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Research paper

Transmission of data from weighing stations for vehicles in motion using wireless sensor network devices

Mariusz Rychlicki[1], Zbigniew Kasprzyk[2], Tomasz Kamiński[3]

Abstract: The paper presents the general characteristics and design of weighing systems for vehicles in motion. A number of problems and limitations that accompany these systems on the way to achieving full automation of the weighing process at the desired level of accuracy are pointed out. The procedure and construction of preselection systems are discussed, and the mechanism of detailed control at the static control point is presented. Attention is drawn to the use of the WiFi standard for data transmission from the system to the control point, with a discussion on the associated limitations and risks. An alternative solution is proposed, using LoRa standard devices, employed in LoRaWAN wireless sensor networks, to transmit data from the station. An own minimum data set for identifying an overloaded vehicle is defined. Based on this, a weighing system emulator was developed, and field measurements were conducted to evaluate the feasibility of using LoRa devices.

Keywords: LPWAN, LoRa, LoRaWAN, traffic safety, weighing vehicles in motion, WIM

[1]PhD., Warsaw University of Technology, Faculty of Transport, Division of Air Transport Engineering and Teleinformatics, 75 Koszykowa St., 00-662 Warsaw, Poland, e-mail: mariusz.rychlicki@pw.edu.pl, ORCID: 0000-0003-4978-3395
[2]PhD., Warsaw University of Technology, Faculty of Transport, Division of Air Transport Engineering and Teleinformatics, 75 Koszykowa St., 00-662 Warsaw, Poland, e-mail: zbigniew.kasprzyk@pw.edu.pl, ORCID: 0000-0002-1745-1946
[3]Prof., DSc., PhD., Eng., Road and Bridge Research Institute, Management Systems and Telematics Division, 1 Instytutowa St., 03-302 Warsaw, Poland, e-mail: tkaminski@ibdim.edu.pl, ORCID: 0000-0002-6695-4136

1. Introduction

Weigh-in-motion (WIM) systems are high-tech solutions that enable the measurement of the total weight and axle loads of vehicles traveling on public roads under normal traffic conditions. The main and ultimate goal of these systems is to weigh vehicles automatically, without the need to stop them, and thus enable automatic fines for overloading vehicles, analogous to speeding violations. Despite the fact that the very idea of WIM has been known for more than 70 years [1] and work on them continues constantly, in many countries these systems have still not reached a level that would make the idea of full automation of measurements possible.

2. Status of the issue

The problem of overloaded trucks traveling on public roads has long been widely discussed in many scientific publications. These discussions can be divided into several groups, among which three main issues can be distinguished. The first is the impact of overloaded vehicles on road infrastructure, the second is their impact on traffic safety, and the third is the analysis of data from the sensors used for measurements and related issues regarding the accuracy class of these measurements. It has long been known and reported in the literature that the impact on the road surface of a single truck overloaded by 30 tons above the permissible total weight is equal to that of a million or more passenger vehicles. Significantly, such an overloaded vehicle causes several times more fatigue damage to the pavement structure than properly loaded vehicles [2]. In general terms, it can be assumed that one overloaded truck affects an asphalt (flexible) pavement as much as 10^4 passenger cars, which reaches the order of 10^9 for concrete (rigid) pavements. Overloaded vehicles not only pose a greater risk to other road users but also to road infrastructure. They are particularly hazardous to bridge structures, where collisions can lead to significant economic losses and negative social impacts [3].

Excessive weight worsens the stability of a truck, even if the cargo itself is properly and securely placed in the vehicle. This can lead to a malfunction of the vehicle's braking system, making it difficult to maneuver and, in extreme cases, even impossible to control. The braking distance of an overloaded vehicle is much longer than that of an unloaded vehicle. Its stability is also compromised, especially when maneuvering. Thus, the risk of violating road safety by an overloaded vehicle is always higher than for a vehicle loaded according to regulations. Additionally, the involvement of overweight vehicles in traffic accidents increases the severity of the consequences [4].

