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DEVELOPMENT OF FIBER OPTIC SENSOR-BASED WEIGH-IN-MOTION SYSTEM FOR BRIDGE APPLICATIONS

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ABSTRACT

Excessive loads carried by vehicles present substantial threats to road infrastructure, traffic safety, and the overall security of transportation systems, potentially resulting in fatalities. This research focuses on characterizing the influence of moving loads on the attenuation of fiber optic signals. Employing a problem-solving methodology, the study utilizes the macrobending method with optical fibers and aims to integrate the findings into the concept of Weigh-in-Motion (WIM) systems. In this context, macrobending is induced by gravitational forces exerted by the contents within the vehicle's cargo bay. The study encompasses two types of loading scenarios: static and dynamic. Dynamic loading is further investigated at varying speeds of 0.1 m/s, 0.2 m/s, and 0.3 m/s. The research findings indicate a direct correlation between loading magnitude and the resulting attenuation in the optical fiber. This correlation is consistently observed across all three-speed variations of the simulated dump truck, considering both front and rear wheels. Notably, the highest sensitivity value is identified at a speed variation of 0.1 m/s, reaching a value of 2.029. This data is a critical reference for establishing optimal speed recommendations for loaded vehicles passing through a fiber optic sensor-based WIM system. Implementing such recommendations can significantly enhance the effectiveness and reliability of the WIM system in mitigating the adverse effects caused by overloaded vehicles.

Keywords: Overload vehicles; WIM; loads; fiber optic sensors; and macro bending

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INTRODUCTION

The incidents involving overloaded vehicles have resulted in numerous fatalities and substantial material damage. Consequently, the National Transportation Safety Committee (NTSC) fervently endorses the Zero Overloading (ODOL) 2023 policy. This initiative is undertaken with the primary goal of enhancing transportation safety. Soerjanto Tjahjono, the Chairman of the NTSC, emphasizes the imperative of a comprehensive implementation of the zero ODOL policy. The Republic of Indonesia has legislated the enforcement of this policy through Law Number 22 of 2009 concerning Road Traffic and Transportation, along with the Minister of Transportation Regulation No. 60 of 2019 addressing the implementation of Goods Transport by Motorized Vehicles on Roads, specifically in Article 12b. This article stipulates that the road infrastructure must conform to the prescribed road class requirements[1-2].

Technological innovations play a pivotal role in addressing this issue, and one such solution is the Weigh-in-Motion (WIM) system. This research introduces a WIM checking system explicitly designed for loaded vehicles. The WIM system measures the load or weight of a moving vehicle. Notably, the WIM checking system proposed in this study employs fiber optics technology.

The utilization of fiber optics offers several advantages. Firstly, it boasts an impressive data transmission speed of up to 1 GB/second. Additionally, it demonstrates resilience against adverse weather conditions and electromagnetic wave interference. Furthermore, the use of optical fiber contributes to low distortion in the overall system, enhancing the accuracy and reliability of the WIM checking process [3]. The research is focused on formulating the problem statement, which revolves around characterizing fiber optic-based weight sensors within the Weigh-In-Motion (WIM) inspection system designed for loaded vehicles. This study's chosen methodology involves applying macrobending to optical fibers. Macrobending refers to the optical signal loss in fiber optic transmission caused by macro curvature[4-6]. Macrobending arises from the interaction between vehicles and bridge systems at a spatial scale.

The primary objective of employing the macrobending method in a problem-solving approach is to operationalize a Weigh-in-Motion (WIM) checking system designed for laden vehicles. Macrobending manifests when a load is applied to the fiber optic line. Fiber optic sensors identify loaded vehicles as they traverse through the WIM checking system. If a loaded vehicle surpasses the prescribed weight limit, it is anticipated that the sensor will issue a warning to the WIM guard. The crux of this research lies in developing an innovative WIM checking system and characterizing weight sensors based on fiber optics. This is pivotal to ensure that the system can effectively communicate warnings to both WIM guards and drivers of overloaded vehicles.

The investigation of Weigh-in-Motion (WIM) utilizing fiber optics has garnered substantial attention and progress from researchers globally. The development of the WIM system has been driven by enhancements in axle detection mechanisms on weighbridges, aiming to achieve superior performance. This line of research holds the potential to furnish a non-destructive methodology for acquiring precise information regarding the weights of vehicles traversing weighbridges[7].

