include: ... Promotion and political and financial support for Trans-Caspian and Trans-Black Sea energy infrastructure to ensure alternative energy supplies to Europe from the Caspian region". [7] warned back in 2010 that „While the recent launch of a long-awaited cross-border oil pipeline between Russia and China has received most of the publicity, it is a part of a much larger Russian initiative aimed at developing new oil export infrastructure in almost every possible direction: Asia, the Baltic Sea region, the Black Sea region, and the Arctic. This export strategy will have considerable policy and economic implications for Eastern and Central Europe..." [8] undertake „A close analysis of contemporary and historical extraction of Caspian oil and its transportation, via pipeline and tanker, to central Europe". [9] „examines Russia's entire oil and gas export network and reveals that there is a considerable surplus pipeline capacity, which is likely to endure in the future. It brings to attention surplus capacity as a concept..." [10] point out that „oil pipelines have a strategic importance in the energy supply of the European Union". They then underline that „the development of oil and storage activities is essential, as well as the establishment of strategic partnerships in oil sector together with the more efficient use of infrastructure and corridors."

As mentioned above, the topic of transportation of crude oil and refined products from the Caspian region to the European Union has received limited attention of researchers. Therefore, it is important to use other sources of information. Among the most interesting and reliable are the publications of international organizations and international financial institutions, data and analytics published by oil companies and specialized journals, oil information agencies and publications of industry consultants and professional associations. Here we can mention the report by [11], which "evaluates the potential demand for oil and oil products transport via the existing rail corridor in the Caucasus, taking into consideration the competition from alternative routes." And [12], which pointed out that „Particular attention must thus be paid to the question of transportation, and also to the countries of origin, investments in infrastructure, their protection, relations with transit countries, 'competing consumers'-notably China and emerging countries, but also the United

States-, energy wastefulness in producing countries, and finally, price. Security of supply depends on adequate and reliable infrastructure and must always be thought of in the longterm." A very interesting Study on the Technical Aspects of Variable Use of Oil Pipelines - Coming into the EU from Third Countries was prepared by [13]. The phrase „from Third Countries" in this context means from the former Soviet Union territory. The same report underlines that „Sufficient and reliable availability of crude oil is one of the most important preconditions for economic stability of industrialized economies." [14] advised that „Historically, Caspian oil and natural gas producers have lacked sufficient export infrastructure. The coastal countries have developed several approaches for international exports. Some countries cooperate and jointly develop oil export capacity, while others focus on attracting enough investment to create their own routes. Kazakhstan and Azerbaijan have had the most success in developing oil export capacity through the construction of the CPC and BTC pipelines, which have become the main transit routes for Caspian oil." A good projection of the future demand was made by [15]: „Between 2016 and 2040, the transportation sector accounts for two out of every three additional barrels consumed. Nevertheless, demand growth is foreseen to decelerate on the back of efficiency improvements driven by technological developments, a tightening of energy policies and a relatively low (albeit increasing) penetration of transportation fuelled by natural gas and electricity. Oil use for industrial purposes (petrochemicals and other industry) is also expected to increase, though at a slower pace than in the transportation sector. Oil consumed for other uses is forecast to grow marginally, particularly because demand in electricity generation is projected to decline, hence, offsetting some growth in other sectors. Energy poverty alleviation measures, coupled with rising income and urbanization levels, will continue to foster a switch away from traditional fuels to oil-based products." [1] assessed „the security of demand for the oil and gas of three countries in the Caspian region: Azerbaijan, Kazakhstan, and Turkmenistan, over a 16-year period, capturing the geopolitical situation and contributing to a greater understanding of the impact of energy-transporting countries' geopolitical situation on energy transportation to the European Union (EU). The results demonstrate that risk of energy security of demand is greater when political risk in energy-transporting countries is included within a measure of energy security of demand, i.e., risky external energy demand." The issue of the European demand was further developed by [10]: "The greatest oil import in Europe in 2016, which amounted to 500 mil. tons, was realised from Russia, i.e. approx. 35,5%, then 12,9% from the West African countries, 12,3% form the Caspian region". The traditional point of view that „European Union has always looked to Central Asia as an alternative source to Russia for its energy demand" was expressed by [16]. He then continued that „EU was particularly concerned to find new energy sources. These concerns and needs increased especially after the price disputes between Russia and Ukraine in 2006 and 2009 as well as the 2014 Crimean crisis and the consequent sanctions imposition."

3. Current situation

3.1. Demand

As we can see from Fig. 1 and Fig. 2 below and as already mentioned above, three out of five Caspian countries, namely Azerbaijan, Kazakhstan and Russia, are the largest suppliers of crude oil and refined products to the European Union. Fig. 1 and Fig. 2 can keep us assured that the demand will remain in place in the near future. The author abstains from giving long-term projections because of volatile and unpredictable nature of the oil industry. Please note that terms "refined product" and "petroleum oil" are used interchangeably throughout this document.

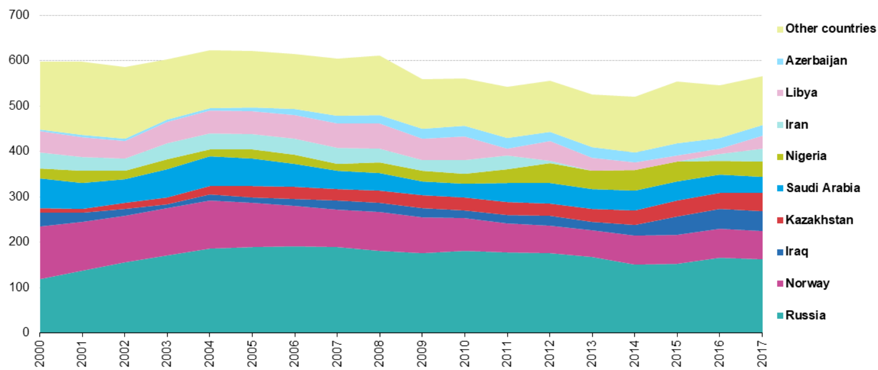

Figure 1. Crude oil imports by country of origin, EU-28, 2000-2017 (million tonnes) [17]

If we wish to consider the percentage growth of the countries under consideration, we receive the results shown in Table 2 below.

Table 2. Percentage growth of imports from the Caspian Sea region [18]

Country	Crude oil imports in 2000, million tones	Crude oil imports in 2017, million tons	Percentage growth
Azerbaijan	3.7	24.1	551.35%
Kazakhstan	9.7	39.7	309.28%
Russia	119.5	163.1	36.49%

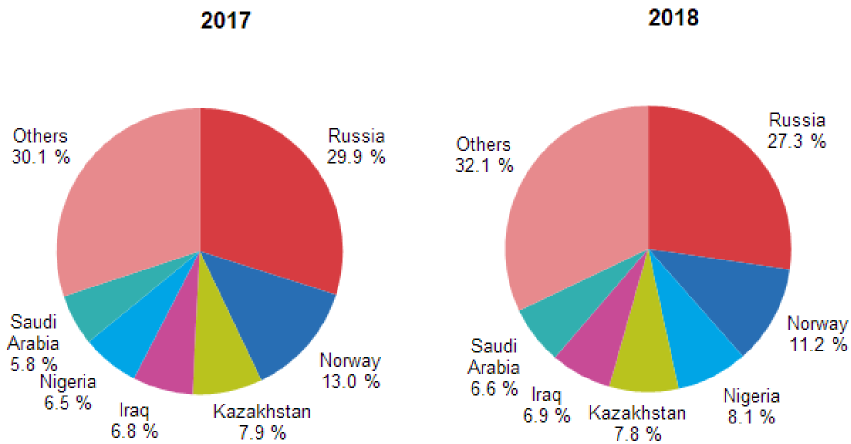

Figure 2. Extra-EU imports of petroleum oil from main trading partners, 2017 and 2018 (share (%) of trade in value) [19]

Finishing this section, the author would like to refer to [12] who is of the view that “the European Union’s hydrocarbon energy supply depends heavily on imports. While the European Commission has recommended diversifying and increasing domestic resources, notably with renewable resources which should grow to 20% by 2020, dependence on hydrocarbon imports will remain not only important, but will increase.”

3.2. Supply and transportation

The supply and transportation are discussed through the example of each country.

Azerbaijan: Considering this country, we can mention relatively small supplies of crude oil and refined products to the European Union (Fig. 1 and Fig. 2). Main crude export routes go through Georgia and Turkey to the Mediterranean or Black Sea ports and represented by the Baku–Tbilisi–Ceyhan and the Baku-Supsa pipelines. Here and elsewhere please refer to Fig. 3 below for more information about the regional pipeline and port network. Smaller volumes of crude go via the Baku-Novorossiysk pipeline in Russia. Azeri refined products are mainly railed to the Georgian Black sea ports. After reaching sea ports, crude or refined products are transhipped onto tankers and then delivered to the European Union.

Iran: The country has been under Western sanctions for the most of the time since the Iranian revolution of 1979. In the periods when the sanctions were lifted, the country supplied very modest amounts of crude to the European Union, mostly to Italy. Iran never had any substantial oil production in the regions close to the Caspian Sea and can be excluded from consideration in this article.

Kazakhstan: Discussing the supply side, we should note that Kazakhstan is the main producer of crude oil in the Caspian region. "Most of Kazakhstan's crude oil exports travel around or across the Caspian Sea to European markets. A significant portion of Kazakhstan's exports transit Italy and the Netherlands" [20]. The Kazakh crude and petroleum oils go via pipelines or by rail mostly to the Russian Black Sea ports. Substantially smaller amounts transit via the Russian Druzhba pipeline network to Central Europe, Russian Baltic Sea ports, the Baku–Tbilisi–Ceyhan pipeline or Georgian Black Sea ports.

Russia: The country is the main producer of petroleum oils in the Caspian region. The Russian crude oil production in the region is substantially smaller. It is at the same time the biggest transiter. The country possesses the most developed and wide-reaching transport infrastructure in the region and exercises its geographic advantage extensively. It adopted the policy of reorienting transit freight traffic to the Russian transport infrastructure. In March 2018, the Government Transport Commission of the Russian Federation approved a roadmap for the development of Baltic and Western Arctic seaports and approaches to them until 2020. „Traditionally, Caspian oil and natural gas went directly to Russia through the Soviet pipeline system, where some of it could go to Western markets" [14]. Russia has been trying to keep this advantage.

Turkmenistan: The country holds large reserves of hydrocarbons, but it is distant from key consumer markets. It produces a very high-quality crude, which travels to Europe first across the Caspian Sea, then via the Baku–Tbilisi–Ceyhan or the Baku-

Novorossiysk pipelines. The refined products mostly shipped by tankers to Russian Black Sea ports via the Volga-Don Ship Canal or to Baku and then to Georgian Black Sea ports.

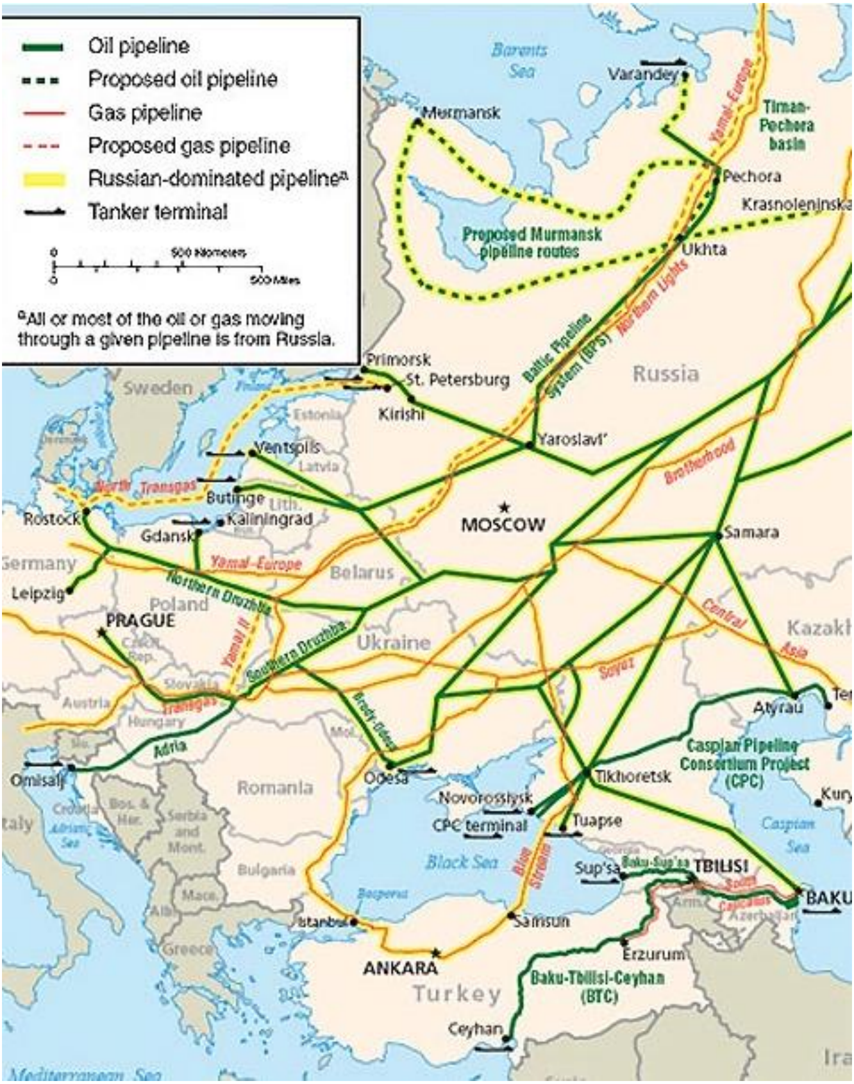

Figure 3. Primary Oil and Gas Pipelines to Europe [25]

Transportation of crude oil and refined products to the European Union is represented by the following modes:

- Pipeline: mainly used to bring crude oil and certain refined products to sea ports for further transportation. A smaller part of crude is transported to the European Union via pipelines without any trans-shipment;
- Rail: this mode is used in situations when there is no access to crude oil pipelines or the shipper prefers to preserve the quality of its crude (please note the Russian Transneft crude pipeline system does not have a quality bank). Also, it is practically the only mode of transportation able to transport many types of refined products;
- Water (sea and river): the cheapest mode though it has well-known limitations;
- Multimodal: it is represented by different combinations of modes mentioned above and is by far the prevailing mode to transportation.

4. Existing and potential issues

In this chapter the author addresses existing and potential issues related to the topic of this article.

4.1. Demand

Being by far the most important factor influencing the transportation of crude oil and refined products to Europe and not only from the Caspian region, demand has been and will mainly be influenced by the following:

- Large-scale transfer to renewable sources of energy and introduction of energy efficient technologies. These factors are already well-known to the large audience and are not discussed here for brevity. It should just be mentioned that though substantially limiting the use of hydrocarbons, the renewables will not, in the foreseeble future, replace them completely. So, the demand for hydrocarbons produced in the Caspian region and, hence, their transportation will remain;
- Technological innovations (TIs): For brevity, the author would like to touch upon just two TIs, which already influence the demand side or will do that in the future. The first TI to mention are hybrid and electric vehicles, which have experienced the exponential growth over the last years. As reports [21], the worldwide number of battery electric vehicles in use increased from 112’920 in 2012 to 3’290’800 in 2018. It is evident that this trend will

continue and the share of conventional vehicles will be decreasing. This is just one, but a very important example of how new technologies affect the market and subsequently form market expectations. Another TI is certainly the introduction of nuclear fusion reactors. Even though lots of engineering issues still remain to be solved, this moment will certainly come and it will decrease the demand for hydrocarbons dramatically;

- Political tensions: this factor has been affecting Russian gas supplies to Europe. There is a probability that it will affect crude and products deliveries as well, but its estimation lies beyond the scope of this article and deserves a separate study.

This section does not consider all the factors, but only those which influence the demand to a significant extent. For example, competition from other suppliers has existed for decades and it is unlikely that it will change the European demand for the Caspian crude and products significantly (please see Figure 1and Figure 2 above).

4.2. Supply and transportation

The European Union has been and will remain the main export market for crude oil and petroleum oils produced in the Caspian region. This situation is explained by the following main considerations:

- Primary energy production in the Caspian region is expected to grow within the next two decades. For example, [15] forecast that the crude oil production in Kazakhstan, which is by far the main crude producer in the region grows from 1.6 million barrel a day (mb/d) in 2016 to 2.7 mb/d in 2040;
- Size of the European market;
- Geographical proximity and well-developed transportation infrastructure;
- The European Union has been the main export market for the Caspian crude and refined products historically.

At the same time, there are different factors and issues that affect or can affect crude oil and refined products deliveries from the Caspian region to the European Union. The main (but not all) ones are:

- Political: interstate conflicts, political sanctions, unequal access to transportation infrastructure, etc.: As mentioned above, this factor has already been affecting Russian gas supplies to Europe. There is no guarantee that the same will not happen with crude oil and petroleum oils. Other political tensions exist as well. For example, the Baku-Supsa pipeline

„was closed down as a safety measure in August during Georgia's 5-day war with neighbouring Russia." [22];

- Technical: outdated infrastructure, violations of operating procedures, etc.: as reports [23] „Between 19 April and the beginning of June 2019, deliveries of crude oil to refineries in Central and Eastern Europe via the Druzhba pipeline were interrupted due to the contamination of crude oil in the system with organic chlorides." The same author continued that „The incident highlighted the risk of procedural violations, negligence and direct forgery of documents" even though this was „the first (incident) on such a scale in the Druzhba pipeline's 50-year history of oil deliveries to Europe". If such incidents continue in the future, there will be a good reason to channel European crude deliveries away from Russian pipeline network;

- Environmental and regulatory: The growing volume of oil traffic through the Turkish Straits is creating significant environmental, public safety and economic risks. In an effort to prevent any possible incident, Turkey introduced new rules for the passage of ships in September 2018 which, „require escorting a tug for more types of vessels than the previous ones". As a result, „The waiting time for passage through the straits for tankers leaving the Black Sea is about 16 days (in 2019), which is significantly longer than the usual 5-6 days and is the maximum since 2014." [24]. Another example is the regulations of the International Maritime Organization for ships to cut sulphur oxide emissions commonly called IMO 2020. IMO 2020 bans ships from using fuels with a sulphur content above 0.5% as of January 2020 as opposed to 3.5% previously. The new tougher rules are named the biggest shake-up for the oil and shipping industries for decades. The regulations are aimed at improving human health by reducing air pollution.

5. Conclusions

Discussing the demand side, we should admit that nothing much can be done about the influence of transfer to renewables and introduction of energy efficient technologies as well as about technological innovations. They are logical historically and environmentally friendly.

On the supply side, there is a real need to improve the governance, risk management and compliance at every stage of crude oil and refined products transportation from the Caspian region to the European Union. This will allow to make the deliveries quicker, safer and cheaper. The improvements will benefit all the stakeholders.

And, as mentioned above, the estimation of political factors lies beyond the scope of this article, though they affect the situation significantly. More business, less politics could be a good advice, but this is not practical as international politics is always a risk for oil business.