By far, the most complex issue with regard to WIM systems is accuracy, particularly concerning the standard piezoelectric sensors used in these systems. There are several factors that affect measurement accuracy, such as the speed and track of the vehicle, the class (type) of vehicle, the temperature of the pavement, and the humidity of the air and pavement. Thus, the accuracy of the sensors used may not only depend on atmospheric conditions and the vehicle being inspected but also on the location of the measurement system itself. The accuracy of such a system will differ in various parts of the world, where climatic conditions can vary significantly [5]. It is well-known and observed that, due to the influence of all these factors on the measurement sensors, there can be significant changes in the accuracy of vehicle weighing over very short periods, even less than one hour [6]. The solution to this problem is possible on several levels. One approach involves technological changes in the production process of measuring sensors to obtain components with higher accuracy and stability. Another involves action on the system itself and the accompanying infrastructure, including appropriate location and implementation. However, the appropriate development and selection of advanced algorithms and methods for self-calibration of the WIM system may prove crucial [7]. Additionally, as with any measurement system of this type, there is a risk that the collected data may be temporarily or permanently lost due to sensor or system transmission failure. This situation would lead to an overall deterioration of the system's functionality and jeopardize its reliability. Models based on deep learning or generative adversarial networks (GANs), which are capable of generating new data that conforms to learned patterns, could provide a solution [8]. The use of WIM models based on the beetle swarm optimization (BSO) algorithm and the back-propagation error (BP) neural network is very promising for improving the accuracy of WIM system measurements [9].

The successful implementation of a WIM system and the achievement of full automation, along with the necessary self-calibration at a preset level of accuracy, is a highly complex, multi-layered process that requires a series of, sometimes disparate, activities. The development of a common standard and guidelines for the design, construction, commissioning, and testing of WIM systems helps achieve this goal. Among the most important international sets of specifications for WIM are COST323 [10], OIML R-134 Part I [11] and Part II [12], ASME E-138 [13], NMi WIM, and the European Commission's Measuring Instruments Directive [14]. For many years, the first three documents have been used to determine the quality of WIM systems around the world [15]. All three documents have their own areas of application, with specific advantages and disadvantages. However, none of these documents covers all applications and operational conditions of WIM systems. The results of an attempt to develop a single, complete international standard for WIM systems are contained in NMi WIM [16].

3. Vehicle weighing systems

3.1. Construction of the preselection system

Preselective WIM systems, which perform the typing of potentially overloaded vehicles for static and precise weight control, use a variety of technologies to measure the weight of vehicles in motion, primarily utilizing measuring sensors. These sensors record the force exerted by vehicles moving on the road and passing through the detection area, then convert it into vehicle weight by measuring the degree of deformation of the measuring element. This data is then processed and can be displayed in real-time, stored for later analysis, or sent to a surveillance center.

The basic schematic of a preselective WIM system is shown in Figure 1. The basic element of the preselection system is a preselection weighing station for vehicles in traffic with B+(7) accuracy according to the COST323 [10] standard [17].

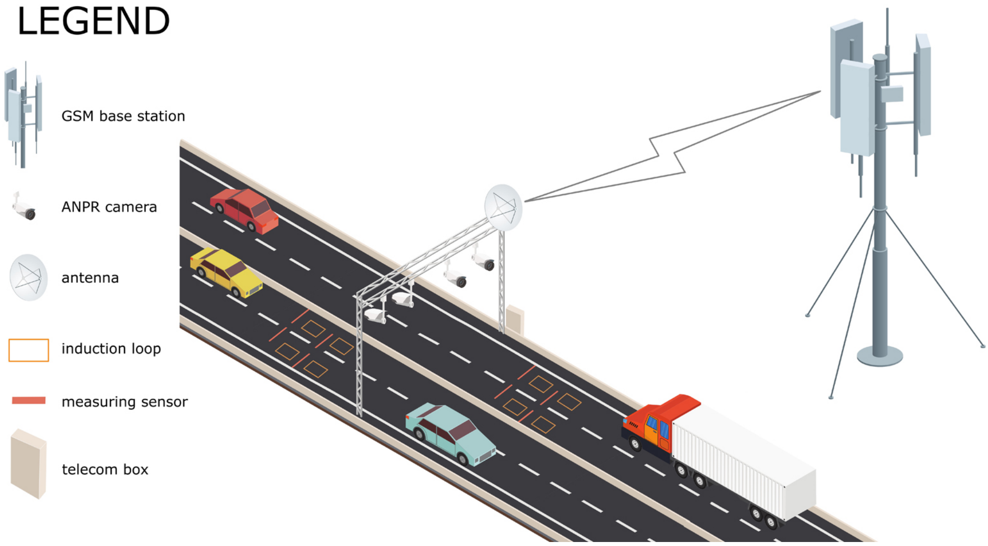

Fig. 1. The Diagram of the WIM system (source: own elaboration)