In addition to the studies above, alternative methodologies for monitoring dynamic vehicle loads through a weighbridge system have been explored in other research endeavors. Specifically, a novel Weigh-In-Motion (WIM) system has been developed, capable of gauging vehicle speed, wheelbase, axial distance, and load utilizing Bragg grating (FBG) sensors, thereby eliminating the need for supplementary devices. This investigative approach relies on the simulation of the vehicle-bridge interaction system, commonly referred to as Vehicle Bridge Interaction (VBI). The findings of in situ testing of the WIM system demonstrate its accuracy in presenting data across diverse environmental conditions[8].

Comparable studies have been conducted on the advancement of fiber optic macro deformers. These deformers are a blend of macro sand grains and silicon rubber. Findings from the research indicate that the fiber optic sensor employed in the Weigh-in-Motion (WIM) system exhibits commendable sensitivity and a broad measurement range. The peak sensitivity performance recorded is 0.0239 mV.N-1, with the maximum measurement range extending up to 30,000 N. This data holds significant potential for application in the enhancement of WIM systems[9].

Continual investigation into Weigh-in-Motion (WIM) systems utilizing low-coherence interferometric fiber optic sensors has been conducted. In this research, a load is applied to the optical fiber in the test arm. The findings of the study indicate that the design of the fiber optic sensor is independent of temperature fluctuations[10]. The findings of this study can be implemented in Weigh-in-Motion (WIM) systems across diverse weather conditions.

In alternative research, a Weigh-in-Motion (WIM) system was devised for monitoring girder rotation at bridge supports. The assessment of girder rotation is closely tied to the load traversing the bridge, facilitated by an optical fiber within the bridge line. The experimental outcomes revealed commendable data accuracy in establishing the correlation between axle weight and girder span rotation[11].

In a comparable study, vehicle parameters on a highway bridge were determined through the analysis of random traffic flows. The research employed a loading method that captured the bridge strain response via a Fiber Bragg Grating (FBG) sensor. The obtained test results demonstrated remarkable accuracy in the identification of vehicle parameters. Specifically, the speed identification error was found to be less than 5%, while the error in identifying vehicle weight was less than 10%[12].

This academic research aims to address the existing gap in the field of innovation within fiber optic winding Weigh-in-Motion (WIM) systems. While previous studies have laid the groundwork, there remains a need for focused research on enhancing WIM systems through the integration of fiber optic sensors. This investigation specifically targets the development and characterization of a fiber optic sensor-based WIM system, with an emphasis on the winding of optical fibers with a diameter of 20 mm. This unique approach is expected to enhance the sensitivity of the fiber optic sensor to Weigh-in-Motion (WIM) applications.

The research plan for the upcoming year outlines a comprehensive strategy to innovate the WIM system and systematically characterize fiber optic-based weight sensors tailored for loaded vehicles. The experimental setup will involve winding optical fibers in a controlled environment, simulating real-world conditions for accurate and reliable results. Conducting the research on a room-scale is imperative to minimize errors and ensure the seamless transition of the WIM system from the laboratory setting to practical implementation on bridges.

The ultimate goal of this research is to contribute to the advancement of Weigh-in-Motion technology, specifically in the context of bridge applications. By leveraging fiber optic sensors and optimizing the WIM system, the proposed Bridge Weigh-In-Motion (B-WIM) system is poised to offer a valuable solution for efficient weight measurement in road traffic scenarios in Indonesia. The outcomes of this research are anticipated to lay the foundation for future developments and implementations in the field of transportation infrastructure.

METHOD

Manufacturing research objects

This research is structured into three primary stages. The initial phase involves the design of a bridge trajectory model for the Weigh-in-Motion (WIM) system employing fiber optic sensors. In the subsequent stage, a set of WIM systems is established to assess loaded vehicles within a room-scale environment. The final stage focuses on characterizing the vehicle load through the measurement of fiber optic light loss. The aim is to provide a comprehensive understanding of moving loading data, which can subsequently serve as a valuable reference for the installation of WIM systems dedicated to loaded vehicles.

The present study employs the macrobending method applied to optical fibers, with the macrobending phenomenon arising due to the movement of loads within the Weigh-in-Motion (WIM) system. The research focuses on constructing a system for weight measurement utilizing a fiber optic sensor. The chosen optical fiber type is the single-mode patchcord step index. The selection of single-mode optical fiber is motivated by its advantageous characteristic of low attenuation, with a value not exceeding ≤ 0.05 dB/km[13].