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Optimal operation of a rail lubrication device with respect to noise reduction and wheel/rail friction coefficient

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Abstract: During research work, three series of studies were performed to support the importance of using rail lubrication at tramway tracks in Budapest. The first task was to determine the noise reduction efficiency of automated rail lubrication: noise measurements were performed in case of lubricated rails with corrugations, non-lubricated rails with corrugations, grinded rails as well as grinded and lubricated rails. Once the conformity was determined, an additional task was to find the right lubricant. After the noise and braking effect tests of various lubricants, it was a legitimate need to determine the optimum lubricant application because the setting of the devices is based only on the experience of the Operator. Finally, the noise mitigation effect and the friction coefficient affecting the wheel/rail contact with different lubricant application settings were investigated simultaneously. It is important that the lubricant be applied in appropriate amount such that even the safe movement of the trams is guaranteed, but at the same time the noise reduction is satisfactory too. Based on the results, the authors make recommendations for the application of the rail lubrication devices.

Keywords: tramway; rail lubrication; noise reduction; rail roughness; friction coefficient; rail grinding

1. Introduction

One of the most important aspects of railway transportation is the environmental-friendly service and operation, but beside them the cost and energy efficiency, the relatively low life cycle costs have also high significance. Some related modern technologies can be mentioned: reduction of ballast particle degradation and connected studies [1]; development of high-tech materials for lowering plastic track settlements and improvement of drainage [2]; development of more precise mathematical methodologies for calculation of corrections of geometrical irregularities of railway tracks [3]; etc. The authors of this paper also deal with special, modern technology, the so-called noise reduction with rail lubrication device that has a very significant environmental and environment protection importance.

In curves, as the vehicle is guided by the flanges, undesirable and disturbing noise is generated which is typically the wheel squeal. Rail lubrication reduces the formation of the wheel and rail wears and mitigates the noise effect, generated by uneven wears and dynamic wheel-rail contact. Nowadays, rail lubrication devices are used to automate and control the lubrication process. In Hungary, various types of rail lubrication systems have already been installed, usually at small radius curves. However, their operation is based solely on the experience of the Operator.

Our research had three main goals which are achieved by performing three different series of measurements on tramways. First of all, to establish that the automated rail lubrication devices used in Budapest can effectively reduce the sound pressure levels caused by trams in small radius curves. Once the suitability of the devices has been proven, the next step was to find the lubricant with which the procedure of rail lubrication was the most effective. Finally, with the knowledge of appropriate equipment and lubricant, it was necessary to determine the amount of lubricant with which rail lubrication devices could be operated cost-effectively, safely (i.e., without affecting the braking performance of trams), as well as satisfactorily in terms of noise reduction.

The three series of measurements were based on simple noise measurements. The results, conclusions and suggestions of the research were determined by a practical method, data collection and accurate evaluation of the values. By comparing the results, the real values of the noise mitigation achieved by the automated rail lubrication can be obtained. The tests proved that the rail lubrication have adequate noise mitigation effect, and the tests of lubricants confirmed that the efficiency of the lubricant does not depend on the type of it. To determine the optimal dosage of lubricant, noise and friction coefficient tests were required simultaneously. It can be stated that although the amount of lubricant required for acceptable noise reduction affects the coefficient of friction, the values recommended in the literature were still measurable.

2. Noise, roughness, and friction coefficient

The rail lubrication devices are usually installed on curved tracks. Depending on the requirements, the lubrication bars or in some cases only bores deposit the lubricant precisely at the right positions on the rails. Various types of lubrication devices and many lubricants are used, such as greases and oils, which have different compositions to reduce the rail and wheel wears and mitigate the rolling noise (especially squealing noise effects) from the direct wheel-rail contact.

According to [4] rolling noise is generated by surface irregularities on the wheel and/or rail running surface which roughnesses cause vibration, hence wheel and rail vibrations radiate noise. The linearity of the relationship between wheel and rail surface roughness and rolling noise was also established [5]. If the surface roughness is reduced, the rolling noise is also mitigated. Various rail lubrication devices can provide a solution for noise and rail roughness mitigation, but the consequences need to be taken into consideration. As a result of rail lubrication, the values of the friction coefficient in the wheel/rail contact clearly decrease, which leads to slips, wheel spin and an increase in the braking distance.

It is now generally agreed that the coefficient of kinetic friction only depends on the nature of the surfaces. Considering Coulomb's law, the adhesion force is limited by friction coefficient and wheel load of the driven wheel [6]. The friction coefficient between wheel and rail is an important parameter that determines the braking performance of trams, and friction plays a key role in noise generation too. The mechanism based on Hertz theory can be learned from [6] and calculated typical creep force-creepage relationships are shown [7].

Based on [8], which focuses on the friction, wear and lubrication of the wheel-rail contact zone (~ 1 cm^2), the ideal friction coefficients in the wheel-rail contact are $0.25 < \mu < 0.4$ at running surfaces and $\mu < 0.1$ at gauge corner of the high (outer) rails. Summarizing the presented examples, in general, the coefficient of friction of non-lubricated rails under dry conditions is 0.5-0.7 and varied between 0.25-0.45 under lubricated conditions.

When a high viscosity material is used, the value of the friction coefficient can fall below 0.1, for example in case of oils, but it can also drop drastically in case of freezing. There is also an example of the effect of the use of oils [9], where the slip of the wheels of vehicles is certain, since the value of the coefficient of friction was measurable well below 0.1. There are several studies on how traffic is affected and disrupted by water or falling leaves in autumn [10]. However, the applicability of natural lubrication (leaves and humidity) has also been investigated [11]. The boundary friction coefficient was estimated in range of 0.2-0.45 under wet conditions [12], which is the same as lubrication ranges in other publications.

3. Measurement processes and conditions

In the course of our research work, three series of measurements were performed to support the importance of using rail lubrication at tramway tracks in Budapest. During the first measurement the efficiency of the rail lubrication equipment was determined, at the second the suitable lubricant, and at the last one the optimal amount of lubricant. The summary of the tests is shown in Table 1.

Table 1. Summary of the three series of measurements

I. EFFICIENCY OF RAIL LUBRICATION DEVICE	
Purpose:	To determine the noise reduction efficiency of an automated rail lubrication
Measurements:	Noise measurements
Instruments:	Class 1 Larson Davis System 824 sound pressure level meter
Recorded data:	Lubricated rails *(17 Tatra / 11 CAF)* Diminishing effect of lubrication *(11 Tatra / 6 CAF each day)* Non-lubricated rails *(19 Tatra / 14 CAF)* Grinded rails *(33 Tatra / 18 CAF)* Grinded and lubricated rails *(17 Tatra / 12 CAF)*
II. TYPE OF LUBRICANT	
Purpose:	To find the right lubricant
Measurements:	Noise and braking performance measurements
Instruments:	Class 1 Larson Davis System 824 sound pressure level meter XL Meter deceleration meter
Recorded data:	Non-lubricated rails *(4x Tatra / CAF / Hanover)* Lubricated (with type A lubricant) rails *(4x Tatra / CAF / Hanover)* Non-lubricated rails *(4x Tatra / CAF / Hanover)* Lubricated (with type B lubricant) rails *(4x Tatra / CAF / Hanover)* *… (7 various types of lubricants)*
III. AMOUNT OF LUBRICANT	
Purpose:	To determine the optimum lubricant application
Measurements:	Noise and friction coefficient measurements
Instruments:	Class 1 Larson Davis System 824 sound pressure level meter TriboRoll friction measuring device
Recorded data:	20% amount of lubricant *(16 Tatra / 13 CAF)* 40% amount of lubricant *(9 Tatra / 10 CAF)* 60% amount of lubricant *(12 Tatra / 11 CAF)* 80% amount of lubricant *(15 Tatra / 16 CAF)*

The first and the third measurements were performed at small radius curves on tram line 17 under an overpass, which is between the station Budafok kocsiszín and Savoya Park end station (Fig. 1). The measuring site was not acoustically appropriate and did not meet the conditions for free space specified in the standard [13] because of the overpass. However, the background noises were minimized, so only the noise of the passing trams could be measured clearly. It is important to note that the measurements can only be compared with themselves. Only the outer track of the curve was examined.

Figure 1. Examined curves between Budafok kocsiszín and Savoya Park stations

The conditions of the measurement were reported in detail [14]. During the tests, a speed limit of 20 km/h was in effect. The rail lubrication device was installed at the beginning of the curve. The lubricant is applied to the rails through four bores in the rail heads. On the external rails, two bores on the gauge corner of the railhead, on the inner rails one bore on the running surface and one bore on the guide (check) rails provide lubrication. Two types of vehicles are running on the line: the nearly 40-year-old, Czechoslovakian-made ČKD Tatra T5C5 (hereinafter referred to as Tatra) and the new, short (34 meters long), Spanish-made CAF Urbos 3 trams (hereinafter referred to as CAF).

For simultaneous testing of noise and braking performance by using different lubricants, the chosen site was a service track connecting tram lines 42 and 50 in Budapest. The vertical grade of the track is almost 0‰. There was suitable straight section available to measure the braking effect after an arc with a radius of 25 m. The measuring point was set at 7.5 meters from the centre line of the curve and the microphone vertically 1.2 meters from top of the rail (Fig. 2).

Figure 2. The examined curve on service track and the measuring point

The maximum speed in the curve was 15 km/h, in the straight section 40 km/h. The place where the braking starts, and the required braking distance were pre-measured. Braking was started by the driver at the designated point, then compliance with the prescribed braking distance was established. In addition to the CAF and Tatra trams, a more than 40-year-old, Germany-made TW 6000 tram (hereinafter referred to as Hanover) was also part of the study. The same three trams were examined on different measurement days. To perform the noise measurements, the road traffic was stopped while the trams were running. The effect on the braking performance of three different types and ages of trams and the extent of noise reduction in a small radius curve were quantified.

During the braking effect test, the data were recorded on the trams with a deceleration meter type XL Meter. The braking distance of the trams was measured, according to safety regulations, before the test and it was marked on the tramway. The recorded values were checked with a measuring wheel with which the distance accurate from the prescribed braking distance to stopped trams was measured. However, compliance with the stopping distance could also be visually proven.

Devices for measuring the friction coefficient are commonly referred to as tribometers. For the third measurement, the TriboRoll friction measuring device was used, which was developed by a Hungarian company, Metalelektro Measuring Technique Ltd. in 2019. The device consists of a measuring frame and a measuring unit with a variable position (5 different angles on the rail head) inside the frame. Friction measurements during the tests only at 90° (running surface) and 45° (gauge corner) to the rail were made. The measuring software of the TriboRoll calculates friction coefficient from the measured forces. A handheld surface roughness meter type PCE-RT 1200 was used to determine the surface roughness of rails. Each device helps set the optimum lubrication of the rails.

The noise measurements were performed with Class 1 Larson Davis System 824 sound pressure level meter, which was calibrated. The instrument measured LAeq values in each second during the passing trams. From these time series energy equivalent sound pressure levels were derived based on the relevant standard method [15], representing each train pass by one single dB(A) value.

Several consequences can be drawn by evaluating the performed noise measurements. The noise reduction results of rail lubrication device and grinding can be quantified. The results can show the transient effect of noise mitigation by eliminating lubrication process. The lower noise emission of trams running on lubricated rails without rail surface defects can be proven. The effect of different lubricants on noise reduction and stopping distance can be easily compared. By changing the dosage, the results show what the right amount of lubricant is with what trams can drive safely, but the resulting noise levels are also tolerable.

4. Measurements

4.1. Noise mitigation

In the course of our research work noise tests were accomplished in case of corrugated and lubricated/non-lubricated rails, grinded rails as well as grinded and lubricated rails on a tramline for 13 days. By comparing the results, the real value of the noise mitigation achieved by the rail lubrication device and grinding can be obtained. The diminishing effect of noise mitigation by switching off the units and the effect of grinding on the efficiency of the lubrication were investigated.

The measurements were carried out during summer 2017, on different days, but in the same time interval, at approximately the same temperature, in sunny, windless, or mildly windy weather and at the same measuring point. The measuring point was set at the connection of the two circular curves (approximately in the middle of the underpass), at 2.5 meters from the centre line of the left (inner) track. The microphone was set vertically 1.2 meters from top of the rail.

For the first two days, the results of corrugated and lubricated rails were recorded. This was a test under normal operating conditions. Subsequently, the rail lubrication device was switched off to determine the diminishing noise reduction effect and the time when the lubricant layer disappears from the rails and the undesired noise effects return. After degreasing and cleaning the rails, the condition of the non-lubricated rails was measured for two days.

On the railheads there was significant corrugation, therefore grinding work was intended to remove them with AT VM 8000-12 Extended type grinding machine. The machine removed the corrugations from the railheads, but the worn profiles remained unchanged. The grinded rails were measured for three days. To prepare for the last test, the rail lubrication device was switched on to operate. About a month after grinding, the results of the grinded and lubricated rails were record for two day as well.

Fig. 3 shows the summary result of noise measurements. The results represent all tram passing by one single dB(A) value per rail condition for each day. The noise reduction values are given in relation to the result of the non-lubricated rails. It can be stated that all three measures – lubrication, grinding as well as lubrication and grinding combined – have noise reduction effect.

It was foreseeable that the Tatra trams would cause higher sound pressure levels than the CAF trams. The results show that the attenuating effects of methods are lower for CAF trams, although the results are positive. If the rails with corrugations are either grinded or lubricated, almost the same noise reduction results can be recorded. According to the test, the appropriate noise reduction on the tramway tracks can be achieved by using both methods together.

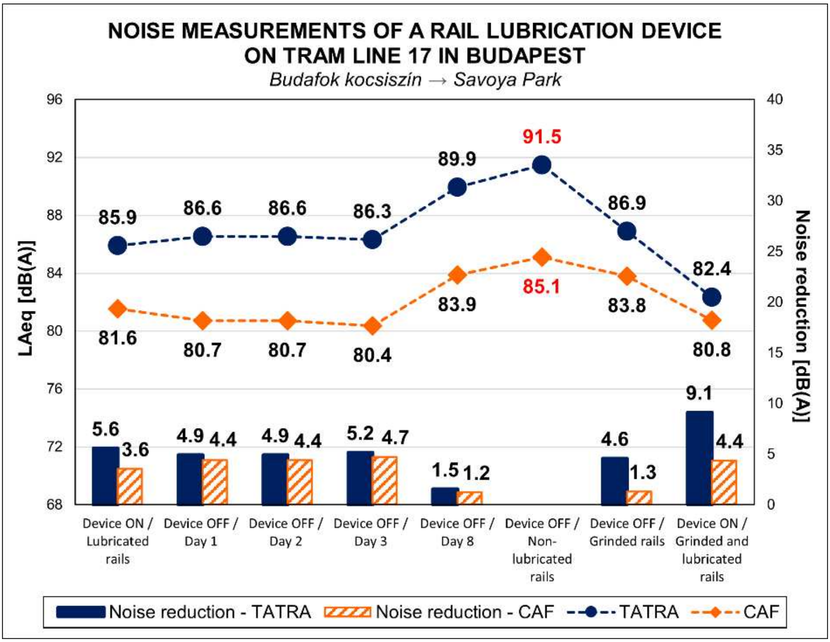

Figure 3. Results of noise measurements of a rail lubrication device on tram line 17 in Budapest

It can be read from the graph that there is no significant change (only a minimal decrease) in the noise levels in the three days after the rail lubrication device was switched off. The differences are not really outstanding. It can be assumed, that the remaining lubricant layer still had reduction effect or the different trams may have affected the results. The evaluation of the results includes the fact that different trams ran on the measurements days. Significant differences were experienced on day 8, which means that by discontinuing lubrication it takes about a week for the unpleasant noise effects to return.

As expected, the maximum values were recorded on days when non-lubricated rails were examined. These values were reduced by grinding, thereby the importance of grinding work was also proven. It is an encouraging result that the two methods are so effective together that the values of the two trams were approaching each other. While with lubricated rails and non-lubricated rail the differences were 4.3 dB(A) and 6.4 dB(A) respectively, finally just 1.6 dB(A) was gained.

4.2. Type of lubricant

It has also been numerically proved that the noise effects in small radius curves can be reduced by rail lubrication. The next task was to find the right lubricant. Therefore, in August and September 2018, noise and brake tests of trams were performed using various lubricants offered by different manufacturers. The purpose of the tests was to identify the lubricants suitable for filling stationary track-side lubrication devices which do not affect the braking performance of trams (i.e., the trams can stop within the prescribed braking distance) but also result in adequate noise reduction. The conditions were planned to test several lubricants with different compositions. Noise levels were recorded at the small radius curve and braking performance measurements in the straight section by passing and stopping the three type of trams (CAF, Tatra, Hanover) Each measurement day one lubricant was tested. The tests were performed in sunny, dry, and windless weather.

Three tests were performed, each in case of non-lubricated and lubricated rails, and before that one test run was also recorded with the trams. The total of 4 non-lubricated and 4 lubricated recorded data per tram were thus measurable on each day. Lubrication of the rails was accomplished, on the one hand, by manual application due to the use of different lubricants and on the other hand due to the short time between tests, as the real layer of lubricant applied from the equipment could not have been recovered. An important aspect was to get as close as possible to simulate the layer applied by automated lubrication. An amount of 1 ml/meter was applied by hand to the running surface and gauge corner of the rails after the non-lubricated tests. However, a double dose of type A lubricant was also used. At the end of each measurement day, the rails were cleaned.

Fig. 4 shows the total results per measurement day, the average noise reduction values of the lubricants. Manufacturers of lubricants are not published. The tests were performed jointly with the Budapest Transport Privately Held Corporation, BKV (hereinafter referred to as Operator), the results are known and available for them.

During the series of lubricant tests, there was usually no squealing at the passing of the trams, even with non-lubricated rails. In the absence of outstanding values, the effect of lubrication is not significant on those test days. The different values of non-lubricated condition were caused by the squealing noise levels that occurred during occasional passing. There was a detectable squeal noise on two days.

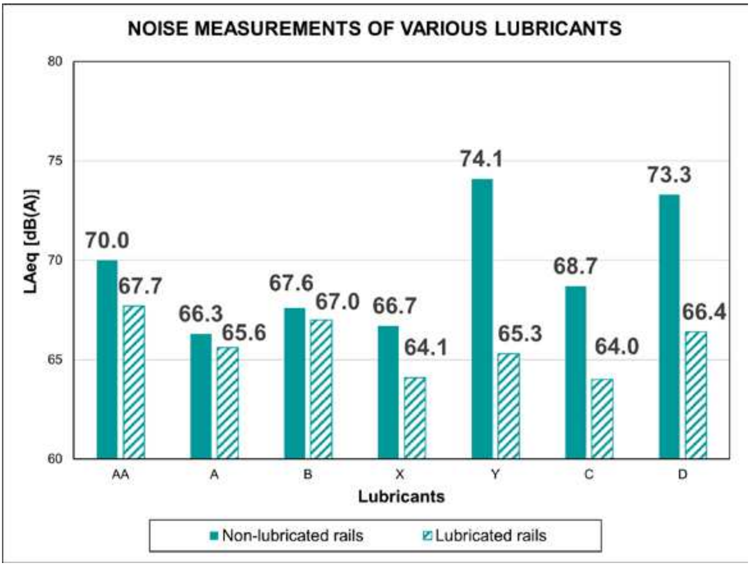

Figure 4. Noise reduction results of the examined lubricants

From the values shown in the above graph, it can be stated that regardless of which lubricant is used, the mitigated results are reduced to almost the same level. The reduced value is on average 65.7 dB(A) and the standard deviation is 1.3 dB(A). The results also show that double amount of lubricant can reduce the noise level to a similar value. As you can see, remarkable damping values of 8.8 and 6.9 dB(A) were obtained with the use of lubricants Y and D. The aggregate results per tram are summarized in Table 2. The results are interesting, as there was no effect on noise of Hanover by lubrication. The noisiest tram is again the Tatra, and thanks to the lubricants, the CAF tram travels with the lowest noise level.