3.2. Data formation and collection

The data collected in the system is formed into a data record, which is then saved to a file in XML format. It contains the following information: iindividual axle pressures, total pressure of all axles, vehicle wheelbase, total vehicle weight, vehicle length (alternate electrical length measured on the induction loop), exceeding the permissible axle load and axle group and the weight allowed for the type of vehicle or combination of vehicles, the maximum permissible total weight of the vehicle, according to the data recorded in the system, resulting from the law in this regard, vehicle speed, lane and direction of traffic, vehicle classification by number and wheelbase, vehicle sequence number, date and time of transit according to UTC and local time, vehicle photos for vehicles alleged to have committed an offense (overloaded vehicles), a photo of the license plate for each vehicle, license plate data reformatted into a text file (recognized license plate number), optional: information about exceeding the maximum height of the vehicle [18]. WIM station generates a rather rich set of measurement data that directly relates to more than just vehicle weight. Represented in text form, the data also reflect variables in integer form of various formats. The MySQL database standard supports the classic SQL integer types INTEGER or INT (8 bytes) and SMALLINT (2 bytes). As an extension of the standard, MySQL also supports TINYINT (1 byte), MEDIUMINT (3 bytes), and BIGINT (8 bytes) integer types [19]. Choosing the appropriate integer type for a given variable range is crucial for the amount of data transferred and thus saving space (memory) in the database itself and on the server. However, a single data record can still reach a size of several hundred bytes in text form alone. For modern database systems, this is not a large value, but it can already make a difference in the data transmission process itself.

3.3. Accurate weighing of the vehicle

Preselection scales, as their name implies, are used only for statistical purposes and for identifying potentially overloaded vehicles for precise, static inspection. This is due to their aforementioned insufficient measurement accuracy and instability, which varies over time, as well as a number of other factors. These issues are also noted by the Supreme Chamber of Control, which in its post-inspection results states that the usefulness of preselection systems is limited due to technical faults (inaccuracy of readings, sensitivity to weather conditions, problems with power supply continuity) and the lack of correlation between their location and the location of vehicle inspection sites. The limited number of such sites and the considerable distance from the preselection points prevent effective control activities aimed at eliminating overloaded vehicles from traffic [20]. The weighing process is therefore subject to the relevant provisions on the requirements for vehicle scales used for weighing vehicles in motion, as well as the detailed scope of tests and checks performed during the legal metrological control of these measuring instruments [21].

4. Wireless sensor networks

A Wireless Sensor Network (WSN) is a network consisting of spatially distributed autonomous sensors that monitor physical or environmental conditions such as temperature, sound-related parameters, pressure, medical data, and more [22]. These sensors work together to transmit the data collected by the network to a primary storage location [23]. WSNs have evolved into distributed networks comprising a large number of small devices, called nodes, which have built-in computing, storage, and communication capabilities [24]. A typical WSN networks consist of several key components that work together to enable data collection, processing, and transmission [26]. These include sensors, processors, communication modules, power systems, end devices and/or gateways, servers, application software, and user interfaces. In the 21st century, WSNs have become a key component of the growing Internet of Things (IoT). The ability to remotely monitor and collect data from a variety of sensors has enabled smart systems in areas such as smart cities, smart homes, healthcare, agriculture, and industry. WSNs have found applications in advanced areas such as monitoring climate change, persistent air pollution [26], managing natural disasters, monitoring building structures, and even in space exploration [27]. Despite their many successes, WSNs still face challenges such as energy management, data security, reliability, and scalability. While the development of technologies such as 5G networks or LoRaWAN may bring solutions to some of these problems, it is noteworthy that the advancement of autonomous vehicles may introduce quite new challenges in terms of security [28]. Another important trend in road transport is the growing share of electric vehicles (EVs) in traffic. While EVs do not generate pollution in the same direct way as traditional internal combustion engine vehicles, their increased weight can contribute to higher noise emissions on poorer-quality roads, especially in rural areas. The use of wireless sensor networks (WSNs) and the collection of real-time measurement data would significantly enhance the modeling studies conducted in this area. [26].

4.1. LoRa/LaRaWAN standard

An example of a WSN is LoRa (Long Range), which is a long-range, low-power wireless data transmission standard designed to transmit small amounts of data. These properties make it ideal for creating wide-area sensor networks that provide data to command, control, and surveillance systems. It is worth noting that LoRa and LoRaWAN are not the same thing. LoRaWAN optimizes energy consumption and manages traffic between nodes, providing secure connections through point-to-point encryption [29]. The protocol also supports wireless registration of new devices and multicast broadcasting (one-to-many communication) [30].