Concurrently, the dynamic load within the Weigh-in-Motion (WIM) system emanates from fluctuations in the weight of the loads positioned on the equipped vehicle (simulated dump truck). This dynamic load induces macroscopic bending in the optical fiber, consequently leading to a loss of light. The alteration in light loss can be discerned by a fiber optic sensor.

The operational mechanism of a fiber optic sensor involves the transmission of light by a laser through modulation using optical fibers. Subsequently, this light interacts with external parameters, leading to the conversion of the light signal into a modulated optical signal[6],[14].

In the course of this study, two distinct types of optical fibers were employed, namely the reference optical fiber and the modulation optical fiber. The reference optical fibers served the purpose of facilitating a comparative analysis of light output on the modulated optical fibers. The reference optical fiber is unloaded. Conversely, the modulated optical fiber was subjected to investigation through the utilization of macro bending, thereby serving as the primary focus of the research. In the subsequent step, the modulated optical signal is conveyed to an optoelectronic device linked to the laptop. The variable under investigation in this study is the load of the loaded vehicle. Concurrently, the optoelectronic device employed is a Analog to Digital Converter (ADC). The research framework is illustrated in Figure 1.

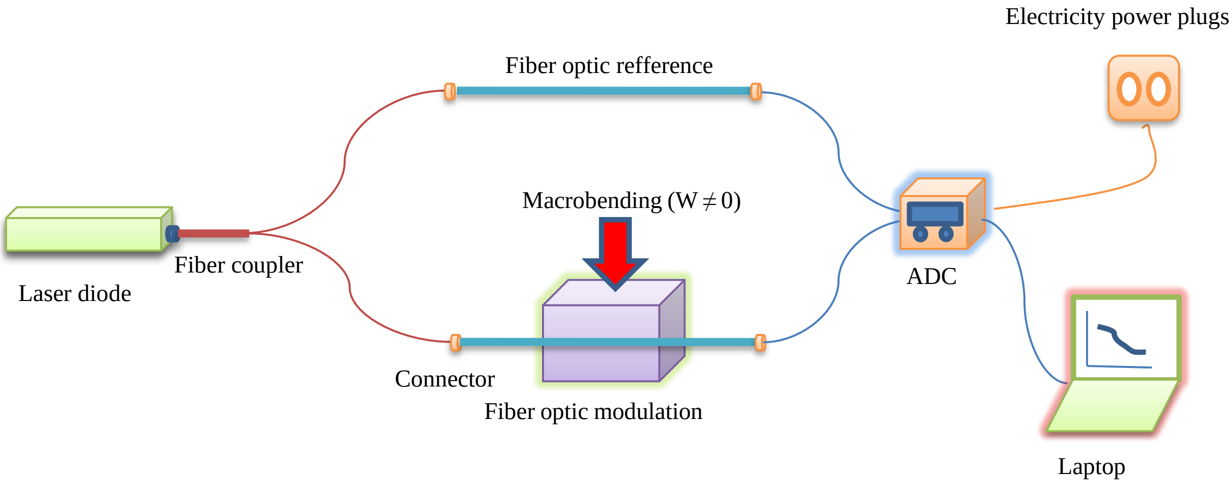
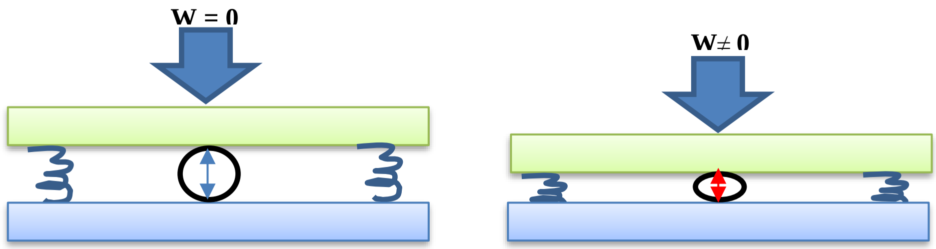


Figure 1. Research Scheme on Fiber Optic Sensor-based WIM System Innovation

The macro-bending modulation system for fiber optic coils is illustrated in Figure 2. The functionality of this system is predicated on the passage of a loaded vehicle, specifically a dummy dump truck, across the Weigh-in-Motion (WIM) sensor system. Upon the dummy dump truck traversing the WIM plane, deformation occurs, leading to a reduction in the coil diameter. This reduction in diameter induces a consequential attenuation in fiber optic light.