Table 2. Aggregate noise reduction results per trams

Trams	**Non-lubricated rails** *[dB(A)]*	**Lubricated rails** *[dB(A)]*	**Difference** *[dB(A)]*
CAF	68.3	63.5	-4.9
TATRA	71.0	67.4	-3.7
HANOVER	66.9	66.6	-0.3

The trams were able to stop at 80% of the required braking distance with non-lubricated rails. As expected, the braking distance increased due to lubrication, but not to a significant degree of safety risk. The trams stopped within the specified distance (approx. at 90%) when using any type of lubricant. However, with the double dosage of the A type lubricant, the trams could no longer meet the requirements: they exceeded the determined value by an average of 3%.

4.3. Amount of lubricant

Currently, rail lubrication equipment used on the tram network is based on Operator experience, so there is a legitimate need to set the optimum lubricant application. In 2019, noise measurements were performed at the same site, under the same conditions and with the same method as the first test was conducted to determine the optimal amount of lubricant [16]. From an operational point of view, it is important to require the dosage by which rail lubricator devices can be operated economically and without loss. Primary consideration is that safety is ensured under all circumstances, accompanied by satisfactory level of noise reduction.

The amount and frequency of lubricant application can be changed with three settings. Lubrication events can be varied with the number of passing axles which are detected by the sensor, the length of dosing pump operation can be adjusted, and finally, with the axle counter and dosing pump operation set, the lubricant dosing level can be selected. The sensor mounted on the rail detects the wheels of the vehicles and sends a signal to the control of the device. The control unit is in a cabinet next to the track and it controls the equipment itself. The lubricant container, from which the grease is dosed with a pump is also placed in the cabinet. The dosing pump is started, and the set amount of grease is delivered to the lubrication bores which deposit the lubricant at the rails. Distribution of the lubricant is carried out by the movement of the wheels thus creating an even grease film on the surface of the rails.

The rails were grinded three weeks before the measurements. To perform the first test, the rail lubrication device was set by the Operator to a 20% lubrication level. Lubricant was applied after each tram with the dosing pump which operating for 8 seconds. The sensor and dosing pump operating parameters have not been set during the different lubrication stages. The maximum dosing of the lubricant (100% operation) means 1.4 cm^3 per bores, for a total of 5.6 cm^3 per tram. Noise, roughness, and friction measurements were performed at 20, 40, 60 and 80% on different days. At the suggestion of the Operator, the 100% dosage was not measured for safety reasons, because the traffic could not be disturbed under any circumstances. One week elapsed between the test days. The noise results with different settings of lubrication device presented in Fig. 5.

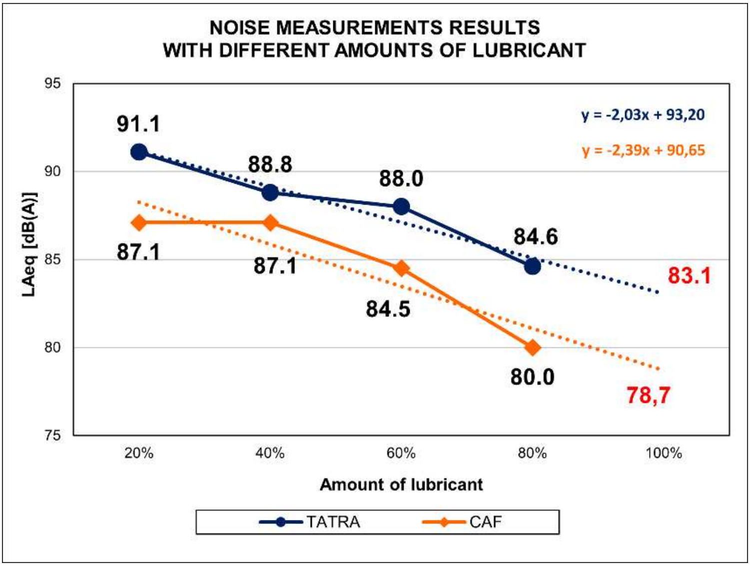

Figure 5. Noise measurement results with different settings of the rail lubrication device

Fig. 5 clearly shows a decreasing trend and again it could be said that the noise levels caused by Tatra trams are higher. The results show the total value of all trams passed on the test day. Furthermore, it can be definitely stated that the more lubricant is applied to the rails, the greater noise reduction can be achieved. There is an average reduction of 2.3 dB(A) between the setting levels. The lowest values were detectable at 80% lubricant dosage, which meant 1.12 cm^3 per bores, for a total of 4.48 cm^3 per tram. Differences between 20-80% mean a noise reduction of 6.5 dB(A) for Tatra trams and 7.1 dB(A) for CAF trams.

In the absence of a test, values with a 100% setting were linearly predicted from the calculated results. Seeing the forecasted results and taking into account the operational aspects and considerations, it is not necessarily cost-effective to operate the rail lubrication devices at 100%. Interestingly, an average of 3.5 dB(A) can be found between the results of two trams, but the noise levels approached each other the most at a setting of 40%. This may be explained by lower noise level of trams in presumably better condition that test day.

In addition to the noise measurement results, it is worth examining the changes in the friction coefficient and surface roughness of the rails as a result of lubrication, which are summarized in Table 3. However, interpretation of the results includes that the refinement of the surface roughness caused by grinding also caused a decrease in the values.

As the amount of grease increased, a decreasing trend in the results became detectable. The difference between the two rails is due to the curve, because the running plane of the trams is shifted on the rails. The results were also affected by significant lateral wear of the rails. Based on the values reported in the literature [8], the recorded results are adequate and ideal. Even with 80% lubricant dosing, the values could be considered safe, presumably acceptable values could have been measured even at maximum dosing. Compared to 20% lubrication, 80% halved the surface roughness values. As demonstrated in the table below, the largest decrease in friction coefficient values was measured on the surface of the left rail.

Table 3. Results of surface roughness and friction coefficient measurements

Operation of rail lubrication device	**Left rail (inner)**			**Right rail (outer)**		
		Friction coefficient *[-]*			**Friction coefficient** *[-]*	
		90°	**45°**		**90°**	**45°**
20%	0.76	0.52	0.29	1.43	0.38	0.23
40%	0.60	0.40	0.29	1.04	0.35	0.24
60%	0.40	0.37	0.27	0.88	0.25	0.22
80%	0.30	0.27	0.23	0.63	0.34	0.18

Considering the results of the noise measurements, as well as the surface roughness, and the friction coefficient, it can be said that the rail lubrication equipment is safe and recommended when operating at 80%. Too much lubricant could result in unacceptably low friction coefficient, which is also supported by practical examples [17]. With the optimal setting, there are benefits during operation. Cost-effectiveness can be achieved by requiring fewer lubricant tanks to be replaced, less human resources for rail lubrication devices and, last but not least, trams being able to travel with guaranteed safety. If the rail lubrication device and its operating costs and the cost of rail replacement over a 5–10-year cycle are compared, the latter may be more worthwhile. To reduce maintenance costs, it is important to determine how much lubrication is required, there is an analysis [18] seeking an answer to this depending on the wear of the rails. Of course, it is also obvious from our results presented in this article that rail lubrication devices do not only play a role in reducing rail wear but at the same time they effectively mitigate noise.

5. Conclusion

The first set of noise measurements were performed in case of lubricated rails with corrugations, non-lubricated rails with corrugations, grinded rails as well as grinded and lubricated rails to determine the noise reduction efficiency of automated rail lubrication. However, the conducted tests and the recorded data allowed several conclusions to be drawn. Afterwards, 7 different types of lubricants were tested, where in addition to noise measurement the effect on braking was also examined. A number of previous conclusions were supported by the results obtained here. Finally, noise measurements were performed, and the value of the friction coefficient and rail roughness was examined by different dosage setting of a rail lubrication device.

- It can be concluded that lubrication and grinding have almost the same, but less than 5 dB(A) noise reduction effect. However, appropriate and significant noise reduction values (which are results of 5 dB(A) or above) have been achieved by grinding and rail lubrication together.

- Clearly, the highest noise reduction can be achieved by applying the lubrication and grinding together. Both methods combined are so effective that there is no significant difference (1.6 dB(A)) in resulting noise levels of the different types and ages of trams (Tatra, CAF). The examination of different lubricants also showed that the difference (deviation 1.3 dB(A)) in noise levels of trams (Tatra, CAF, Hanover) due to rail lubrication is minimal.

- According to the results, noise reduction of 6.5-9.1 dB(A) for Tatra trams and 4.4-7.1 dB(A) for CAF trams was measurable, which, in addition to rail lubrication, are achieved by grinding as well as increasing the amount of lubricant.
- This study also confirms that grinding is one of the basic maintenance tasks, which – in addition to extending the life of the rails – results in noise reduction. In accordance with the expectations, the measurements support that the grinding improves the noise reduction of rail lubrication.
- General thesis is that the more lubricant is applied to the rails, the more effective noise reduction can be achieved. The delivery of the lubricants is limited by railway safety: the required braking distance of the trams must be ensured under all circumstances. As the amount of lubricant was increased, the coefficient of friction and rail roughness decreased. There was an average noise reduction of 2.3 dB(A) between the setting levels.
- Based on the results of noise, friction coefficient and surface roughness measurements, the equipment operated with 80% lubricant application (1.12 cm^3 per bores, for a total of 4.48 cm^3 per tram) is suitable. The amount of lubricant (type of the examined grease) applied in this way is suitable for reducing unpleasant noise effect and providing the required braking distance for trams. The results of friction coefficient (0.18-0.34) under lubricated rails are in accordance with the values reported in the literature.
- Optimal noise reduction solution in small radius curves for newly built track: automated rail lubrication, for existing track: automated rail lubrication after elimination of rail surface defects. It is not necessary to operate the rail lubrication devices in Budapest with the maximum lubricant application, which can thus lead to a reduction in maintenance costs.

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Examination of the cost ratio of the formwork

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Abstract: In case of construction investments, the cost estimation was always important. The reason for this is that after the planning, the most important issue is the cost of the investment. There are many different estimation methods. These estimates may vary in depth, depending on the task and the plan. The question is what happens if we wanted to predict not only the total cost of the investment but also the cost of some parts and structures. Such a cost element is the formwork cost of the monolithic reinforced concrete structures. This is a special processing aid, which makes it difficult to calculate accurately. The study is based on a cost analysis of the construction of 22 completed buildings over the last 10 years. Here, the cost of the formwork was compared to the total cost of the construction. By examining the 22 buildings together, we made findings over the years. We wanted to find out how much the construction price changes affected the structure and the formwork costs. The other direction of our research was the cost analysis within each building type, focusing on the formwork. In this analysis, we defined six types of buildings, such as detached, dwelling, condominium, public, office buildings, and other types of buildings. This study does not include the cost of the formwork types specific to each component, but from the foundation to the ascending structures, it analyses them in a single system.

Keywords: formwork; cost ratio; buildings

1. Introduction

The three most frequently asked questions for construction investment are what, when and for what cost. The price has always been one of the most important from these three questions. That is why we are focusing on this issue.

The total cost of a construction investment is made up of three major cost categories. The first is the construction cost. This includes material, fee and machinery costs, as well as closely related additional costs such as freight or material management costs [1].

The second major cost group is the additional cost. This is not directly related to the construction work, but it has a connection to it. These include design costs, such as the cost of pre-studies, cost of geodesic-soil mechanics measurements, or legal costs.

The third major cost category is also an additional cost. It can be projected on a per square meter basis for construction costs, such as interior design, mobiles, or lump sum, or using some special technology, such as kitchen technology or warehousing.

In this paper, we have examined the cost of formwork, reinforcement and concreting of the 3 main building stages of the reinforced concrete construction in case of different types of buildings [2]. These were compared to the other phases of work and to the total cost. From the three main elements, the formwork is the only one which can be treated as a temporary structure, meaning that it is not presented in the final product [3]. At the same time, it is a significant cost factor, but its amount cannot be calculated precisely, because the amount of the material used during the construction, rarely matches the amount of the actual formwork [4].

Calculations prove that the calculated and actual formwork requirements are the same for a one-storey building with a floor area of one to two hundred square meters. In case of other buildings, large differences may occur, resulting in a deviation from the projected cost estimate. We will examine the possible causes of these differences in the context of this paper.

2. Literature review

2.1 What does modern formwork mean?

The formwork was already known in ancient times as a processing aid for making and supporting arch belts. The real major step in the formwork was the invention of reinforced concrete in the middle of the 19th century. With the development of reinforced concrete, the formwork has played an important role in the surface formation besides the supporting task so far.

By the turn of the century, the development of the formwork had already begun. It has become clear that formwork requires the most work from reinforced concrete works, ahead of concreting [5].

The next major development had begun at the end of World War II. This is mainly due to the increased demand for preformed reinforced concrete structures [6]. Sliding formwork and climbing formwork [7] were created and by the end of the 1960s the large - scale formwork system had become widespread [8].

However, in the current construction industry, attitudes have changed again. The quantitative attitude after the world war was replaced by customized construction [9]. Companies specializing in certain types of construction work have been transformed and their activities had expanded. This change has also brought great advances in the formwork industry [10]. The so-called multi-purpose, modern formwork systems have been created. In contrast to the earlier ones, this formwork was already universal and extensive [11]. The same type of formwork can be used for shuttering a dwelling house or even a hydroelectric power plant. These formworks combine small-scale and large-scale formwork [12]. The boards can be used to assemble large panels of up to 30-40 m^2 with quick clamps [13].

The application of automation and robotics in construction industry, has shown significant growth inrecent decades with examples to include, among others, adaptive casting techniques [14] whose application appears in various robotic tasks. Robots have been mostly applied for the development of complex and non-standard structures with highly customized and variable morphologies and in cases where conventional construction approaches would be less feasible and cost-effective [15]. Such applications include, among others, robotic casting, additive manufacturing and 3D printing.

2.2 Formwork

The types of formwork can be grouped in many different ways, such as vertical or horizontal formwork, based on their size or material characteristics. In this study, the cost analysis of the formwork is the main guideline, so following types of formwork will be examined [16]:

- formwork for substructures,
- formwork for ascending structures,
  - wall formwork,
  - pillar formwork,

- beam and pillar formwork,
- slab formwork,
- stair formwork.

Formwork for substructure works generally uses a lightweight steel framed formwork system with a plywood shell structure and a relatively small number of element widths that can be moved manually without a crane. Typically, such structures were used for grounding formwork in the examined buildings. An exception to this, are a few family houses that use traditional slatted sidewall formwork [17].

Formwork of rising structures are wall formwork, pillar formwork, beam formwork, slab formwork and stair formwork.

Thinking of a modern formwork system, formwork can be divided into two main groups based on their structure: large-panel wall formwork with wooden box and framed formwork systems [18].

- Large panel wall formwork with wooden box: in its structural principle, it rather evokes the past in a modern robe. It means that, instead of the classic wall brackets, modern glued I-section timber brackets take the load and pass it on to modern double U profile cross brackets. The shell is a glued laminated board, phenol coated but with free edges [19].

- Framed formwork systems: typically, plywood enclosed in a steel support frame with a formwork. A wide variety of board widths (usually in 10-15 cm raster jumps), systems with high level (270-300-330 cm) and half-height (120-150 cm) elements with quick-release clips. Crane or hand-operated structures (in the case of high-rise boards they are aluminium framed) [20].

Pillar formwork, like wall formwork, can be divided into two large groups based on their structure: wooden boxes and frame structure. In case of framed systems, the boards have special bridges. It means that the bridging is possible not only at the edges, but the boards are perforated in 5 cm scales. In this way with a 75 cm wide board, we can create a 30x30 cm or even 60x60 cm pillar with a butterfly bond. Of course, in a plugged it in state, these special boards can also be used as a standard formwork element.

Among the slab formwork in Hungary, the most common formwork system is the wooden slab system. Its structure is based on a simple, main and drawer system. the final transfer of load is made through the steel supports to the lower slab.

Usually, the main and drawer are glued wooden boxes supports of the same cross section with an "I" profile design. The concrete surface of the formwork consists of wooden formwork boards. It is used with a three-layer glued pine design, but phenol-coated plywood is also common. Because the connection of the wooden supports is not fixed, only laid, and overlapped, therefore, it is very easy to follow the formwork of structures with varied geometry. Of course, the aluminium-framed slab formwork system and its drop-in version are also used, but because of its framework, its geometric possibilities are more knitted.

In case of stair formwork, the base frame is the same as the wood support system, but its cover can be a cut formwork board or a plank in case of stairs with drawn arms.

3. Evaluation method

The data is based on the specific contractor budget for each building. Their quantitative data set was obtained from designers' budget. The data is the cost taken from the detailed contractor budget, which includes material and labour costs. For each building, we collected the costs of the formwork, reinforcing, and concreting from my total budget. The sum of these amounts shows the total cost of the structure.

Each building is listed in a separate database with the relevant structural cost tables. In the summary worksheet, the rows contain the examined buildings (22 in total). The columns contain the calculated quantities for the various test items, broken down by type of structure and formwork, with material quantities and cost (in HUF) data.

In the current study, we analysed the cost of the structural constructions within the first major cost group, and within that, the cost and proportion of the formwork.

Earlier statistics showed that the 40% of the total construction was the formwork activity. To analyse this, we examined 22 buildings. The examined buildings can be classified into six main categories according to their type. The categories are:

- detached,
- dwelling,
- condominium,
- public building,
- office building,
- and other types of buildings.

For the sake of accuracy, here is what we mean by each group:

- Detached house: in general, a single-family residential building, typically with a loft, usually with a maximum of two levels of monolithic reinforced concrete slabs, depending on the characteristics of the basement. Typical groundworks are beam-reinforced slate, with a relatively thin but sized reinforced base plate, which works as a structure working with the ironed base beams. Its load-bearing structure is a masonry structure with reinforced concrete wooden pillars due to the new MSZ EN [21] (Eurocode) scaling. The wreath of the reinforced concrete appears as a separate structure (not built in the slab), typically in loft structures.

- Dwelling house: It is typically larger, it has one or two floors, with 2-3 monolithic reinforced concrete slabs, but still with load-bearing masonry, with few reinforced concrete pillars.
- Condominium: They are reinforced concrete pillar buildings. They have 3-6 floors with monolithic reinforced concrete slabs, reinforced concrete with staircase, elevator shaft and reinforcing walls, typically with base plate foundation.
- Public building: In these category 4 buildings were analysed. They include an educational building, a new hospital wing, and a rehabilitation and early development centre. Their structure is quite mixed, basically pillar buildings, but in some of them the monolithic reinforced concrete façade wall system is dominant. Each of them is made of monolithic reinforced concrete slabs with different thickness.
- Office buildings: These are modern, pillar buildings with monolithic reinforced concrete slabs, reinforced walls and filling ceramic masonry. They are based on metal, with some deep ground (piles).
- Other types of buildings: This group includes the construction of a new wing of a kindergarten, the construction of a new temple, and a yoga house of a smaller condominium. They are typically masonry with a monolithic reinforced concrete slab, reinforced strip, or thin reinforced concrete slab.