The typical architecture of a LoRaWAN consists of four main components: EN (End Nodes) devices; GW (Gateway) gateways (base stations, routers); NS (Network Server) [31]. These servers manage the network, processing data and ensuring secure communication; AS (Application Server). Transmissions between devices using LoRa technology can reach many kilometres, even hundreds, depending on the terrain, type of terrain, and the type and location of antennas. However, such a large range is associated with a limitation of data throughput. Data transfer speeds, depending on the modem configuration, can range from kilobytes to a few bytes per second. Nonetheless, achieving the distances mentioned, with low power consumption, is possible by using appropriate modulation of the radio signal. LoRaWAN technology uses CSS (Chirp Spread Spectrum) modulation, where the data stream is modulated with a signal of linearly increasing frequency. The implementation of the CSS signal modulation process depends on its three main parameters: *BW* (Modulation Bandwidth) – describes the extent to which the modulation frequency varies; *SF* (Spread Factor) – determines how fast the modulating frequency changes; *CR* (Code Rate) – introduces redundancy, while providing correction of errors arising during transmission. The above parameters affect the maximum range and throughput of the LoRaWAN link and are described by relation (4.1):

$$R_b\ [\text{b/s}] = SF \cdot \frac{CR \cdot BW\ [\text{Hz}]}{2^{SF}} \tag{4.1}$$

where individual parameters can take the following values: $BW \in$ {7.8 kHz, 10.4 kHz, 15.6 kHz, 20.8 kHz, 31.25 kHz, 41.7 kHz, 62.5 kHz, 125 kHz, 250 kHz, 500 kHz}, $SF \in$ {6, 7, 8, 9, 10, 11, 12}, $CR \in$ {4/5, 4/6, 4/7, 4/8}.

5. Data reception at the static control point

Since data from the WIM system is transmitted to the central server at intervals ranging from 15 to more than 120 minutes, it is not possible to use this data in real time at static control sites if it is transmitted from the central server. Static checkpoints should be located at a certain distance, which must not be too short, since the static checkpoint attendant must have time to react and safely stop the vehicle. In practice, this distance can range from a kilometres to several kilometres, depending on the terrain and location possibilities. However, this does not mean that such a solution is without disadvantages - quite the contrary. Many implementations have chosen the WiFi standard for the practical implementation of such a wireless link [17]. Since The WiFi standard has several significant drawbacks, especially when used in open spaces over distances of several kilometres [30]. Even small obstacles can significantly reduce the range of the signal, further hindering its effective use over long distances [32]. The limitations and disadvantages of wireless transmission can be mitigated by using a traditional wired network in WIM stations. This solution, which is also used in practice, can provide efficient and reliable transmission over long distances, especially when fiber optics are employed. However, it significantly increases the cost of implementation and may require various permits, as well as the development of detailed designs and extensive implementation documentation. For these reasons, a wireless solution ultimately appears to be more attractive for practical applications.

5.1. Comparison of LoRaWAN and WiFi standards

The WiFi and LoRaWAN standards differ in many respects, from application and architecture to range and power consumption. In both standards, these issues are crucial and play a significant role [35]. Both technologies, WiFi and LoRaWAN, have their specific security challenges [35]. WiFi, due to its popularity and widespread use, is a frequent target of attacks, requiring constant monitoring and security updates. LoRaWAN, although less widespread, faces challenges in protecting distributed and often remotely managed IoT devices. Both technologies use advanced encryption methods, but their effectiveness depends on proper implementation and management of cryptographic keys. In terms of securing against unauthorized access, WiFi offers strong user authentication mechanisms that can be managed centrally, especially in enterprise environments. LoRaWAN, on the other hand, relies on unique device identifiers and session keys to secure device-to-server communications even in distributed IoT networks [36]. WiFi and LoRaWAN both offer advanced security mechanisms, but differ in their approach and implementation specifics (Table 1). WiFi, with its advanced authentication and encryption protocols, is well-suited to high-bandwidth and dense network traffic environments. LoRaWAN, with its dual encryption and unique session keys, is the optimal solution for secure communication in IoT networks, where devices operate over long distances with low power consumption and relatively small amounts of data.