Additionally, the movement of the load contributes to a shift in distance or displacement along the WIM system path. This displacement, in turn, brings about a variation in the diameter of the fiber optic coil.



(a) (b)

Figure 2. Macro bending concept in a WIM system based on fiber optic sensors: (a) WIM system before loading; (b) WIM system after loading

Assembly of WIM systems based on fiber optic sensors

The operational mechanism of a fiber optic sensor involves the transmission of light by a laser through modulation using an optical fiber. Subsequently, this light interacts with external parameters, leading to the conversion of the light signal into a modulated optical signal[3],[8],[14]. In this study, a diode laser operating at a wavelength of 1310 nm was employed. Subsequently, the modulated optical signal was transmitted to an optoelectronic device interfaced with a laptop. The optical output signal, received by a photodiode, underwent conversion into voltage (volts) through an Analog to Digital Converter (ADC). The variable under investigation in this research pertains to the load borne by the vehicle. The configuration of the Weigh-in-Motion (WIM) system utilized in this investigation is illustrated in Figure 3.

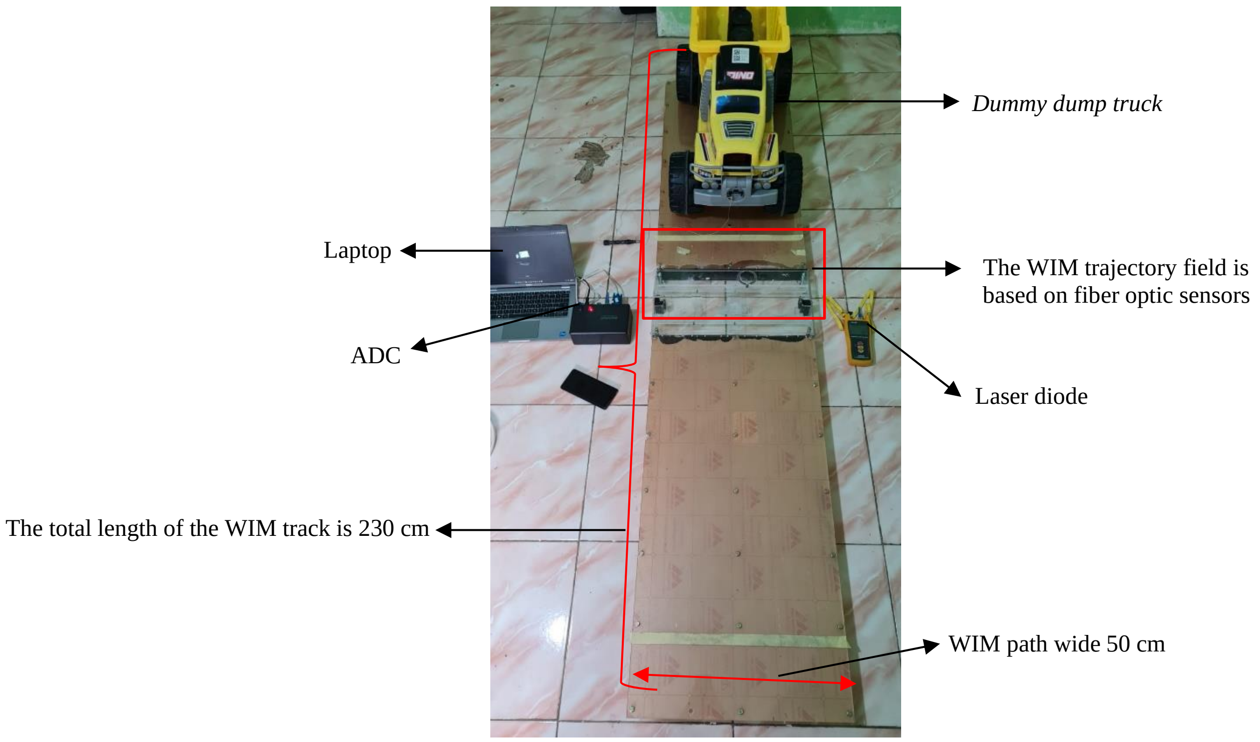
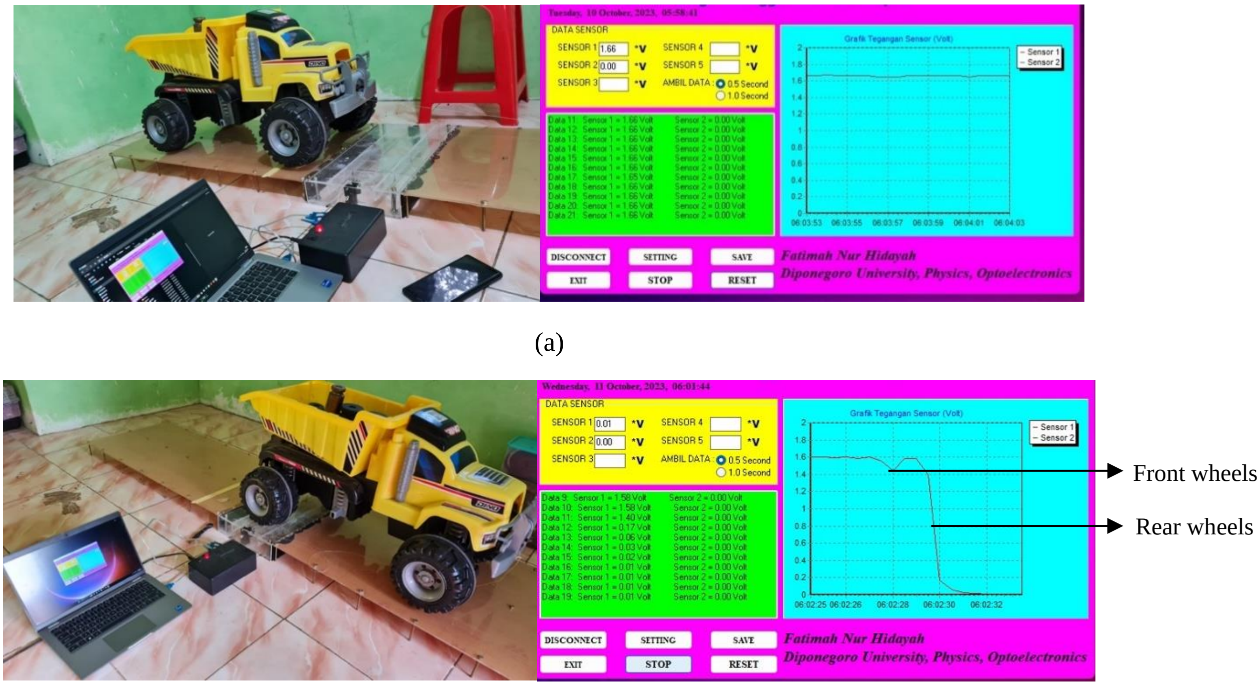