The authors examined the period of construction from 2007 to 2017, so the last 10 years. Of course, this includes the crisis period of the Hungarian construction industry and the booming time of the last 3-5 years. It is important that in the study, the interpretation of structure construction refers to the construction of monolithic reinforced concrete structure, so for works on concrete and reinforced concrete.

These are the following:

- Flat base groundwork: slate slabs, beam grid, sheet base, head beam, slate base wreath, dimensioned reinforced based concrete (thin slab base),

- Rising vertical structures: concrete and reinforced concrete walls, blade walls and reinforced concrete pillars,
- Rising horizontal structures: reinforced concrete slabs, coffin slabs, reinforced concrete beams, wreaths, etc. stair structures.

The above-mentioned threefold classification is also valid from the structural side. However, in our study, we make this triple categorization for the use of formwork for the following consideration. The main difference between vertical and horizontal formwork is the time of formwork, i.e. the rate of formwork rotation. In case of vertical structures, it can be rotated in 24-hour daily cycles. This means that the same structure can be concreted again, whereas for horizontal structures this is usually 5-7 days for shuttering time. Of course, this is greatly influenced by the type of structure, the thickness of the structure, the quality of the concrete, the weather, and many other factors. In this case, we do not deal with special slab formwork systems, where this formwork time can be reduced to 48 hours.

However, the flat base groundwork is not considered to a separate category because of the formwork time, this is due to the volume ratio of formwork to the concrete. These structures have three main cost components: formwork, rebar installation, and concreting.

Our examinations were carried out in three stages:

- We analysed the average formwork cost per square meter of all 22 buildings over the years.
- We examined the ratio of total formwork costs related to the structure, over the whole sample (22 buildings).
- We examined the ratio of total formwork costs related to the complete construction in case of every building types.

In the summary table, we collected the quantities of the typical formwork types for every building. To this we added material and labour fees.

Analysing the budget of the 22 examined buildings, as well as the construction technology of the completed buildings, it can be concluded that each building was built with a modern formwork system. So, the results are relevantly comparable.

4. Definition of the calculated quantities

According to any of the Hungarian norms, it can be said that the quantity of the formwork surface is based on the actual size of the formwork contacting the concrete and reinforced concrete structures. Based on the measurement rule, apertures greater than 1,0 m^2 in the formwork shall be subtracted. However, the cross-beam formwork of such apertures shall be added to the area. These sizes are calculated from static plans.

The first important question is: What do formwork costs include?

The so-called two-post budgeting is very common in Hungary. This is divided into material and labour, based on resource requirements. The budget of the 22 buildings I examined is also a two-column budget. The three resource needs are the followings:

- time requirements: This is in national and industrial standards, in technical guidelines or regulations a time required operation grouped by professions. An important part is preparation, handling, servicing, incorporation, and post treatment etc.
- machine work requirements: Suitable for performing the operations and the work requirements of the most typical construction machinery under domestic conditions, detailed as machine types, and expressed in shifts.
- material requirement: to produce the amount of structure a technically justified and standardized material standard is required.

4.1. What does modern formwork mean?

The fee is a time requirement, so the standard time and the exact value multiplied by the calculated quantity (formwork surface). In generally the value of the machine work requirement is expressed in the fees.

Speed of erection, safety, cost-efficiency, and flexibility are among the attributes of modern formwork systems. Modern formwork and scaffolding systems are attractive for their speed of erection, safety, cost-efficiency, and flexibility.

4.2. Material cost

However, calculating the cost of materials is not an easy task. The material requirements for reinforcement and concreting are part of the final structure. Their quantitative calculations can be handled exactly based on construction and static plans. In contrast, only the surface of the formwork can be accurately calculated in terms of the amount of formwork. According to the above-mentioned rules, the amount of formwork used at the construction site is the formwork rotation. This is a variable value depending on its efficiency that needs to be optimized. Therefore, the specific cost per square meter of the formwork is not the price of the formwork lease, or the percentage of the purchase price. It is a number calculated from the result of a scheduled, formwork plan.

5. Definition of the calculated quantities

Based on the Hungarian Central Statistical Office data, it can be stated that in the construction industry, between 2007 and 2017, the construction materials and labour prices showed an increasing tendency. Fig. 1 shows the variation of the average formwork cost per square metre in case of the 22 buildings we examined over the years.

It can be stated that Fig. 1 shows two very low formwork prices per square meter. In the category of the small house the price was 3,920 HUF/m^2 and in the other category the construction of a yoga house was 3,088 HUF/m^2. Both construction projects are related to the year 2017, where the average price of the other seven buildings was 6,583 HUF/m^2. It can be explained by a mispriced unit price, which is smaller and in case of an individual building is a typical preparation error. It occurs when there is no shutter roll plan and no execution time schedule, consequently, the price per square meter is either a number generated from the budget software database or a value "taken over" from a previous construction.

Figure 1. Change of the cost of the average formwork per square metre over the years

5.1. Structural formwork cost ratio for the whole structure

In the first examination, we analysed the ratio of total monolithic reinforced concrete structural cost to the total formwork cost, regarding to the building type for all buildings.

The average value is 30%, which is much lower than the previous statistics. One reason for this is the big change in the economy in the 1990s. From this time, the imported goods into Hungary had no longer dependence from the large foreign trade companies, but the goods could be bought independently by anyone from a foreign manufacturer.

This was also the case with the modern formwork systems, which subsequently came to Hungary in large quantities. It has significantly reformed the system of the formwork use and its reproduction. Domestic subsidiaries of well-known European formwork companies were established. As a result of it, the market for formwork systems were created in Hungary and the concept of formwork rental. This new concept, both economically and technically, has increased the importance of the formwork, therefore, not only did the contractors use their own formwork as before. They became part of a rent-based, profit-oriented system.

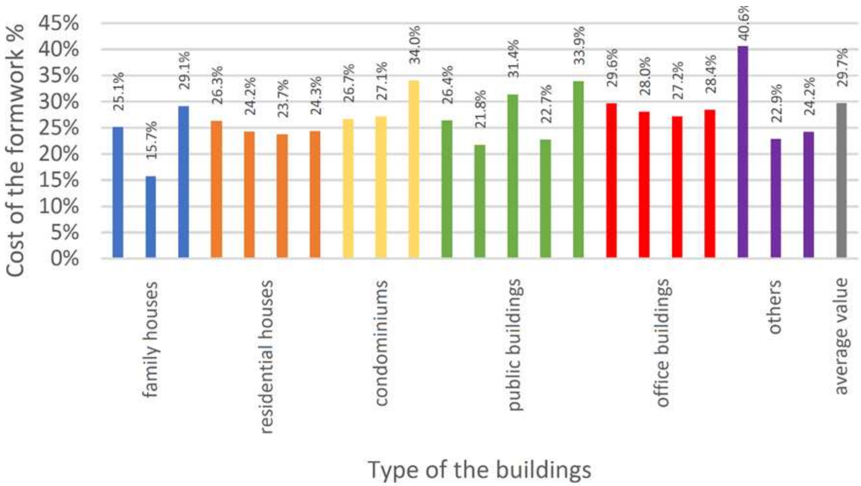

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Figure 2. Proportion of the total formwork costs of all examined buildings related to the whole building structure

As a result of two factors, namely the use of rental formwork and the use of modern formwork systems, it can be concluded that much less formwork is now being used in the same time as in the system based on planned economy. It means that there is a lower cost ratio on the formwork side for the whole construction.

Analysing the Fig. 2, we can see that the average 30% shuttering cost for the whole building type shows quite large fluctuations between 16% and 41%. Therefore, the results were also examined by building types. If there is a significant deviation from 30% then real costs need to be reviewed there. Thanks to this, we have developed a new method for the approximate control of formwork costs.

5.3 The rate of the construction cost of the formwork for the total structure for all building types

Analysing the Fig. 3a and 3b, the extremely low rate of the formwork (16%) in case of family houses has two main causes. One is that the building has a one-storied reinforced concrete slab, without reinforced concrete walls. The other reason is that due to the poor subsoil (because it was built on a former cornfield), the building is built on a disproportionately large base. It has a specific need for the formwork. However, the uptake of concrete and the reinforcing steel is high, so they distort the rates of the formwork.

Conclusion: in the category of detached houses and residential buildings, the average formwork cost is 24-25% of the whole structural construction costs. This represents a 5-6 percent reduction over the average cost of 30% of all 22 buildings. The reason is that the vertical structures of both the detached house and the residential building types were made of load-bearing masonry. These houses contain very few reinforced concrete pillars.

Perhaps the most consistent values were for the condominium category (Figure 4a) and in case of the office buildings (Fig. 5a). Here the deviation from the average is plus or minus 3-4%. The explanation for it can be found in the relatively homogeneous pillar structures, where no large specific differences are expected.

In case of public buildings (Fig. 4b), two extremely low values are found, which are 22% and 23%.

The explanation for it could be the following:

- This could be explained by the formwork surface area per cubic meter. In case of the 22 buildings, the formwork area per cubic meter of the concrete is an average of 4.63 formwork (m^2)/concrete (m^3). For the two buildings with extremely low value, these rates are 4.18 and 4.04 m^2/m^3, which is more than 10% under the average.
- The other explanation is the rate of the reinforced concrete and the formwork prices tested in the current year. We have examined the change in cost ratio compared to the date of the construction. In terms of 22 data, the first building was completed in 2007 and the last in 2017. Prices did not change linearly. It can be stated that the lowest prices were in the crisis years of 2008-2009, while the highest ones were in the year of 2017. The increase was 70% in 10 years, but in 2011 it was also outstanding value.

What is interesting about the measurements is that the prices of formwork and reinforced concrete structures have changed similarly over the years. On average, the cost of reinforced concrete per cubic meter is 12 times more than the cost of formwork per square metre. This rate is also shown in 2007, 2015 and 2017.

In case of the two above-mentioned public buildings, where we look for the rates of very low formwork and total construction costs, we can see that, compared to the average number (12), the cost of the reinforced concrete per cubic meter is 14 and 15 times more expensive than the formwork cost per square meter. This explains the low (below average) value of the formwork cost ratio of the tested structure construction for the whole structure.

In the last graph, (Fig. 5b), we examined the rate of the "other" buildings' formwork costs related to the structure of the entire building. The buildings under examination, for example kindergarten, temple, and yoga house, cannot be classified into the above-mentioned categories so they are included in the group of "other". It is clear from the graphs that their formwork costs need to be examined on an individual way. We cannot say general statements for it.

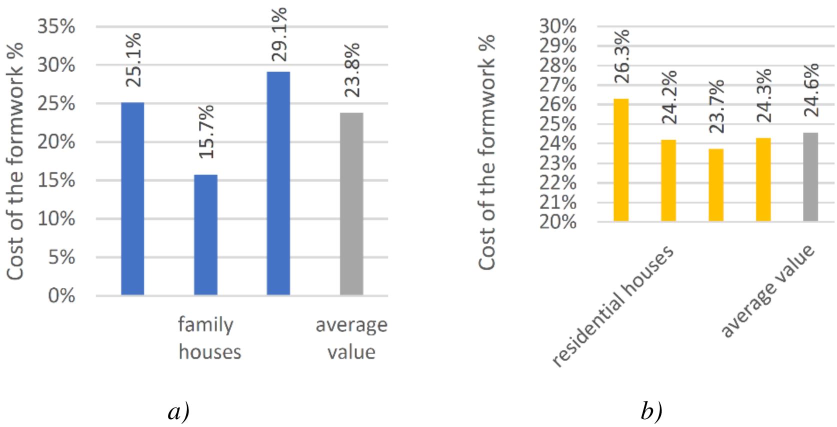

Figure 3. Proportion of the formwork costs according to the structure of the whole building a) in detached houses b) in residential houses

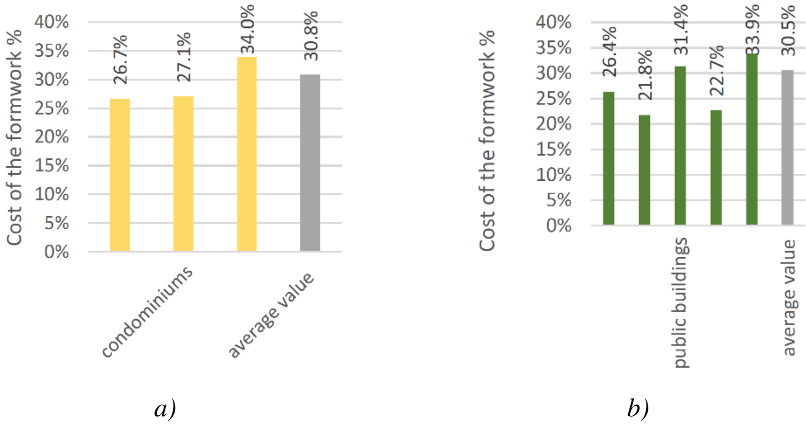

Figure 4. Proportion of the formwork costs according to the structure of the whole building a) in condominiums b) in public buildings

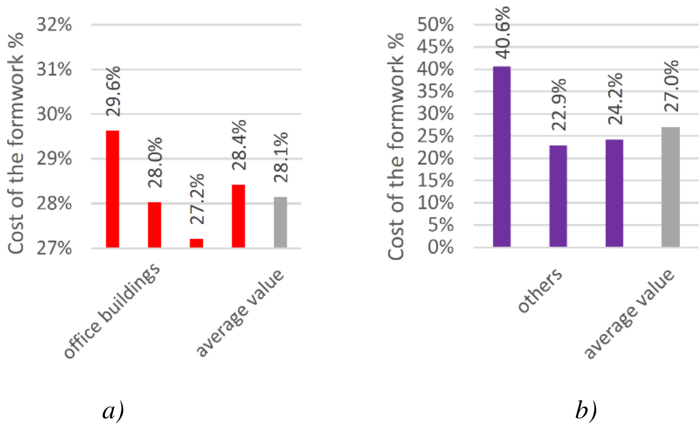

Figure 5. Proportion of the formwork costs according to the structure of the whole building a) in office buildings b) in other type of buildings

In the last graph, (Fig. 5b), we examined the rate of the "other" buildings' formwork costs related to the structure of the entire building. The buildings under examination, for example kindergarten, temple, and yoga house, cannot be classified into the above-mentioned categories so they are included in the group of "other". It is clear from the graphs that their formwork costs need to be examined on an individual way. We cannot say general statements for it.

Conclusions

The purpose of this paper was to estimate the cost of the formwork for each type of building as defined by the authors in relation to the whole structure. To reach this goal, we analysed the construction and implementation budgets of 22 buildings made in recent years in tabular and graphic form. The numerical results of the measurements show that the recent drastic increases in construction prices (especially in the last 3-5 years) do not apply to structural construction so significantly. So, this is a projected price estimate for the future, with much greater accuracy.

Another important result of the paper is that based on the concrete measurements and calculations, we have now obtained real rates for the formwork costs. One of the utilise possibilities of this result is that the total cost of the structure can be calculated with a good engineering estimate from the amount of calculated or known formwork surfaces.

Otherwise, it’s inverse is also true. The type of the building also influences the cost ratio of the formwork to the total structural cost, especially in case of typing within residential buildings. Measurements show that the ratio is about 24-25% in case of the detached house and the house we have defined, until the average for condominiums is 31%. It means that the cost of the formwork is higher in relation to the total cost of the construction for multi-storey residential buildings than for one or two apartment buildings.

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Dynamic seismic analysis of bridge using response spectrum and time history method

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Abstract: Dynamic analysis is very important to better understand the performance of structural elements of a bridge. For this purpose, a seismic analysis of an Algerian highway bridge designed with the new Algerian seismic bridge regulation (RPOA -2008) was carried out using linear and nonlinear analyses. Therefore, response spectrum, time history analyses were performed to evaluate the seismic responses of the designed bridge. The performance of the designed bridge is assessed using 10 ground motion records. The proposed methodology allows an efficient comparison of the seismic response of the bridge in terms of base shear forces, bending moment and displacements. Finally, the paper concludes with a discussion of the specific outcomes.

Keywords: response spectrum; time history; artificial accelerograms; plastic hinge

1. Introduction

The northern region of Algeria is in an active seismic zone [1], all bridge structures must be designed to resist potential events in the future. A structure subjected to a violent earthquake may be stressed beyond its elastic limit and behave in a non-linear way. Furthermore, resilience influenced structural performance by three properties; strength, stiffness, and ductility [2]. Due to the elasto-plastic character of reinforced concrete, strength and stiffness degradation may appear either progressively or abruptly in various parts of the bridge structure, causing permanent deformation and damage. Consequently, the use of linear elastic analysis becomes insufficient, or require structural elements that would be very costly. In order to create a safer, more efficient design, a nonlinear time history analysis becomes necessary.

In many regions, the number of recording stations for earthquake motion is limited, and we cannot produce a real accelerogram for each region where we wish to build a structure. Therefore, we have to generate artificial accelerograms compatible with a response spectrum envelope meeting building code requirements. The determination of the response spectrum from an accelerogram is a straightforward procedure. Whereas the generation of accelerograms from a design (often simplified) response spectrum is a difficult inverse problem. We must also take into account the geology and seismology of the region studied.

This paper presents a dynamic study of a girder bridge, using the time history method driven by artificial accelerograms. We will also compare linear analyses (response spectrum and time history method) to nonlinear analysis (time history method).

2. Overview of the analytical methodology and description of the bridge

2.1. Analysis methods

2.1.1. Response spectrum analysis (RSA)

Response spectrum analysis is an elastic analysis of dynamic responses of all significant vibration modes within the structure. The method is based on determining fundamental modes of vibration, usually by eigenvalue/eigenvector calculation. The major modes are then amplified according to the earthquake acceleration spectrum used in the analysis. Finally, the modes are combined using a modified form of superposition. It may generally include statically determined differential displacements [3].

2.1.2. Linear time history analysis 'LTHA'

In time history analysis, seismic actions retrieved from a strong motion database or generated artificially. Accelerograms from the database should come from conditions similar to the site of interest. When that is not possible (due to lack of records that match) accelerograms may be scaled to match peak amplitude or filtered to adjust its frequency content. In this way, many more acceleration time histories are available similar to the response spectrum analysis method, the structure is assumed to be linear elastic [3].

Huang, [4] and various building codes (IBC [5], EuroCode [6]) suggest this analysis must contain a sufficient number (about ten) of accelerograms to obtain a reliable estimate of the effects of seismic action. It must match the response spectrum of the site within certain maximum and minimum limits.

2.1.3. Nonlinear time history analysis 'NLTHA'

In this analysis the response of the structure over time is computed by the nonlinear modal time history analysis method. The seismic loading should consist of a temporal description of the ground motion developed for the particular site and preferably representing real earthquakes [3].

2.2. Bridge description

A typical bridge in Algeria was selected for this analysis. The highway bridge is a regular, seven discontinuous span of 35 m in length (Fig. 1). It consists of a reinforced concrete deck-girder system using precast beams (Fig. 2 and 3) isolated by rubber bearings installed below the concrete girder supported on top of the pier cap. The piers bearings were assumed to be fixed in the transverse direction and free in the longitudinal direction.