Table 1. Comparison of LoRaWAN and WiFi standards [35]

	LoRaWAN	**WiFi**
Wireless network	Low-power wide area network (LPWAN)	Local area network (LAN)
Operating band	433, 869 and 915 MHz	2.4 and 5 GHz
Data rate	50 kbps	11–54 Mbps
Bandwidth	$\leq$ 500 kHz	22 MHz
Transmission range	5 km (urban), 10 km (rural) and more	100–300 m

5.2. Possibilities of using LoRaWAN devices to receive data from WIM stations at a fixed control point

In LoRa technology, the amount of data that can be transmitted in a single frame depends on several factors, such as bit rate (data rate) and geographic region, which determines regulatory restrictions. In general, the maximum data size in a single LoRaWAN frame is up to 243 bytes. This is a theoretical maximum and in practice may be smaller due to protocol overheads and other restrictions [37]. The typical WIM data, whose size for a single record runs into hundreds of bytes, is therefore too large for simple transmission in a single LoRaWAN data frame. However, it is important to note that at the stationary checkpoint, the entire and complete process of vehicle and driver inspection takes place, not only for overloading. Only the results of this inspection can be the basis for imposing fines or taking other additional actions, including taking the vehicle or driver out of service. Thus, this full set of data is not necessarily needed to select and refer a vehicle for stationary inspection. This is especially true since the data transfer would take place in real-time. Therefore, what is required is the transmission of a minimum data set to identify an overloaded (according to the measurement at the WIM station) vehicle, possibly supplemented with the basic, most relevant data. Let's therefore introduce a minimum dataset to identify an overloaded vehicle, designated as MDIOV (Minimum Dataset to Identify an Overloaded Vehicle).A typical LoRa data frame consists of several elements: Preamble: is a sequence of bits at the beginning of a data frame, used to prepare the receiver to receive incoming data; Header: contains the information necessary for the receiver to process the frame, such as the source and destination addresses to identify the sender and receiver of the data; Payload or Data: this is the actual part of the frame, containing the transmitted information or user data; Frame Check Sequence (FCS): usually placed at the end of the frame, contains information used to detect errors in transmission. Most often it is a checksum or CRC (Cyclic Redundancy Check) value. It is worth noting that the vast possibilities and diverse applications of sensor networks extend far beyond the simple transmission of data from a single WIM station. The use of LoRaWAN devices in this context allows for the easy and significant expansion of an existing system to transmit additional sensor data. These sensors do not need to be located directly at the WIM station but can be positioned in front of it or between the station and the static control point. Depending on the sensors used, this could include information about driver behavior (e.g., changes in speed) or noise emissions.

The transmitted load in this case will be the MDIOV, which consists of: NoF – consecutive frame number (Number of Frame), two bytes, four hexadecimal characters; Cat/NoA – Vehicle Category (Vehicle Category) / Number of Axles (Number of Axles), one byte, two hexadecimal characters; Sp – vehicle speed (Speed), one byte, two hexadecimal characters; LDNP – the last (four) digits of the vehicle registration number (Last Digits of the Number Plate), four bytes, eight hexadecimal characters; NoA1, . . . , NoA5 – number of overloaded axis (Number of Overloaded Axle), one byte, two hexadecimal characters, zero value for no axis; AOP1, . . . , AOP5 – Axle Overload in Percentage, one byte, two hexadecimal characters, zero value for no axis; CRC – CRC checksum (Cyclic Redundancy Check), two bytes, four hexadecimal characters.

As you can see, MDIOV consists of only 40 hexadecimal characters, which corresponds to 20 bytes of data. This layout is proposed to achieve maximum simplicity in the hardware implementation of the proposed solution. However, it is worth noting that this set can be even smaller, since both the license plate digits, the overloaded axle number, and the overload percentage can be stored in fewer bits than used in the example solution. Therefore, a simple compression mechanism or a change in the encoding system can be implemented in this solution. An example data frame could look as follows:

0 × 01 0 × 06 0 × 5E 0 × 05 0 × 03 0 × 00 0 × 02 0 × 07 0 × 01 0 × 00 . . .
0 × 02 0 × 0F 0 × 03 0 × 18 0 × 04 0 × 0C 0 × 05 0 × 140 × 8E 0 × AD

6. Hardware implementation and field testing

In order to verify the theoretical assumptions of using LoRa devices and LoRaWAN wireless sensor networks to transmit MDIOV data, a WIM system emulator was developed. Its task is to generate random events and values at set time intervals. Events are understood as the appearance of vehicles of a certain category and their overloads on individual axles. The emulator was developed using a simple and popular Arduino system, and the control program was written in the language of this environment, based on C++. Algorithm 1, demonstrating the operation of the software, is shown below in Table 2.

As a result of the emulator's control program, a thousand MDIOV data frames are sent through the serial port at random intervals of 2 to 7 seconds. The frames contain data about vehicles of random categories and their random overloads on individual axles. This prepared data then needs to be sent with the LoRa device. Of course, on the receiving side, there must be an analogous LoRa device and the ability to verify the correctness of the transmission. For this purpose, an analogous Arduino device was developed for the receiving side, which receives and decodes the MDIOV frame, and then verifies the correctness of the transmission by checking the CRC checksum.