Its superstructure is a pre-stressed reinforced concrete girder consists of a two way RC deck slab 11.25 m wide and supported by fixed-free piers and fixed abutment at each end. The piers have 2 m diameter and height from 12 to 19 m. Pier P3 (height = 14.73 m) was used in our analysis.

The analysis of the bridge was conducted according to Algerian standards (RPOA-2008).

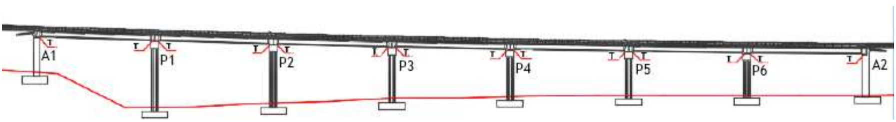

Figure 1. Longitudinal view of the investigated bridge

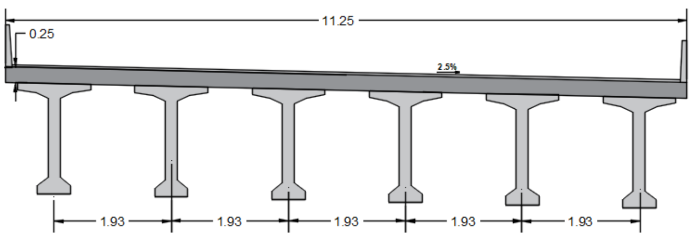

Figure 2. Cross section of the deck

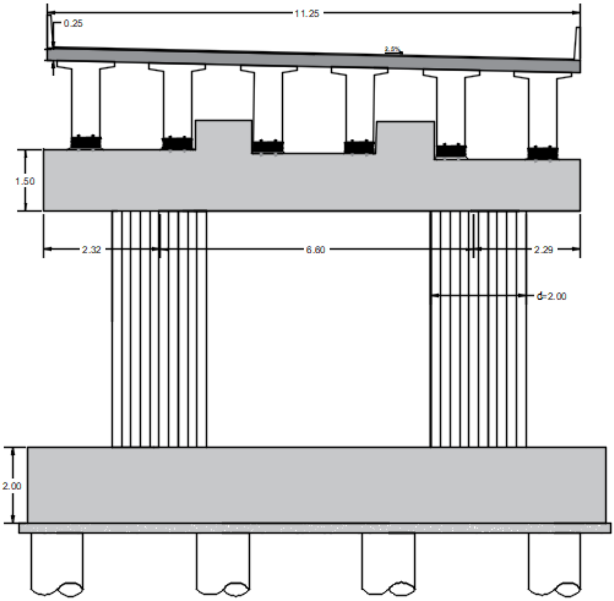

Figure 3. Transversal cross section at pier

3. Analytical modelling

3.1. Ground motion selection

Without adequate empirical data and considering the importance of the different characteristics of input ground motion, as duration, frequency, site type, etc. 10 real records from varying stations chosen from Boumerdess Earthquake (21 May 2003) were used as input excitation to examine the seismic behaviour of the designed bridge.

For this analysis, real earthquakes (Table 1) compatible with the response spectrum of (RPOA-2008) were generated using SiesmoArtif2021 software [7], considering the local soil conditions.

Fig. 4 shows the response spectra of the scaled and modified accelerograms, compared to the (RPOA-2008) elastic response spectrum. The RPOA classification for this spectrum was: bridge group 02 (important bridge), zone IIa (medium seismicity), soil type S2.

Fig. 5 shows the selected artificial records.

Table 1. Seismic records used in the study

N°	Magnitude	PGA (g)	Earthquake name	Station and direction	Year
01	6.8	0.322	Boumerdess	Boumerdes_EW	2003
02	6.8	0.365		Azazga_L	
03	6.8	0.224		Blida_L	
04	6.8	0.227		El Afroun_L	
05	6.8	0.308		Dar El-Beida_L	
06	6.8	0.292		Hussein Dey_L	
07	6.8	0.332		Keddara1_EW	
08	6.8	0.310		Keddara2_EW	
09	6.8	0.296		Aïn Defla_L	
10	6.8	0.253		Hammam Righa_L	

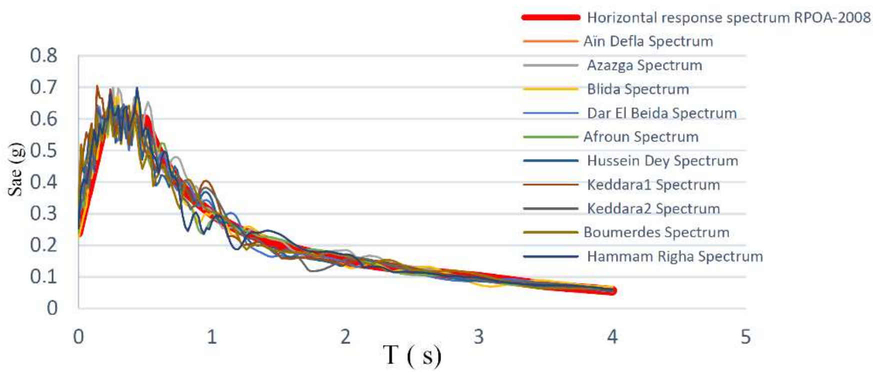

Figure 4. The elastic response spectrum amortized at 5% of the RPOA compared with the ten generated spectrum

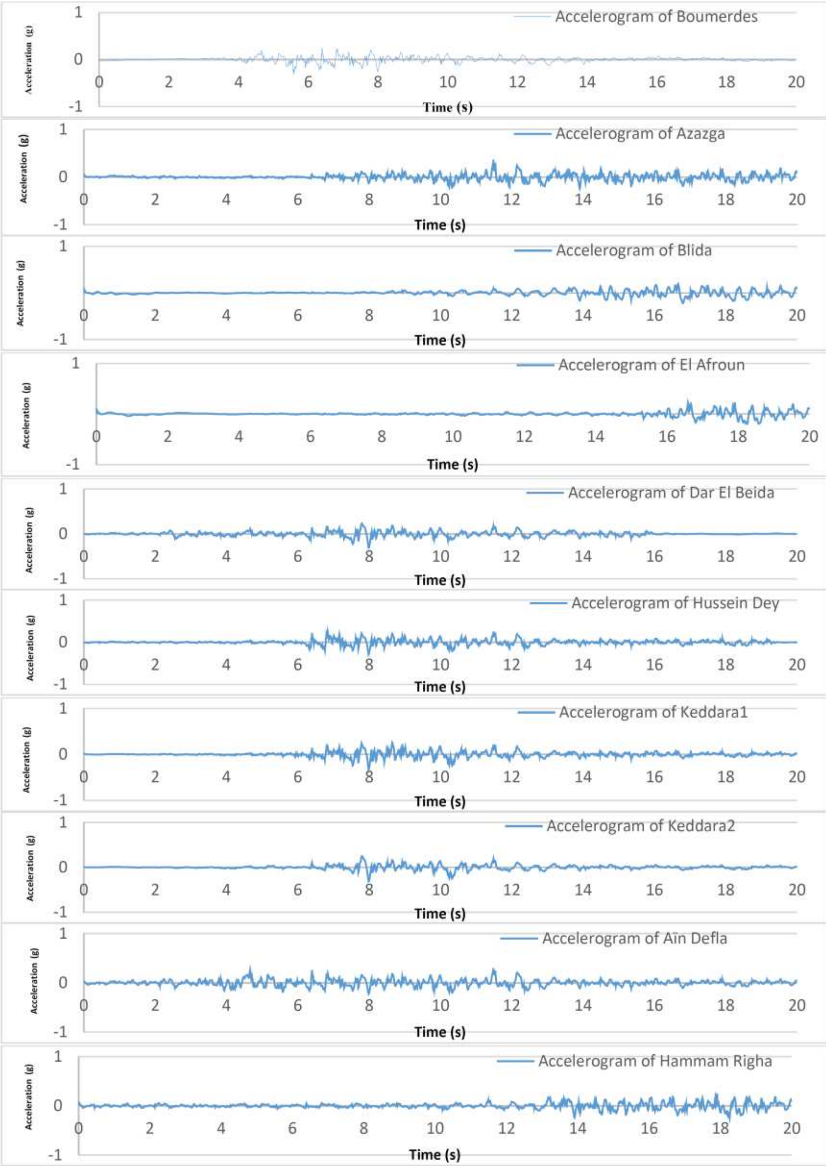

Figure 5. Artificiel grounds motions

Analytical bridge models

Three-dimensional linear and non-linear analytical models were developed for use in the dynamic analysis. A set of 189 modes are estimated by combining the maximums responses of individual modes using Complete Quadratic Combination (CQC) method. Referring to [8], [9] and [10], the CQC method is adequate for most bridge systems. The design seismic action is calculated using the following combination [6] (see equation (1)).

$$\mathrm{E} = E_x \pm 30\% E_y + 30\% E_z, \tag{1}$$

Where; E_x, E_y and E_z are the components of the seismic action in each of the respective directions x, y and z.

The deck is modelled with beam and shell elements (Fig. 6). Considering that the superstructure should remain elastic under the effect of seismic excitation, the deck is connected to the bents and the abutments with elastomeric bearings.

Figure 6. Bridge model

In this study, we consider the nonlinear behaviour of the piers. Therefore, the nonlinearity of the materials constitutes these elements. To simulate the inelastic behaviour of the pier columns, a plastic hinge model is used.

When maximum bending moment is reached, the plastic hinge formed at the base of the pier [11].

Fig. 7 shows the non-linear behaviour of the bridge pier cross-sections and the idealized moment-curvature with axial force due to dead weight.

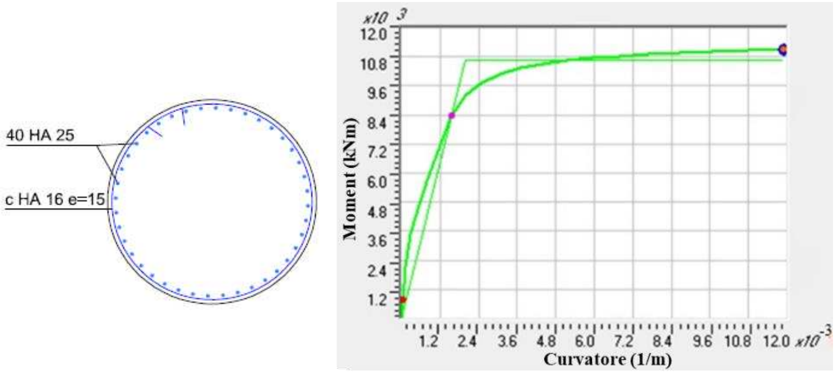

Figure 7. Cross section and moment-curvature relationship of the bridge pier

The nonlinear behaviour of elements is approximated by the use of plastic hinges. In our study, compound compression and bending plastic hinges (P-M) are considered. The data presented in moment-curvature graphs helps us to construct an idealized model of hinge represented by a force-deformation curve to estimate the damage condition curve for each pier. This curve, composed of 5 points A-B-C-D-E, represents the behaviour before and after plasticization of the pier and an example is shown in Fig. 8.

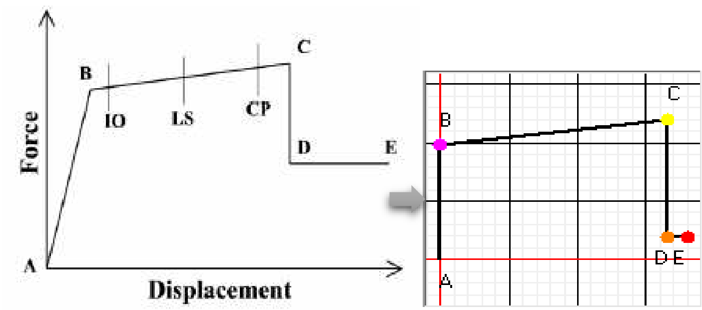

Figure 8. Behaviour law and damage levels used for 3rd pier

The performance levels, matching to the expected damage, are defined (Fig. 8) [12]:

- A: the origin
- B: no plastic deformation

- IO: Immediate Occupancy
- LS: Life safety
- CP: Collapse prevention
- C, D: no resistance capacity
- E: total failure

Although, Taucer, Spacone, & Filippou [13] created fiber models for the nonlinear analysis of RC members, in these members the element is subdivided into longitudinal fibers, which use non-linear stress-strain relationships for different materials, such as reinforcing steel, confined concrete and unconfined concrete, etc.

4. Seismic response of the bridge

4.1. Results and interpretation

For the generated ground motions at different scaled levels of peak ground accelerations (PGA) time history analyses were performed. During seismic excitation the displacement at the top of bridge pier was recorded.

Fig. 9 shows the lateral displacement for NLTHA response of the third pier subjected to the Dar El-Beida earthquake for an illustration.

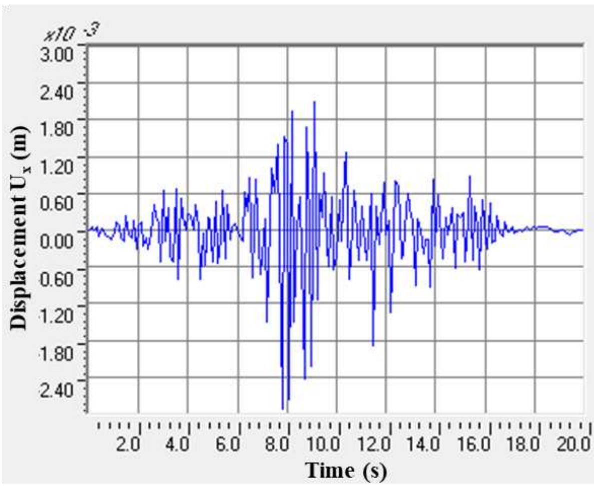

Figure 9. Variation of displacement response of the bridge pier P3 for nonlinear analysis, Dar El-Beida station

The maximum results are estimated in terms of internal forces; shear force V (kN) bending moment M (kNm) and displacement (m). In this analysis, the seismic action is applied in the longitudinal direction of the bridge.

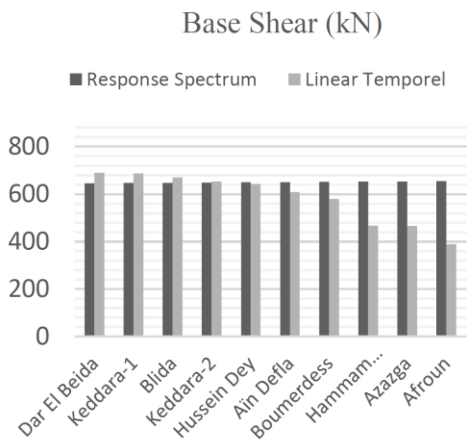

Figure 10. Variation in base shear force at the pier for the linear analysis

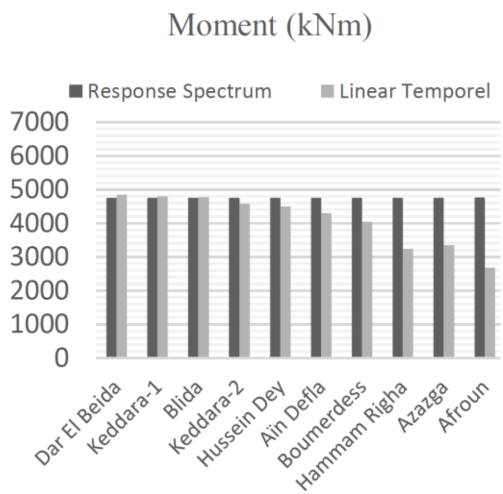

Figure 11. Variation in bending moment at the pier for the linear analysis

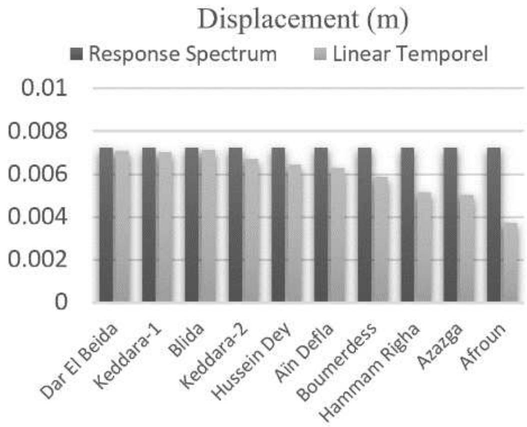

Figure 12. Variation in displacement at the pier for the linear analysis

Fig. 10-12 show that the results of internal forces at the pier section for the linear response spectrum and time history analyses are similar for most of the ground motions. It proves that the generation of modified accelerograms is appropriate.

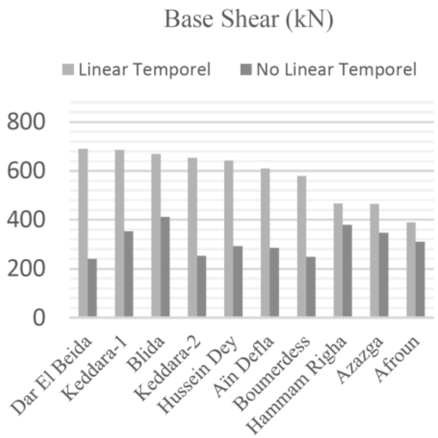

Figure 13. Variation in base shear force at the pier for the linear and nonlinear analyses

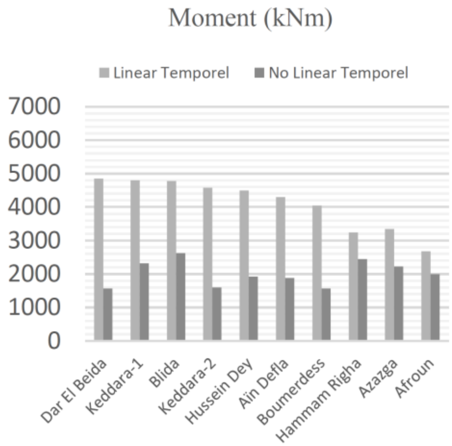

Figure 14. Variation in bending moment at the pier for the linear and nonlinear analyses

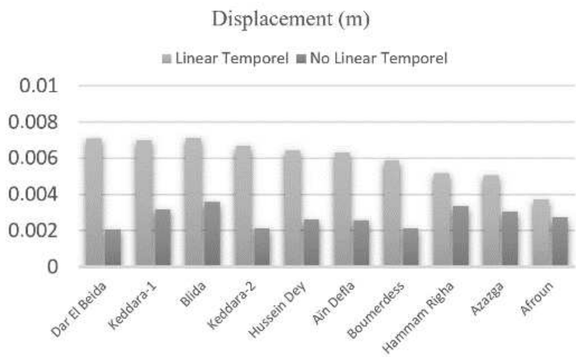

Figure 15. Variation in displacement at the pier for the linear and nonlinear analyses

Fig. 13-15 show that the results of internal forces for the linear time history analysis are larger than that of the nonlinear time history analysis.

It is noted that the results obtained for the nonlinear analysis are more realistic compared to the results obtained for the linear analysis. In this case, a large part of the seismic energy was absorbed by the pier in form of plasticization energy of the tensioned reinforcement and crushing failure of the confined concrete. Therefore, the ductility of the pier that appears in strong (amplified) earthquakes is better represented by the non-linear model.