Table 2. WIM system emulator algorithm

Algorithm 1: WIM system emulator.
Initialization of LCD display (2 × 16) and UART serial port
LED pin assignment
Set the value of the variable *frameNumber = 0*
do
Drawing the value of the variable *category* from 1 to 8
Drawing the value of the *speed* variable from 70 to 130
Drawing the value of the variable *ldnp* from 0 to 9999
Initialization of variables *numberOfAxles*, *axleNumber*[], *axleOverload*[] = 0

Table continued on the next page

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Drawing of overloaded axles and percentage of overload by *category*
end switch
Creating text variables *lcdText1* and *lcdText2* for LCD display
Text display on two lines of LCD display
Create a text variable *serialData*, containing the values of the variables *frameNumber*, *category*, *speed*, *numberOfAxles*, and the pair *axleNumber[i]*:*axleOverload[i]*
Calculate the CRC checksum for the *serialData* variable and add it to this *serialData variable*
Create *serialDataHEX[20]* array containing hexadecimal values of *serialData* variable
Sending *serialDataHEX[20]* array through serial port
LED flashing with 300ms light time
wait
Pause the program for a random time from 2 to 7 seconds
end wait
Increase the value of the *frameNumber* variable (++*1*)
loop until *frameNumber* <1000

For the first tests, a very basic and simple modem/converter, the USR-LG206-H-P, was chosen as the LoRa device. It is an industrial RS232/RS485 to LoRa media converter, housed in a metal case, operating at 803–930 MHz. It can operate completely transparently and supports point-to-point protocol and fixed point transmission mode. It transmits and receives data serially and can implement one-to-one or one-to-many communication [38]. The device can be configured using a set of AT commands, similar to a classic GSM modem. Among the most important configuration parameters are the serial port settings, the device's operating channel, and the transmitted power.

6.1. Location of apparatus during tests and measurements

The key to ensuring efficient and effective wireless transmission is to ensure that the link balance (budget) is correct. This calculation takes into account all signal gains and losses along the transmission path between transmitter and receiver. This includes transmit power, antenna gains, cable and connector losses, propagation losses (caused by signal propagation through the atmosphere, obstacles, etc.), and margins for interference and other unforeseen losses. The resulting link budget shows whether the signal will be strong enough to be correctly received by the receiver after it has traversed the entire transmission path. The main purpose of calculating the link balance is to ensure that the wireless system will have sufficient signal margin to allow reliable communication under assumed operational conditions. This allows for proper system design, equipment selection, and infrastructure deployment planning to meet coverage and transmission quality requirements. Link budget is a key tool in the design of wireless networks, including cellular networks and other wireless applications such as LoRaWAN and Wi-Fi.

Basic information about radio signal loss during propagation is provided by the Free Space Path Loss (FSPL) attenuation model, which describes the power loss of a radio signal that propagates through free space, without physical obstructions or the influence of the atmosphere. This is the basic type of attenuation that occurs when radio waves travel the distance from transmitter to receiver in open space, such as outer space or Earth's theoretically ideal, obstacle-free atmosphere. Attenuation in free space (FSPL) can be calculated using Formula 6.1, which assumes that the signal propagates spherically from a point source.

$$\text{FSPL}\,(db) = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right) \tag{6.1}$$

where: d – is the distance between the transmitter and receiver in meters, f – is the frequency of the signal in Hertz, c – is the speed of light in a vacuum (3×10^8 m/s).

Using relation (6.1), you can draw up a link balance and calculate the theoretical transmission range. This result is only illustrative and will not have much practical significance because it does not account for real operating conditions, where signal attenuation is primarily affected by terrain and land use. Such information can be provided by advanced propagation models implemented in specialized radio planning software, such as HTZ Communication. A good example is the Deygout 94 diffraction model, which has been further extended with the "Area" sub-path attenuation model [39]. For it, to define the losses that lower obstacles cause, the area "obscured" by them in the first Fresnel zone is found. The sub-pathway attenuation is calculated according to equation (6.2).

$$L_{sp} = 6,4 + 20\log\left[v + \sqrt{(1 + v^{2)}}\right] \tag{6.2}$$

where: $v = \sqrt{\frac{H}{R}}$; H/R is the ratio of the obscured area to the area of half the Fresnel zone.