5. Conclusions

To better show the differences between the linear analysis and the nonlinear analysis, a comparative study has been produced considering a reinforced concrete bridge.

This paper illustrates the results of the dynamic seismic analysis study and is aimed to develop the seismic response based on numerical simulations for typical Algerian bridge. The bridge designed with the new Algerian seismic bridge regulation, and a great number of accelerogram records from Algerian earthquake major event were selected.

A response spectral analysis response has been carried out, and for this type of analysis an elastic response spectrum from the Algerian seismic regulations characterizing the actions of the earthquake was developed. Furthermore, a nonlinear time history dynamic analysis was then performed to discover the capacity behind the no elastic states.

The main results through this analysis are the following:

- The response spectrum analysis is an approximate approach used to evaluate the maximum value of internal forces.
- Considering nonlinearities at the pier section reduce the internal forces and displacement compared to linear analysis.
- The nonlinear time history method produced a more realistic results of bridge behaviour compared to the linear method. It is usually recommended for geometrically complex bridges.

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A survey on the performance analysis of IPv6 transition technologies

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Abstract: As the public IPv4 address space has already been depleted, the full deployment of IPv6 became indispensable, especially for service providers, as it offers a sufficient address pool. However, the ongoing IPv6 transition seems to be a lengthy task because of the numerous challenges it faces. Therefore, it is expected that IPv4 and IPv6 will coexist for a long time. Consequently, many transition technologies have been developed for this purpose. Several research papers have conducted performance analysis for a number of these transition technologies and even compared them based on some measuring metrics like RTT, throughput, jitter, packet loss, and so on. This paper reviews the results of these papers, discusses their findings, and gives some guidelines fora feasible benchmarking methodology.

Keywords: IPv6 Transition Technologies; 464XLAT; Dual Stack; Tunneling; MAP-T/E

1. Introduction

The rapid growth of the Internet over the past few years has led to the actual depletion of IPv4 addresses in 2011 [1], which makes the adoption of IPv6 a necessity more than ever before. In addition to solving this problem, transitioning from IPv4 to IPv6 can help in solving many other problems such as the burden of NAT translation, the need for scalable routing tables, and the delay of the defragmentation process in the intermediary devices [2]. However, migrating the entire Internet from IPv4 to IPv6 is not an easy task and can take a considerably long time as this will need to modify many technologies, protocols, services, and so on to work properly in the new IPv6 environment. Consequently, IPv4 and IPv6 will need to coexist for some time before IPv4 can be completely excluded. As IPv4 and IPv6 are not compatible with each other, numerous transition technologies have been developed by the IETF to help in the gradual yet smooth full adoption of IPv6 [3].

Many research papers have been conducted in literature aiming to compare IPv6 transition technologies and executed a significant analysis of their performance. This paper surveys the work done by some of these research papers to highlight the feasibility and effectiveness of the most important IPv6 transition technologies, which may depend on several network conditions and parameters.

The remainder of this paper is organized as follows. Section 2 gives a brief introduction to the most important IPv6 transition technologies. Section 3 surveys the performance analysis of these IPv6 transition technologies accomplished by several research papers in the literature. Section 4 discusses the results of the work done by these surveyed research papers. Section 5 outlines future work. Section 6 concludes this paper.

2. IPv6 Transition Technologies

Many different IPv6 transition technologies have been developed to make communication between IPv4 and IPv6 networks possible and powerful. This paper follows the classification presented in [4] for these technologies, namely Dual Stack, encapsulation, single translation, and double translation technologies. It considers that the production network transitioning to IPv6 as being consisted of three IP domains, namely, domain A, core domain, and domain B. Domains A and B are IPvX-specific domains, while the core domain can be either IPvY-specific or Dual Stack (IPvX and IPvY) domain, where X and Y are part of the set (4,6) and X is not equal to Y.

2.1. Dual Stack

RFC 4213 [5] describes Dual Stack as a mechanism that supports both IPv4 and IPv6 by including both stacks at the same time in the network nodes, but one of them could be disabled and allow the other to communicate. However, this mechanism can result in significant communication delays. For instance, when a host wants to connect to a remote server, it initiates a DNS request asking for all available addresses of that remote server. The DNS server replies with both IPv4 and IPv6 address information (i.e. A and AAAA records). Then, the host may choose, by default, the IPv6 address to start the TCP session with. Once the IPv6 communication fails with the remote server, the host will switch to IPv4. Consequently, this causes latency in communication.

To alleviate the effects of this problem, a method of connection establishment called "Happy Eyeballs" has been proposed in [6] and improved in [7]. Its algorithm targets a better user experience by selecting the proper IP version for packet delivery after initiating multiple asynchronous connection attempts and then establishing the first successful one and cancelling all other attempts.

However, Dual Stack, even with "Happy Eyeballs", introduces unnecessary complication as both IPv4 and IPv6 protocols should be maintained and makes the network nodes more vulnerable to security threats. Not to say that it does not participate in solving the problem of the depletion of IPv4 addresses [3].

2.2. Encapsulation

The transition mechanisms under this category encapsulate packets coming from IPvX-specific domain by the header of IPvY at the edge between IPvX-specific domain and IPvY-specific domain. Then, the IPvY encapsulated packets are de-encapsulated at the edge between the IPvY-specific domain and another IPvX-specific domain before being received by the nodes of the latter one [4].

2.2.1. Manual Tunneling

Manual Tunneling [5], also called Explicit Tunneling or Configured Tunneling, is the very basic idea of this type of transition technologies, where IPv6 hosts/sites are linked together throughout an IPv4 infrastructure by encapsulating the IPv6 traffic into IPv4 packets (in this case the value of the protocol type field of the IPv4 headershould be 41) at one tunnel endpoint and then decapsulating them at the other tunnel endpoint. Both endpoints have to be Dual Stack and configured manually by the network administrator. Thus, configuring this type of point-to-point tunnels requires additional administration efforts and doesn't scale well. 6in4 technology is considered some sort of this type of tunneling.

2.2.2. 6to4

6to4 [8] overcomes the problems of 6in4 manual tunneling by allowing IPv6 hosts/sites, which have at least one public IPv4 address, to communicate with each other over an IPv4 network without explicit tunnel setup. It also supports the communication between IPv6 hosts/sites and native IPv6 domains via relay routers. To apply the automatic setup of one-to-many tunnels, 6to4 includes a predefined prefix (2002::/16) to distinct its packets over the public IPv4 network and embeds the public IPv4 address into the IPv6 address. However, as [9] mentioned, several problems with 6to4 were documented in [10] and [11].

2.2.3. Teredo

Teredo[12]enables IPv4 hosts that do not have a public IPv4 address, but rather are sitting behind NAT, to connect to IPv6 nodes by tunneling the IPv6 packets over UDP. To accomplish this task, Teredo deploys two types of devices: Teredo server and Teredo relay. The Teredo server is responsible for configuring the Teredo tunnel while the Teredo relay acts as an IPv6 router and is responsible for forwarding traffic to/from Teredo clients. Each Teredo host is assigned an IPv6 address starting with a special service prefix (2001:0000:/32). Teredo is mainly developed to provide a "last resort" option for nodes that want to connect to IPv6 Internet and no other IPv6 transition technology is rather deployed.

2.2.4. ISATAP

Intra-Site Automatic Addressing Protocol (ISATAP) [13] is mainly designed to connect Dual Stack nodes to IPv6 nodes via IPv4 networks and it deploys an automatic tunneling mechanism for this purpose. The ISATAP host forms a well-defined IPv6 address format from a predefined 64-bit prefix obtained from an ISATAP server, followed by a reserved interface identifier (::5efe), and ended with the 32-bit IPv4 address. It then uses this address for communication over the ISATAP network[14].

2.2.5. 6rd

IPv6 Rapid Deployment (6rd) [15] is derived from 6to4 technology. Instead of using the 6to4's well-known IPv6 prefix 2002::/16, rather it permits for each ISP to deploy its own prefix. This gives ISPs more control over their network. 6rd can be considered stateless as it relies upon an algorithmic mapping between IPv6 and IPv4 addresses, which enables IPv4 tunnel endpoints to be automatically determined from IPv6 prefixes.

2.2.6. Tunnel Broker

Tunnel Broker [16] is not considered a technology by itself, but rather a way of managing IPv4 tunnels for IPv6 hosts/sites by deploying dedicated servers for automatically processing tunnel requests coming from these IPv6 hosts/sites. It, therefore, aims to stimulate expanding the number of IPv6 interconnected hosts and allowing IPv6 network providers to supply easy access to their IPv6 networks.

2.2.7. DS-Lite

Dual Stack-Lite (DS-Lite) [17] facilitates the incremental deployment of IPv6 by decoupling it in the broadband service provider network and enables IPv4 address sharing by combining two well-known technologies: IP in IP, more specifically IPv4 in IPv6, and stateful Network Address and Port Translation (NAPT).

DS-Lite operates by deploying two different devices: The Basic Bridging BroadBand (B4) device and the Address Family Transition Router (AFTR). The B4 device can be either a directly connected host device or a Customer Premise Equipment (CPE), which acts as a home gateway for customers and it is supplied with a WAN interface that is provisioned only with IPv6 by the service provider. The B4 device encapsulates the customer's IPv4 traffic into the service provider's IPv6 traffic before sending it to its destination. When the AFTR device receives this traffic, it decapsulates the IPv4 embedded IPv6 traffic and performs a stateful NAPT44 [18] function to translate the decapsulated IPv4 payload into packets with public IPv4 source address before sending it to its intended destination. The reply packets will also traverse these devices, but now the devices perform reverse encapsulation/decapsulation processes. Fig. 1 depicts the architecture of DS-Lite.

```
                                         +-------------+
        Private +----------+ IPv4-in-IPv6|Stateful AFTR|
+------+  IPv4  |    B4    |    tunnel    |------+------+    _______
| IPv4 |------->| Encap./  |------------>|Encap.|      |   ( IPv4  )
|Device|<-------|  decap.  |<------------|  /   | NAPT +--( Internet )
+------+        +----------+      ^      |Decap.|  44  |   (________)
                                  |      +------+------+
                           Operator IPv6
                              network
```

Figure 1. DS-Lite Architecture[19]

2.2.8. MAP-E

Mapping of Address and Port with Encapsulation (MAP-E)[20] uses a stateless algorithm which is based on designated rules that target configuring IPv4 address information (and also port information in case of shared IPv4 addresses) and embedding this information into the IPv6 prefix assigned to an end-user Customer Edge (CE) device when constructing the IPv6 packets during encapsulation at CE and then validate this information when decapsulating the arrived IPv6 packets at a Border Relay (BR) that belongs to the same MAP domain. However, these MAP rules are also used when encapsulating the reply packets at BR before forwarding them in the opposite direction.

A MAP domain virtually connects one or more CE and BR devices that share the same mapping rule set. A service provider can control one or more MAP domains. On the other hand, a single CE may be connected to more than one MAP domain if it has more than one IPv6-enabled interface. However, each one of these MAP domains utilizes its own mapping rule set that is different from those of other domains. The communications inside one particular MAP domain (e.g. between two different CEs) can be either according to "mesh mode" (i.e. direct communication without the support of a BR) or according to "hub-and-spoke mode" (i.e. all traffic must be first forwarded to a BR belongs to the same MAP domain). In contrast, all communications with nodes from outside one particular MAP domain should be accomplished through one of the domain's BR devices. Fig. 2 depicts MAP-E architecture.

All CE devices typically perform stateful NAPT44 before encapsulating the IPv4 traffic into IPv6 packets using MAP rules and then send these IPv6 packets to their intended destination through the related MAP domain. When a BR receives traffic intended for a destination outside its MAP domain, it decapsulates the IPv6 header and validates IPv4 address (and port if necessary) information using the related MAP rules before sending the IPv4 payload to its intended destination.

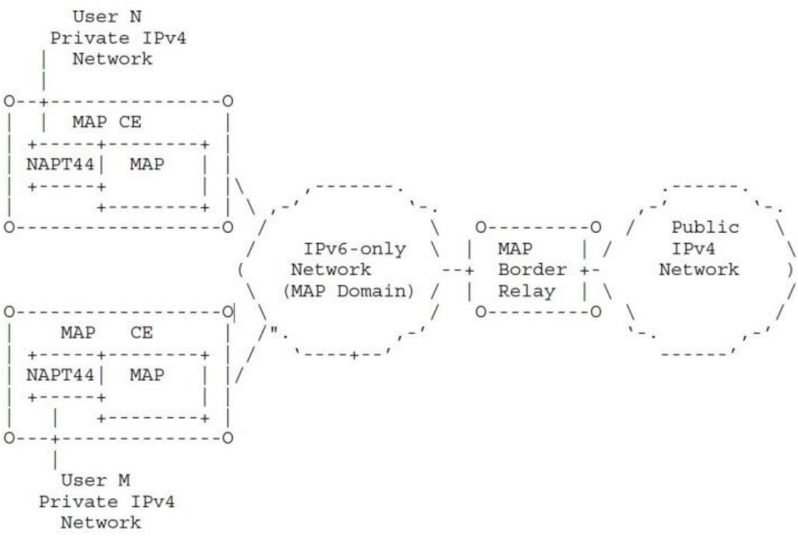

Figure 2. MAP-E Architecture[20]

2.2.9. Lw4o6

Lightweight 4over6 [21] is an extension to DS-Lite. In contrast to DS-Lite, lw4o6 relocates the NAPT function from the centralized AFTR (here it is rather called lwAFTR) device to the distributed B4(here it is rather called lwB4) devices. This solution noticeably reduces the overhead of maintaining traffic states from per-flow to per-subscriber and thus logging overhead and also considerably relieves lwAFTR from being overloaded by translation tasks as it already has other tasks like encapsulation/decapsulation, softwire maintaining and lookup, and A+P routing. Fig.3 shows the architecture of lw4o6.

```
                 +-------------+            +----------+
         Private |    lwB4     |IPv4-in-IPv6| Stateless|
+------+  IPv4   |------+------|   tunnel   |  lwAFTR  |      _______
| IPv4 |-------->|      |Encap.|----------->|(encap/A+P|     ( IPv4  )
|Device|<--------| NAPT |  /   |<-----------|bind. tab +--( Internet )
+------+         |  44  |Decap.|     ^      | routing) |    (_______)
                 +------+------+     |      +----------+
                               Operator IPv6
                                  network
```

Figure 3. The architecture of lw4o6 [19]

In addition to creating a tunnel to a lwAFTR, the B4 device supports port-restricted IPv4 address allocation and performs stateful NAPT44 function, whereas lwAFTR represents the other endpoint of the tunnel and maintains the so-called softwires (i.e. two different IP versions binding entries) in an address binding table. Each entry in the binding table is constructed on a per-subscriber basis and belongs to a particular lwB4. The lwAFTR uses each entry of the table to implement two functions: the IPv6 encapsulation of ingress IPv4 packets destined to a customer connected to the related lwB4 device and the validation of egress IPv4-in-IPv6 packets received from the related lwB4 to decapsulate them and then forward the decapsulated IPv4 packets to their intended destination.

Lw4o6 also supports hair-pinning to enable direct communication between two lwB4s which are associated with the same lwAFTR.

Finally, lw4o6 maintains a provisioning mechanism for assigning specific IPv4 public address and port set for each lwB4 device. This assigned information should also be synched with that of the lwAFTR binding table.

2.3. Single Translation

The transition mechanisms under this category translate packets coming from IPvX-specific domain to packets that go to IPvY-specific domain and vice versa (i.e. reverse translation) at the edge between these two domains [4]. By this translation, the communication between IPvX-only nodes and IPvY-only nodes becomes possible and feasible.

2.3.1. Stateful NAT64 along with DNS64

Although DNS64 [22] is not considered a single translation transition technology, it is discussed here along with stateful NAT64 [23] as they are commonly used together to enable IPv6-only clients to communicate with IPv4-only servers. It is quite appropriate to deploy this communication scenario instead of using the regular NAT444 (also called Carrier Grade NAT [24]) and practically transfer hosts to the IPv6 usage to shorten the transition period [9].

RFC 6146 [23] gives a behavior walk-through of NAT64 and DNS64 via a detailed example. To summarize the operation of this technology, consider the scenario depicted in Fig. 4. Here, an IPv6-only client wants to communicate to an IPv4-only server. It first sends a request to the DNS64 server asking for the IPv6 address (i.e. the AAAA record) of the **www.hit.bme.hu** web server. The DNS64 server asks the DNS system for this address. Since the DNS system has no such record, it will eventually respond with the corresponding IPv4 address (i.e. the A record), which is in this case 152.66.248.44. The DNS64 server uses the 64:ff9b::/96 NAT64 Well-Known Prefix [25] to synthesize the so-called *IPv4-embedded IPv6 address* by appending the received 32-bit IPv4 address (i.e. 152.66.248.44) and responds to the client with this synthesized address. The IPv6-only client starts the TCP session and sets the received *IPv4-embedded IPv6 address* (i.e. 64:ff9b::9842:f82c where the last 32-bit 0x9842f82c represents exactly the 152.66.248.44 IPv4 address) as the destination address of the IPv6 packet. As a prerequisite to this technology, all packets destined to a 64:ff9b::/96 prefixed address must be routed to the NAT64 gateway. Thus, the NAT64 gateway receives this packet via its IPv6 interface, constructs an IPv4 packet using the last 32-bit of the address (i.e. 152.66.248.44) as the destination IPv4 address and its IPv4 interface address as the source address of the IPv4 packet, registers the connection into its connection tracking table, and then sends the IPv4 packet to the IPv4-only web server. The server responds to the NAT64 gateway. The NAT64 gateway receives the IPv4 reply packet from the server, constructs an IPv6 packet from the relevant information using those registered in the state table, and sends this IPv6 packet to the IPv6-only client [26].

However, this technology still needs to implement Dual Stack at NAT64 gateways and DNS64 servers to work properly. Also, according to [27], it seems that this technology doesn’t work well with peer-to-peer applications.

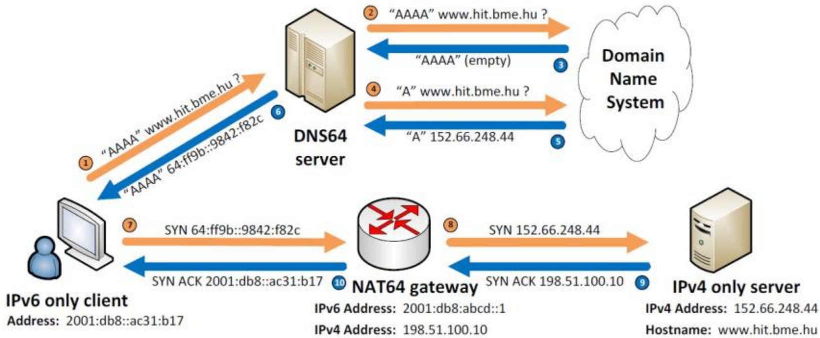

Figure 4. NAT64 and DNS64 scenario: An IPv6-only client communicates with an IPv4-only server [26]

2.3.2. SIIT

The Stateless IP/ICMP Translation (SIIT) technology [28] translates IPv4 to IPv6 packet headers (including ICMP headers) and vice versa by implementing an address mapping algorithm and based on the configuration of the translator and the being translated packet information. Additionally, the translator doesn't maintain any dynamic session or binding state. Therefore, packets in a single session or flow can traverse more than one translator instead of a single one as stateful translators do.

2.3.3. NAT-PT

RFC 2766 [29] defined this technology in 2000. But, then, it was moved to historic status for many reasons stated by authors of RFC 4966 [30]. Therefore, it is out of the interest of this paper even though its performance has been analyzed by many research papers.

2.4. Double Translation

The transition mechanisms under this category translate packets coming from IPvX-specific domain to packets that go through the IPvY-specific core domain (of the network operator) and then to another IPvX-specific domain. The first translation is accomplished at the edge between the first IPvX domain and the IPvY core domain, while the second translation is accomplished at the edge between the IPvY core domain and the second IPvX domain [4]. Subsequently, the reply packets can also be double translated in the reverse direction.

2.4.1. 464XLAT

This technology is clearly described in [31]. Since then, it was deployed by several network operators [32] such as the US mobile telecommunication company T-Mobile [33]. It enables the service providers to deploy IPv6-only devices for their infrastructure while keeping customers still running applications that use socket APIs and literal IPv4 addresses like Skype, Google Talk, and so on[32]. Thus, this technology is also considered an *IPv4aaS* technology [9].

464XLAT uses two different devices, namely, the CLAT and PLAT devices. The CLAT is located at the client-side and it performs stateless NAT46 translation for the private IPv4 packets received from IPv4 clients to global IPv6 packets sent over the ISP's IPv6 core network and later translates back the reply packets (i.e. it performs SIIT). The PLAT device is located at the ISP side and it performs stateful NAT64 translation for the global IPv6 packets received from the IPv6 core network to global IPv4 packets sent to the IPv4 server [31]. For a clearer picture of the architecture of this technology, see Fig.5.

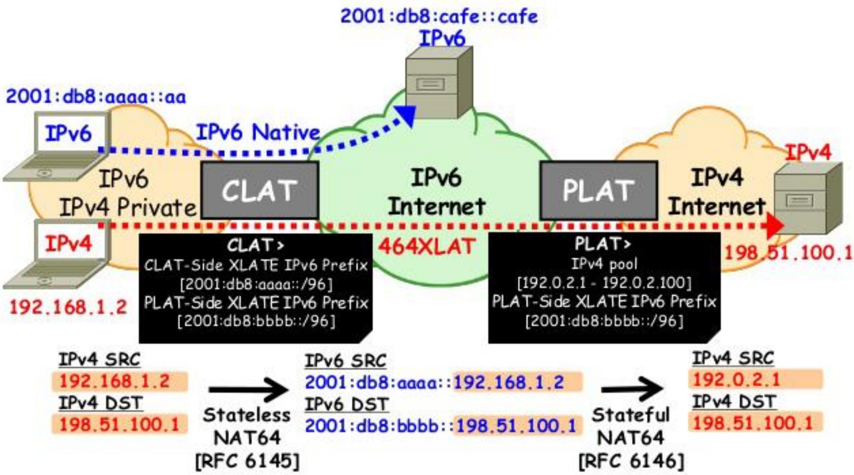

Figure 5. 464XLATArchitecture[34]

Although this technology is listed here as a double translation technology, that is when CLAT and PLAT translations are executed one after another, it can also operate as a single translation technology. This happens when an IPv6 client wants to communicate to an IPv4 server. In this case, the only translation needed is the PLAT one. However, this means that the PLAT's stateful NAT64 will need DNS64 for name resolution. Here, the CLAT acts as a DNS proxy [9]. One more case is the no translation case, which can be happened when an IPv6 client wants to communicate to an IPv6 server. Here, the CLAT acts as a router for IPv6 traffic [9]. The three case scenarios are listed in Table 1.

Table 1. 464XLAT Traffic Treatment Scenarios[31]

Application and Host	Server	Traffic Treatment	Location of Translation
IPv6	IPv6	Native IPv6	None
IPv6	IPv4	Stateful NAT64 + DNS64	PLAT
IPv4	IPv4	464XLAT (i.e. SIIT/Stateful NAT64)	CLAT/PLAT

2.4.2. MAP-T

Mapping of Address and Port using Translation (MAP-T) [35] can be compared to MAP-E as it uses mapping rules and can be compared to 464XLAT as it uses a stateless double NAT64 translation rather than encapsulation. This can give MAP-T the advantage of using the strength of mapping in scenarios where encapsulation is being ruled out such as those presented in [35]. Thus, it targets diminishing the overhead of encapsulation and allowing IPv4 and IPv6 traffic to be treated as the same as possible.

MAP-T deploys the same technique as MAP-E in terms of using MAP rules. As shown in Fig. 6, its architecture is so identical to that of MAP-E and it uses similar terminology as MAP-E does (e.g. MAP domain, Customer Edge (CE) device, Border Relay (BR) router, and so on). However, it uses, of course, a double translation instead of encapsulation to enable IPv6-only connectivity to its operator network.

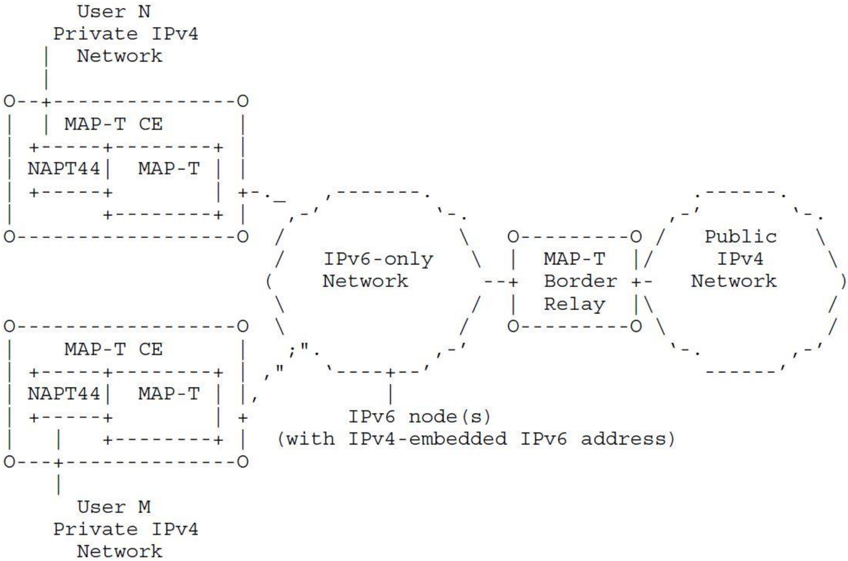

Figure 6. MAP-T Architecture[35]

3. Performance Analysis of IPv6 Transition Technologies

Several research papers have analyzed the performance of different IPv6 transition technologies in the literature. This section is intended to give a clear summary of their findings. However, there are some others which are not covered in this paper because they are either relatively old (e.g. [36], [37], and [38]) or out of the scope of this paper such as those measuring or comparing the performance of different implementations of a single technology (e.g. [39] for DNS64 implementations, [40] for NAT64 implementations, and [41] for 6to4 implementations).

Altangerel et al. [2] performed performance analysis on some IPv6 transition technologies, namely Dual Stack, manual tunneling, ISATAP, and 6to4. Their experiments were implemented in a real network environment by transmitting 30,000 TCP segments of size of approximately 31,000 bytes generated by Poisson distribution in MATLAB. They applied these different technologies to a single user and also to a varying number of users. Then, they calculated the average results of both RTT and throughput obtained from the two cases. They also used GNS3 and OPNET simulators to complete their comparison and analysis of the before mentioned technologies. The experiments showed that both manual tunneling and 6to4 proved higher throughput and lower RTT whereas Dual Stack was the worst as it resulted in the minimum throughput and the maximum RTT.

Georgescu et al. [42] proposed an IPv6 Network Evaluation Testbed (IPv6NET) as a measuring tool to test the feasibility of transition technologies in a series of scenario-based network situations. The article took one of the enterprise network scenarios, which has been introduced by the IETF in [43], as a case study for their research. The scenario targets enterprises using one of the *IPv4aaS* technologies, where the core network is IPv6-only while the end-user and server nodes are IPv4-capable. Thus, they selected 464XLAT and MAP-T as translation-based technologies and MAP-E and DS-Lite as encapsulation-based technologies to implement this scenario. Additionally, the authors selected the free software *Asamap/Vyatta Distribution* [44]as an implementation, which supports the four chosen technologies. The authors also used the Distributed Internet Traffic Generator (D-ITG) described in [45] to generate traffic for their experiments.

As an empirical methodology, IPv6NET tested two types of environments: closed environments for thorough network performance data and open environments for operational capability data. To quantify closed environment results, well-established metrics such as *round-trip delay*, *jitter*, *throughput*, and *packet loss* have been used. For open environment testing, an operational capability indicator has been proposed, which states how much a certain technology is suitable for a certain environment or how it can successfully pass operational problems. For this purpose, three different metrics have been introduced, *configuration capability*, which measures how much a network implementation is capable of in the context of contextual configuration or reconfiguration, *troubleshooting capability*, which measures how much a network implementation is capable of in terms of isolating and identifying faults, and *applications capability*, which measures how much a device is capable at ensuring compatibility with well-known end-user protocols.

The empirical results of IPv6NET experiments indicated that MAP-E showed the best network performance over other tested technologies. Moreover, the translation-based technologies (464XLAT and MAP-T) had better performance in terms of latency, whereas the encapsulation-based technologies (MAP-E and DS-Lite) had better performance in terms of throughput. However, the authors asserted that the results are greatly dependent on the quality of the deployed implementation. Thus, their results should be coupled with the quality of the Asamap implementation that they have chosen for their experiments.

Hossain et al. [46] executed Dual Stack, 6to4, and NAT-PT in the Packet Tracer simulator and analyzed their performance through three metrics: latency, throughput, and packet loss. They concluded that 6to4 had the best performance as its latency and packet loss were the lowest and its throughput was the highest. In contrast, NAT-PT was the worst as it showed the poorest performance in terms of the three metrics.

Quintero et al. [47] compared the performance of ISATAP, 6to4, and NAT64 in real testbeds executed in various operating systems. They measured the One Way Delay (OWD) and throughput for TCP and UDP traffic of each one of the measured technologies. To calculate OWD, they used the benchmark described in [48], and to calculate throughput, they used Iperf [49]. Their research confirmed that generally, both ISATAP and 6to4 have similar performance, whereas NAT64 showed the best performance in terms of OWD and throughput for both TCP and UDP traffic. One simple exception is the case of measuring OWD for UDP traffic of TAYGA-NAT64 as it showed unexpected high values.

Sookun et al. [14] evaluated the performance of Dual Stack, 6to4, ISATAP, and 6rd upon three measurements: the Round Trip Time (RTT), throughput, and CPU usage. For this purpose, they installed their testbeds using the GNS3 simulator. They found that Dual Stack recorded the best performance in terms of the highest throughput and the lowest RTT, followed by 6rd, whereas 6to4 recorded the worst performance. Additionally, Dual Stack recorded the highest CPU usage as it has to maintain two routing tables while the other technologies had almost the same CPU usage.

Singalar et al. [50]simulated the function of three technologies: Dual Stack, 6in4, and NAT-PT using the packet tracer simulator. They measured their results against RTT and throughput. They concluded that Dual Stack produced the highest throughput and the lowest RTT. Hence, the Dual Stack was the best. Conversely, NAT-PT had the poorest performance in terms of all measured metrics.

Yu et al. [51] analyzed the performance of both NAT-PT and NAT64. For NAT-PT, they used the open-source *naptd* daemon in conjunction with DNS-ALG for DNS64, and for NAT64, they used *Ecdysis* implementation [52] in conjunction with the DNS64 synthesizing resolver [22] for DNS64. The study showed that NAT64 is relatively more efficient than NAT-PT, especially for small networks or when a network has only a native IPv6-only connection to an IPv4-only server and no other transition technology deployed. The only exception is in the case of a network that has a considerable amount of large outbound packets and few simultaneous connections.

Sans et al. [54] compared the performance of ISATAP,6to4,6rd, and Teredo in terms of RTT and the throughput for both TCP and UDP over both Ethernet and Fast Ethernet using a real testbed. To calculate RTT, they used the benchmark described in [48], and to calculate throughput, they used Iperf[49]. It can also be noted that the authors deployed a free implementation of Teredo called Miredo [57]to implement Teredo. Their experiments showed that ISATAP presents the best performance over all other tested technologies.

Table 2. Summary of technologies covered by each research paper

IPv6 Transition Technology		***Surveyed Research Paper***										
		[2]	**[42]**	**[46]**	**[47]**	**[14]**	**[50]**	**[51]**	**[53]**	**[54]**	**[55]**	**[56]**
Dual Stack		✓		✓		✓	✓				✓	
Encapsulation	Manual Tunneling	✓					✓				✓	✓
	6to4	✓		✓	✓	✓			✓	✓	✓	✓
	Teredo									✓		
	ISATAP	✓			✓	✓			✓	✓		
	6rd					✓				✓		
	Tunnel Broker											
	DS-Lite		✓									
	MAP-E		✓									
	Lw4o6											
Single Translation	NAT64+ DNS64				✓			✓				
	SIIT											
	NAT-PT			✓			✓	✓				
Double Translation	464XLAT		✓									
	MAP-T		✓									

Shah et al. [55] examined the performance of Dual Stack, 6to4, and 6in4 through three metrics: throughput, response time, and TCP delay by using the OPNET simulator. The results showed that 6to4 had better performance than the others, while Dual Stack was the worst.

Hadiya et al. [56] setup real testbed experiments to analyze the performance of both 6to4 and configured tunneling and compare them against different metrics like throughput, jitter, and delay. They found that 6to4 gives better performance than configured tunneling.

Table 2 gives a summary of which IPv6 transition technologies were measured by each one of the surveyed research papers. Table 3 and Table 4 explain the measurement details of each surveyed research paper.

Table 3. Measurement details of the surveyed research papers – part 1

Surveyed research paper	***Test method***	***Tested technology***	***Technology implementation***	***Measured metrics***	***Traffic generation method***
[2]	Real testbed + Simulation (GNS3 & OPNET)	Dual Stack	Unspecified for all tested technologies	RTT and throughput	Poison distribution by MATLAB
		Manual Tunneling			
		ISATAP			
		6to4			
[42]	Real testbed and by using a proprietary tool (IPv6NET)	464XLAT	AsamapVyatta Distribution for all tested technologies	RTT, jitter, throughput, and packet loss	D-ITG
		MAP-T			
		MAP-E			
		DS-Lite			
[46]	Simulation (Packet Tracer)	Dual Stack	Packet Tracer's implementation	Latency, throughput, and packet loss	Packet Tracer's PDU generator
		6to4			
		NAT-PT			
[47]	Real testbed	ISATAP	Daemon	One Way Delay (OWD) and throughput	Proprietary for OWD &Iperf for throughput
		6to4	Daemon		
		NAT64+ DNS64	TAYGA & JOOL		
[14]	Simulation (GNS3)	Dual Stack	GNS3's implementation	RTT, throughput, and CPU usage	GNS3's packet generator
		6to4			
		ISATAP			
		6rd			

Table 4. Measurement details of the surveyed research papers – part 2

Surveyed research paper	***Test method***	***Tested technology***	***Technology implementation***	***Measured metrics***	***Traffic generation method***
[50]	Simulation (Packet Tracer)	Dual Stack	Packet Tracer's implementation	RTT and throughput	Packet Tracer's PDU generator
		6in4			
		NAT-PT			
[51]	Real testbed	NAT-PT	Daemon	RTT	HTTP packets from the client and the server
		NAT-PT's DNS64	DNS-ALG		
		NAT64	Ecdysis		
		NAT64's DNS64	DNS64 Synthesizing Resolver		
[53]	Real testbed	ISATAP	Unspecified	Throughput, EtoE Delay, RTT, and jitter	UDP audio & video streams and ICMP-Ping
		6to4	Unspecified		
[54]	Real testbed	ISATAP	Daemon for PCs and configuration for routers	RTT and throughput	Proprietary for RTT &Iperf for throughput
		6to4	Router configuration		
		6rd	Router configuration		
		Teredo	Miredo		
[55]	Simulation (OPNET)	Dual Stack	OPNET's implementation	Throughput, response time, and TCP delay	OPNET's HTTP traffic generator
		6to4			
		6in4			
[56]	Real testbed	6to4	Unspecified	Throughput, jitter, and delay	D-ITG
		Manual Tunneling	Unspecified		

Discussion

As it may be noticed, no research paper has revealed a remarkable bias that one of the IPv6 transition technologies is adequate for all network environments and situations. It is quite obvious that the results of their performance analysis of IPv6 transition technologies were distinct from each other. This leads us to the fact that their results were highly dependent on many factors including, but not limited to, the followings:

- The selected IPv6 transition technologies have been tested in their experiments.
- The type of their tests (i.e. real testbeds, simulations, etc.).
- The tools they used for testing such as:
  - The type and number of equipment.
  - The chosen simulator, in case of simulations (e.g. GNS3, OPNET, Packet Tracer, etc.).
  - The software implementation of the IPv6 transition technology (e.g. TAYGA, Jool, Asamap, system daemons like *isatapd,* etc.)
  - The type of operating system of the PCs used in the experiments (Linux, Windows 10, etc.).
- The network topology of the experiments.
- The values of configuration parameters of the experiments.
- The number of running iterations of the experiments.
- The form of the applied scenarios in the experiments.

Therefore, deciding which technology is the best for transitioning is a challenging question. The answer may change as the situation or type of network changes. But, at least, a standard benchmarking methodology is essentially needed for testing IPv6 transition technologies. This already has been done through the IETF's RFC 8219 [4], which mainly targets encapsulation and translation technologies. Furthermore, the IETF's RFCs 2544 [58] and RFC 5180 [59] give recommendations for testing Dual Stack. So, they can be used as guides for building compliant testers for various IPv6 transition technologies.

4. Future Work

As stated earlier, the IPv4aaS technologies use IPv6-only devices in the core layer while keep providing IPv4 services for customers at their access layer. This gives the network operators the opportunity to accomplish a gradual yet smooth transition to IPv6 in their core network while allowing customers to still run applications that use socket APIs and literal IPv4 addresses like Skype, Google Talk, and so on and then easily plug in their devices to IPv6 once it becomes necessary. As [19] stated, the five most prominent technologies that are considered IPv4aaS ones are: 464XLAT [31], DS-Lite [17], lw4o6 [21], MAP-E [20], and MAP-T [35].

Building an RFC 8219 compliant tester for each one of the IPv4aaS technologies could be promising. There are some of the steps that have already been taken in this direction. For instance, siitperf [60] is an 8219 compliant tester for benchmarking stateless NAT64 (also known as SIIT), which is also the CLAT part of 464XLAT. Also, dns64perf++ [61] is also an 8219 compliant tester but for benchmarking DNS64. Moreover, a DS-Lite tester is now being developed under the project of 6transperf [62].

As for future work, we are planning to develop an RFC8219 compliant tester for the other IPv4aaS technologies like lw4o6, MAP-E, and MAP-T in conjunction with typical benchmarking measurements.