This approach allows for creating a model of the radio link in the aforementioned software and performing simulations of radio coverage. However, this paper focuses on actual field tests and measurements of transmission range, defined by the number of correctly received frames. The area of the municipality of Ożarów Mazowiecki was chosen as the test site. The municipality is located in the center of the Mazovia province, in the district of Warsaw-West. It borders Warsaw to the east and extends towards Błonie and Sochaczew along important international transport routes: the A2 highway, national road No. 92, and the Warsaw-Berlin railroad line. It borders, among others, the municipality of Błonie, which in recent years has begun to change its profile. Large international companies are locating their headquarters and warehouses on former agricultural land. Only 2 kilometres separate the borders of the municipality from the "Tłuste" junction of the A2 highway. Additionally, the international east-west railroad trunk line runs through the municipality, and there is a railroad siding at the railroad station in Błonie suitable for unloading construction materials, containers, etc. There are large logistics bases and manufacturing plants in its area. All this translates into very heavy vehicular traffic, with a significant share of trucks. To avoid interfering with existing equipment and to maintain the legally required EIRP value, the operating power of the device was limited to 17 dBm. The location map of the measurement points is shown in Figure 2, and the location and appearance of the transmitting part of the WIM emulator are shown in Figure 3. The receiving part has an identical appearance. Both the transmitting and receiving parts are powered by 12 V/12 Ah batteries through a 12 V DC stabilizer circuit.

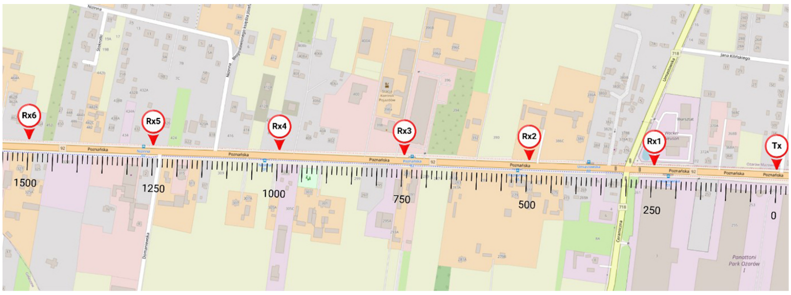

Fig. 2. Distribution map of measurement points (source: own elaboration)

Fig. 3. Appearance and location of the WIM emulator during testing (source: own elaboration)

Measurements were made in several series of 1000 frames each, at six measurement points, not counting the transmitter site. Each point was distant from the previous and the next by a maximum distance (as far as field conditions allowed) close to 250 meters. Classical omnidirectional antennas with 5 dBi gain were used. These antennas were placed on a simple boom, at a height of only 2 meters above the ground.

6.2. Measurement results

The results obtained during the measurements are shown in Figure 4. They contain averaged data from several measurement series, representing the percentage of correctly received frames at each measurement point. FrC_{LoRa} denotes the percentage of correctly received frames by the converter, and FrC_{MDIOV} denotes the percentage of correctly received frames by the WIM emulator.

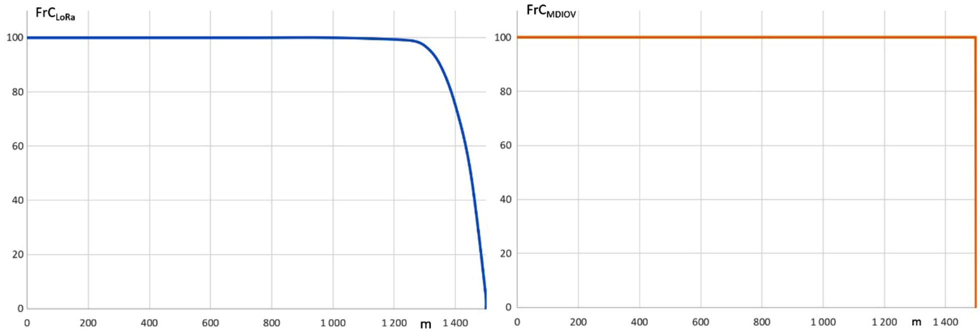

Fig. 4. Percentage results of measurements – number of correctly received frames (source: own elaboration)