5. Conclusion

Many IPv6 transition technologies have been developed over the past few years to mitigate the effect of the problem of IPv4 depletion and help in taking serious steps headed for the full adoption of the successor IP version, IPv6. Several research papers have analyzed the performance of these technologies and compared them in the literature. Their methodology of testing varies in terms of the type of testbed, technology's implementation method, traffic generation method, and number and type of metrics (e.g. RTT, throughput, jitter, packet loss, and so on). This paper surveyed these papers, discussed their results, and gave some guidelines fora standardized benchmarking methodology.

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Functional and environmental impacts of the use of reclaimed asphalt pavement materials and of foamed asphalt

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Abstract: Environmental safety related to asphalt mixing plants has been a growing concern due to the high temperature of asphalt mixture production resulting in a lot of energy used and much air pollutants released. Asphalt mixtures with foamed bitumen and RAP can reduce this problem. This paper deals with their functional and environmental effects. In the paper, it was introduced that the hot mix asphalt mixtures bound by foamed bitumen and containing RAP materials provides a good workability, in comparison to "traditional" hot mix asphalt mixtures. However, producing foamed bitumen needs special technological steps before using it as asphalt binder. The use of RAP materials reduces environmental harm and construction costs, besides it preserves the limited resources of stone, sand and gravel.

Keywords: foamed bitumen; RAP; warm asphalt mix; environmental harm; asphalt functional properties

1. Introduction

Changes in the environment and its continuous degradation are among the most important problems in the modern world due to extremely dangerous compounds that pollute the environment such as: carbon dioxide (CO_2) which has a greenhouse effect, carbon monoxide (CO), sulphur dioxide (SO_2) and nitrogen oxide (NO_X), which causes excess acidity in the environment [1]. Hot asphalt mixing plants have a large contribution to these emissions because they require heating the asphalt to high temperatures ranging between 140 and 200ºC to ensure the best coating with aggregates during production HMA, in addition to heating the stones to a high degree [2].

On the other hand, high temperatures require use of much energy and lead to high emissions of dangerous gases (CO_2, SO_2, NOx) with dust scattering in the atmosphere (Fig. 1) [3], which threatens the environment and workers' health. In order to mitigate these harmful effects, modern asphalt technology concentrates on the use of eco- friendly technologies [4]. Several techniques were developed that led to a significant decrease in temperature (Fig. 2) and the emission of harmful compounds [5].

Figure 1. Emissions of mixing plant pollutants [3]

Many countries seek to spend money on new construction methods instead of spending on maintenance and rehabilitation due to the convergence of their costs in a large proportion, so they must find feasible alternatives [6]. Foamed bitumen was found to be the best alternative because of the following reasons:

- In pavements with “unfoamed” bitumen, the damage increases twice when the load is increased by 20%, while in the pavements with foamed bitumen binder the damage does not increase more than twice as a consequence of 20% increase in load [7].

- Foamed bitumen has a higher resistance to fatigue in wet conditions compared to that of bituminous emulsions and mixes [8].

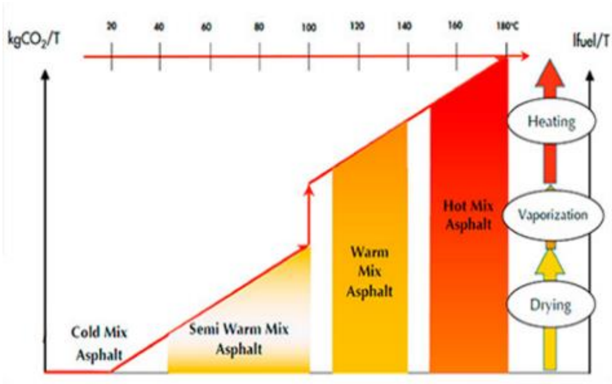

Figure 2. Heating needs of various asphalt mixture types [8]

Foamed bitumen is suitable for pavement repair that has been repeatedly patched; and it can offer a durable solution for pavement sections with large and uncontrollable overloading. There are some other important advantages: increase in granular shear resistance, favourable fatigue resistance, low moisture content compared to bituminous emulsion, good resistance to extreme weather (e.g. heavy rain) effects, fastest way of pavement rehabilitation due to ease of application, speed and compatibility with a wide range of species [9].

2. Application areas of foamed bitumen

Foamed bitumen is used mainly as the binder of a warm or a cold asphalt mixture.

2.1. Warm asphalt mixes

The development of warm mix asphalt when producing asphalt led to the significant reduction of carbon footprint, coming from its rather low mixing temperature between 100 and 140°C [10]. The water is heated above 100°C in the hot bitumen so some of it evaporates resulting a mixture of steam, water and bitumen, which is then mixed with the aggregate at low temperature. This foaming enables the aggregates to be coated by the bitumen at a lower temperature as shown in Fig. 3 [11].

Figure 3. Environmental difference between the production of HMA or WMA [11]

The quantity of water used amounts to 1.2-2.0% of bitumen weight, which is controlled by a flow meter [10].

The main benefits of producing warm mix asphalt compared to traditional hot one are as follows:

- Lower manufacturing costs
- Less fuel consumption
- Reducing carbon dioxide emissions into the atmosphere
- Reducing harmful vapour and smell in the asphalt mixing plant
- Reducing harmful vapour and smell at the paving site (Fig. 4), thus providing a safer working environment for pavers [12].

- The major advantage of using warm mix asphalts is the significant reduction in emissions, every 11°C reduction in mixing temperature halves the emissions entering the atmosphere [13]. It is also an important fact that any HMA production plant can be used to produce WMA, as well [14]. Table 1 presents the production of warm mix asphalt in some selected countries in the period 2013-2019 [15].

Figure 4. Environmental difference between the laying of HMA and WMA [12]

Table 1. Production of warm mix asphalt in some selected countries in the period 2013-2019 [15]

Country	Warm (100-150°C) asphalt mixture production (million tons) in year				
	2013	2015	2017	2018	2019
Czech Republic	0.03	0.02	0.07	0.08	0.00
Denmark	0.12	0.20	0.34	0.33	0.32
Finland	0.00	0.24	0.43	0.31	0.20
France	3.55	4.55	3.82	3.73	4.31
Hungary	0.02	0.07	0.21	0.00	0.18
Netherlands	0.06	0.10	0.06	0.79	0.79
Spain	0.09	0.14	0.20	0.18	0.38
USA	69.00	109.00	137.00	143.00	72.00

2.2. Cold asphalt mixes

Cold asphalt mixing plants (Fig. 5) are becoming more and more widely used in a lot of countries for producing road base material.

Figure 5. Cold asphalt mixing plant [16]

The initial, operating and maintenance costs of this kind of plant are low, because there is no heating or dust collection; so the unit cost of cold asphalt mix is much below that of HMA. However, it is an important requirement that pre-graded, single size aggregates must be used for the production of high quality cold asphalt material [16].

As a binder of cold mix asphalt mixtures produced in these kinds of plants either foamed bitumen or bituminous emulsion is used,

The benefits of cold mix plants are as follows [17]:

- Low initial cost of equipment
- Low maintenance and operating costs
- Low unit cost of cold asphalt mixture produced
- Minimizing the environmental impact since no aggregate heating and drying are needed
- Ease of achieving high capabilities
- No waste materials
- RAP can be also used.

Table 2 presents the production of cold mix asphalt in some selected countries in the period 2011-2019 [15].

Table 2. Production of cold mix asphalt in some selected countries in the period 2011-2019[15]

Country	***Cold (below 50°C), asphalt mixture production (thousand tons) in the year***				
	2011	*2013*	*2015*	*2017*	*2019*
Czech Republic	9.9	9.6	5.4	4.0	6.0
France	1,600.0	1,550.0	1,808.0	1,977.0	1,672.0
Hungary	40.0	58.8	60.0	50.0	60.0
Slovakia	3.0	0.0	1.0	1.0	3.0
Spain	200.0	86.7	94.0	80.0	110.0
Turkey	1,020.0	1,050.0	783.0	1,048.0	905.0

3. Usages RAP material

When using cold and warm bitumen mixtures, there is a possibility not only to reduce the energy needed but also less new aggregate is necessary if RAP materials are applied in a "conventional" or a foamed bitumen asphalt mixture. The following asphalt mixing plant types could be suitable for the use of reclaimed asphalt pavement material.

3.1. Drum mix plant

In a drum mix plant, 15-20% of RAP can be added by an enforcement mounted around the rotating cylinder at the start of the mixing zone. Diameters of RAP grain sizes should be less than 30mm. It is fed into a hopper that is a ramp through a variable speed feeder, and onto a RAP conveyor belt [18].

The new aggregates are heated in the drying and heating section, then the RAP is mixed with the new aggregates, the filler and the bitumen are in the mixing section [19]. The percentage of RAP is limited due to the production of fumes or blue smoke when the RAP is mixed with the superheated new aggregates.

3.2. Counter flow drum mix plants

In a counter flow drum mix plant, max. 60% RAP materials with diameters not exceeding 30mm can be used. The reclaimed material is fed into the rotating drum through a collar wrapped around the drum, then the aggregate is heated to a high temperature to allow heat transfer to the RAP, and removing any moisture present in the RAP, then the combined mixture is heated. RAP fumes are extracted by a fan [20].

Table 3 presents the total quantity and application shares of RAP materials in some European countries in 2019 [15].

Table 3. The total quantities and application shares of RAP materials in some European countries in 2019 [15]

Country	***All available RAP (million tons)***	***% of RAP used in***		
		hot and warm asphalt	***on-site cold asphalt***	***plant cold asphalt***
Belgium	1.64	79	0	0
Croatia	0.21	35	2.5	no data
Czech Republic	2.80	14	25	0
Finland	1.50	100	0	0
Germany	13.40	82	0	0
Hungary	0.15	98	1	1
Norway	1.17	28	0	1
Romania	0.61	0	5	0
Slovakia	0.16	40	48	0
Slovenia	0.15	23	10	0
Spain	1.49	0.1	1	6

4. Laboratory tests on RAP materials and foamed bitumen

A laboratory test series was carried out to determine the influence of various RAP-content and the use of foamed bitumen binder on the Marshall-stability value of asphalt mixtures [21]. Some of the test results will be presented.

4.1. Aggregates

In the test series, five mixture types with different RAP materials percentage in aggregate were used, as follows:

- Type (A) - 100% new aggregate.
- Type (B) - 75% new aggregate + 25% RAP.
- Type (C) - 50% new aggregate + 50% RAP.

- Type (D) - 25% new aggregate + 75% RAP.
- Type (E) - 100% RAP.

All of the aggregate variants had been pre-calibrated according to standard test methods for particle size distribution as shown in Fig. 6, before they were used to produce "**conventional**" HMA mixtures and foamed bitumen mixtures.

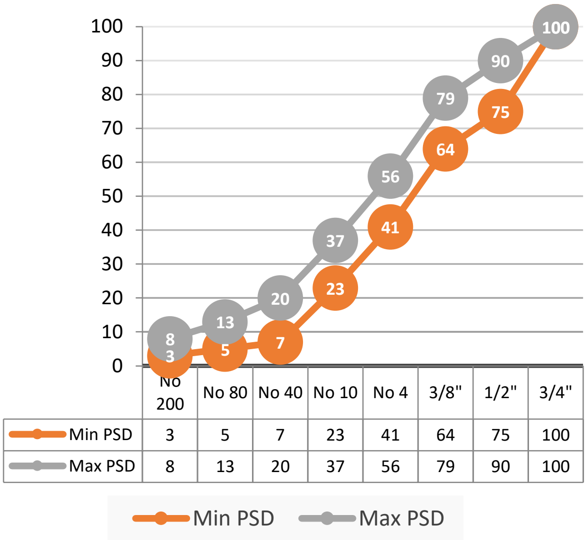

Figure 6. Gradation limits for checking aggregate variants [21]

4.2. Bituminous binder

The bitumen used as binder in producing HMA and foam bitumen asphalt mixtures had the characteristics are shown in Table 4.

Table 4. Characteristics of test bitumen

Laboratory test	***Before loss of heating test***	***After loss of heating test***
Penetration (0.1 mm)	66	51
Softening point (°C)	49	53
Ductility (cm)	153	112
Loss of heating (%)	0.2	0.2

4.2.1."Conventional" hot mix asphalt (HMA) mixtures

The HMA mixtures were produced using 5% by weight bitumen as binder. The specimens for stability measurement were made by Marshall-method, in a cylindrical mold with a diameter of 4 inches (about 100mm) and a height of 2.5 inches (about 63mm) –. The samples were stacked inside the mold with a hammer weighing 10 pounds (about 4.5 kg) freely falling from a height of 18 inches (about 450mm), where the sample is stacked on both sides by 75 blows.

Fig. 7 presents the Marshall-stability (an important performance prediction measure) results, while Fig. 8 shows the VFb (voids filled with bitumen) results of the 5 HMA variants listed in point 4.1.

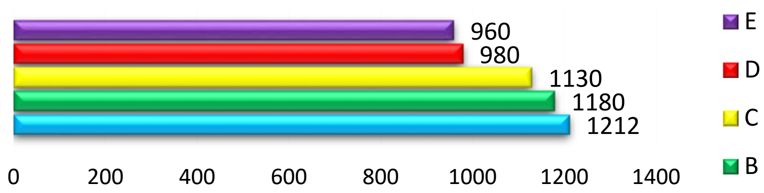

Figure 7. Marshall-stability results (kg) of 5 HMA variants

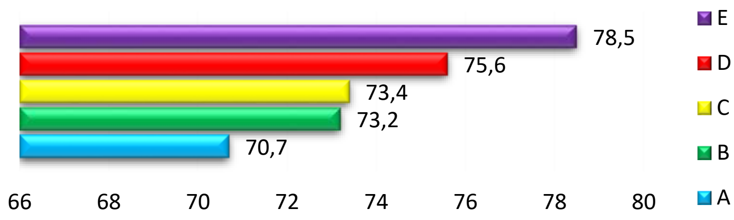

Figure 8. VFb (voids filled with bitumen) results (vol%) of 5 HMA variants

4.2.2. Foamed bitumen bound asphalt mixtures

The foamed bitumen bound asphalt mixtures were produced using 2.5% by weight foamed bitumen as binder.

Fig. 9 presents the Marshall-stability results of the 5 foamed bitumen asphalt variants listed in point 4.1.

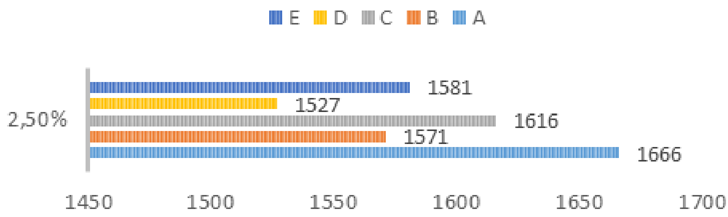

Figure 9. Marshall-stability (kg) results of 5 foamed bitumen asphalt variants

5. Discussion

Fig. 10 shows that the chosen gradation limits were away from the restricted zone [22], thus, the dust proportion values would not effect on the mixture. Several studies state that the restricted zone has a considerable negative effect on the rutting performance of asphalt mixtures [23].

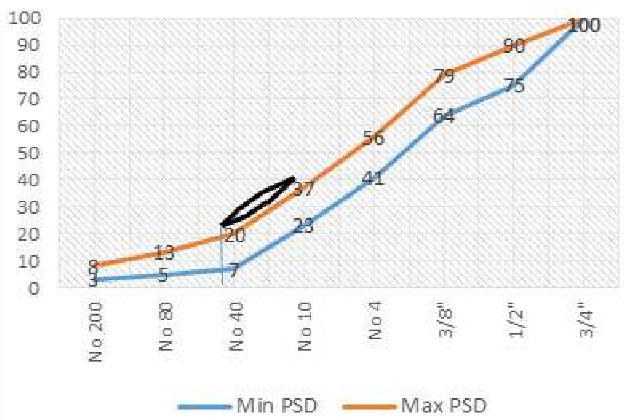

Figure 10. Gradation outside the restricted zone

Fig. 7 shows that the Marshall-stability values decrease with increasing RAP materials share, because the residual bitumen in the reclaimed asphalt pavement increases the Marshall-flow value in the mixture resulting lower cohesion, thus dissociation takes place in the asphalt mixture reducing its stability. Fig. 8 illustrates that voids filled with bitumen are increased with higher RAP-share. This tendency can be explained by the residual bitumen in the reclaimed asphalt pavement that increases the quantity of bitumen in the mixture. Consequently, the total asphalt binder would be unable to hold aggregate in place – segregation of the mix during construction could occur – resulting in too low in-place density.

Fig. 11 presents that the Marshall-stability values are considerably increased due to fact that the asphalt mixture is made at lower temperatures, so the residual bitumen in the RAP increases the hardness of the asphalt mixture. In addition to it, the aggregate grains covered with bitumen provide a suitable surface for sticking to the foam at ambient temperature resulting a rather stable mixture. It can be quantified in the relatively high Marshall-stability values measured.

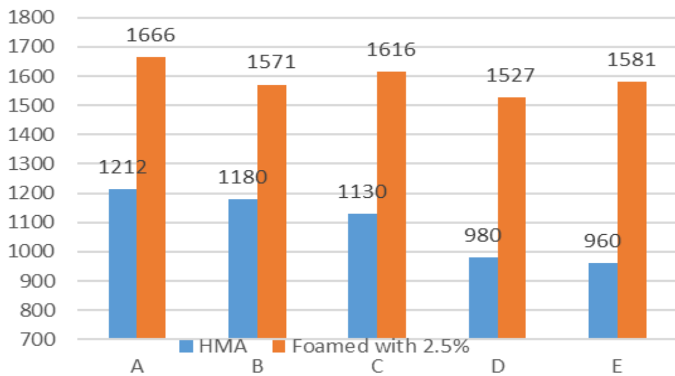

Figure 11. Comparison of the Marshall-stability values of HMA and foamed asphalt mixture

6. Concluding remarks

Environmental safety related to asphalt mixing plants has been a growing concern due to the high temperature of asphalt mixture production resulting in a lot of energy used and much air pollutants released. That is why many research works have been concentrated on the reduction of asphalt mixing temperature by using warm, half-warm and cold mixtures all over the world. One of the most successful relevant research directions is the application of foamed bitumen as a binder of asphalt mixture, besides an important environment-friendly research area is the use of RAP (reclaimed asphalt pavement materials) in new asphalt mixtures.

In this paper, it was introduced that the hot mix asphalt mixtures bound by foamed bitumen and containing RAP materials provides a good workability, in comparison to "conventional" hot mix asphalt mixtures. However, producing foamed bitumen needs special technological steps before using it as asphalt binder. Nevertheless, the use of RAP materials in a new asphalt mixture has several economic-ecological advantages, among others, reduction in the construction costs; much lower greenhouse gas emissions by eliminating the significant fuel consumption required to acquire and process raw materials for "virgin" mix; preservation of the limited resources of stone, sand and gravel; ensuring at least as high quality as the "conventional" asphalt mixture has. The results of a laboratory test series showed in the point 4 of present paper prove that adding RAP materials in a growing proportion increases the Marshall-stability value (an important performance prediction measure) of the mixture. The continuation of the research work mentioned would concentrate on the development of a performance optimizing mathematical model for the clarification of the relationship between the variables of bitumen foaming process.

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