It may come as some surprise that MDIOV frames are received with 100% efficiency throughout the transmitter's operating area, and reach zero only after the range limit is exceeded. However, this result is as expected and can be attributed to the transmission mechanism of the LoRa converter. The converter uses its own error control mechanisms and transmits only correctly received frames to the decoder. Therefore, the MDIOV frame check at the decoder only confirms its correctness. If more coverage is required, it can be increased by optimizing various LoRa/LoRaWAN technology and environmental parameters. One key factor affecting range is the spreading factor (SF). Increasing the SF value (e.g., to SF12) makes the signal more resistant to noise and interference, which increases the range. However, it is important to note that a higher SF reduces throughput. Another important factor is the transmit power (Tx power). Higher transmit power allows stronger signals to be sent, enabling the signal to travel greater distances. However, it is important to keep in mind that regulations on maximum permissible transmit power vary by region. While increasing transmit power can improve coverage, these legal restrictions must be adhered to. Antenna selection also plays a critical role. Using higher-gain antennas, for example, 10 dBi instead of 5 dBi, can significantly improve coverage. Such antennas focus the signal energy more effectively in a particular direction, minimizing losses. Improved antenna characteristics positively affect both transmitting and receiving signals, enhancing communication quality over longer distances. However, it is essential to consider legal limitations related to the EIRP (Equivalent Isotropically Radiated Power) parameter. Receiver sensitivity is another factor that affects range. Receivers with higher sensitivity (e.g., –130 dBm) can effectively capture weaker signals, allowing communication over longer distances. Improved receiver sensitivity is a critical aspect of equipment selection. Reducing bandwidth (BW) can also extend range. Narrower bandwidth makes the signal more concentrated and resistant to interference, enabling more effective communication over longer distances. However, reducing BW enhances coverage at the expense of data throughput, so, like with SF, the decision to optimize this parameter should be based on network priorities. In addition to optimizing technical parameters, the positioning and location of antennas is crucial. Installing antennas at higher elevations can significantly improve coverage by eliminating terrain obstacles such as trees or buildings that can attenuate the signal. Ensuring a clear line of sight between the transmitter and receiver is essential for effective communication over longer distances.

7. Applications

Weighing systems for vehicles in motion are a crucial element in improving traffic safety, protecting roads from degradation, and increasing the level of fair competition by leveling the playing field between carriers who comply with regulations and those who operate overloaded vehicles. For these reasons, work on their development is constantly underway, aiming to achieve a level of accuracy and reliability that allows full automation of the weighing process and the imposition of penalties for overloaded vehicles. However, several existing problems, primarily in ensuring the stability and accuracy of measurement sensors, mean that static inspections may still be necessary for a long time to come. Therefore, the approach presented in this paper for transmitting data from WIM stations to static control points using LoRa devices is particularly interesting. The results of the conducted experiment confirm that the use of LoRa devices in this context is not only possible but also offers a number of new possibilities with a completely new approach. Among these possibilities is the use of commonly available LoRa transceiver components to build a cheap and simple LoRa terminal that can receive data directly from the WIM station without the need for a computer and operating system (usually Windows). The experiment's results confirm the feasibility of reliable transmission over a distance of more than a kilometres. It should be noted that this result was achieved using omnidirectional antennas placed at a height of only two meters. Simply increasing this height would measurably translate into a real and noticeable increase in the distance of effective transmission. Thus, the effective use of LoRa wireless devices in LoRaWAN sensor networks for transmitting data from WIM vehicle weighing stations to static control points is feasible and can serve as an alternative to classical solutions based on WiFi networks.

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Transmisja danych ze stacji ważenia pojazdów w ruchu za pomocą urządzeń bezprzewodowej sieci czujników

Słowa kluczowe: LPWAN, LoRa, LoRaWAN, bezpieczeństwo ruchu, ważenie pojazdów w ruchu, WIM

Streszczenie:

W artykule przedstawiono ogólną charakterystykę i budowę systemów ważenia pojazdów w ruchu. Wskazano na szereg problemów i ograniczeń, które towarzyszą tym systemom na drodze do osiągnięcia pełnej automatyzacji procesu ważenia na pożądanym poziomie dokładności. Omówiono procedurę i budowę układów preselekcji oraz przedstawiono mechanizm szczegółowej kontroli w statycznym punkcie kontrolnym. Zwrócono uwagę na wykorzystanie standardu WiFi do transmisji danych z systemu do punktu kontrolnego, z omówieniem związanych z tym ograniczeń i zagrożeń. Zaproponowano alternatywne rozwiązanie, wykorzystujące urządzenia standardu LoRa, stosowane w bezprzewodowych sieciach czujników LoRaWAN, do przesyłania danych ze stacji. Zdefiniowano własny, minimalny zestaw danych do identyfikacji przeciążonego pojazdu. Na tej podstawie opracowano emulator systemu ważenia pojazdów w ruchu i przeprowadzono pomiary terenowe w celu oceny możliwości wykorzystania urządzeń technologii LoRa.

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