Figure 3. Assembly of a Weigh-in-Motion System Utilizing Fiber Optic Sensors

Set up WIM systems

The WIM system set up in this research is that when the dummy dump truck has not passed the fiber optic sensor, the data trend displayed on the display screen is straight. This data trend indicates that the optical fiber has not experienced any light loss. Meanwhile, when the wheels of a loaded vehicle touch the fiber optic sensor area, macro bending will occur, which results in fiber optic light loss or a decrease in light intensity. This light loss can be monitored via a fiber optic sensor system connected to the display screen. Light loss occurs due to macro bending by the front and rear wheels of the dummy dump truck.

The system detects the mass movement of a moving vehicle through its front and rear wheels. This is due to the fact that the areas of the vehicle in contact with the WIM sensor are the front and rear wheels, resulting in varying attenuation values for each wheel. This scheme can be seen in Figure 4.



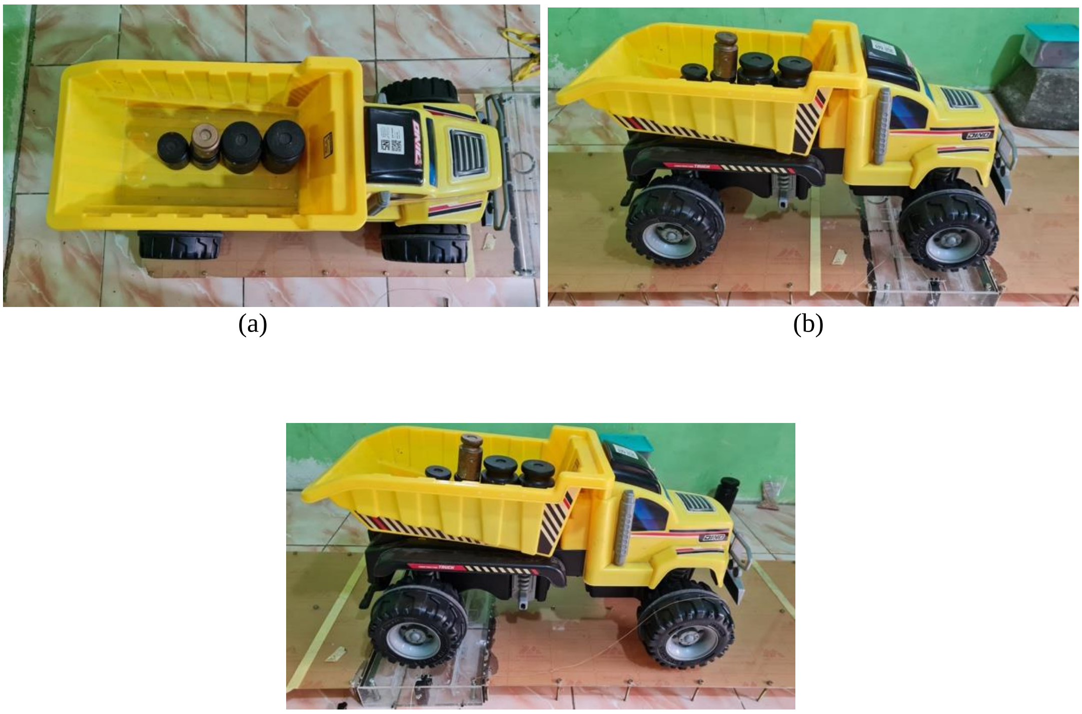
(a)

(b)

Figure 4. WIM System Set up: (a) Dummy dump truck before passing through the WIM system; (b) Dummy dump truck when passing through the WIM system

Macro bending system testing

At this stage, each characteristic of a series of Weigh-in-Motion (WIM) systems utilizing fiber optic sensors is undergoing thorough examination. The testing protocol involves evaluating the performance of the fiber optic sensor along the WIM path, assessing the stability of the light source, and gauging the sensitivity of the photodiode interfaced with the Analog-to-Digital Converter (ADC). The independent variables in this research encompass the weight load (in kilograms) and the velocity (in meters per second). The weight load is varied within the range of 0 to 15 kg, while the velocity undergoes variations of 0.1 m/s, 0.1 m/s, and 0.3 m/s. The determination of velocity values is achieved through the utilization of a set of dimmers and electric motors intricately connected to the WIM system. The dependent variable is light loss or fiber optic attenuation (dB). System testing is done by placing a load on a dummy dump truck, both statically (still) and moving. The macro bending system test can be seen in Figure 5.



(a) (b)

(c)

Figure 5. Macro bending system testing: (a) Loading on the dummy dump truck; (b) Front wheels; (c) Rear wheels

RESULTS AND DISCUSSION

Data collection in this research encompasses variations in both load and speed parameters of the dummy dump truck traversing the Weigh-In-Motion (WIM) track area. The measurement of fiber optic light transmittance is recorded in the form of voltage values. These values are acquired for each alteration in load imposed by the dummy dump truck, both at the front and rear wheels. The equation governing voltage values is employed to calculate the optical fiber attenuation value.

The equality representing attenuation in this study is articulated as follows[16]:

$$dB = 10 \log\left(\frac{P_{in}}{P_{out}}\right) \tag{1}$$

Through the utilization of the power equation, $P = IV$ and voltage equation $V = IR$, a novel equation is derived.

$$dB = 20 \log\left(\frac{V_{in}}{V_{out}}\right) \tag{2}$$

Subsequently, derived from the transmittance equation, $T = \frac{V_{out}}{V_{in}}$. Then, a new equation can be obtained:

$$dB = 20 \log\left(\frac{1}{T}\right) \tag{3}$$

The research employs a photodiode as the light sensor. The underlying principle of light detection in a photodiode involves the generation of electron-hole pairs in response to the incident photon current. Specifically, the electrons migrate towards the positive source, while the holes move towards the negative source, resulting in the generation of a voltage pulse by the photodiode. The magnitude of the photon current (ΣE) directly influences the number of voltage pulses (ΣV) produced. This relationship between photon current and voltage pulses is mathematically articulated by the following equation[14]:

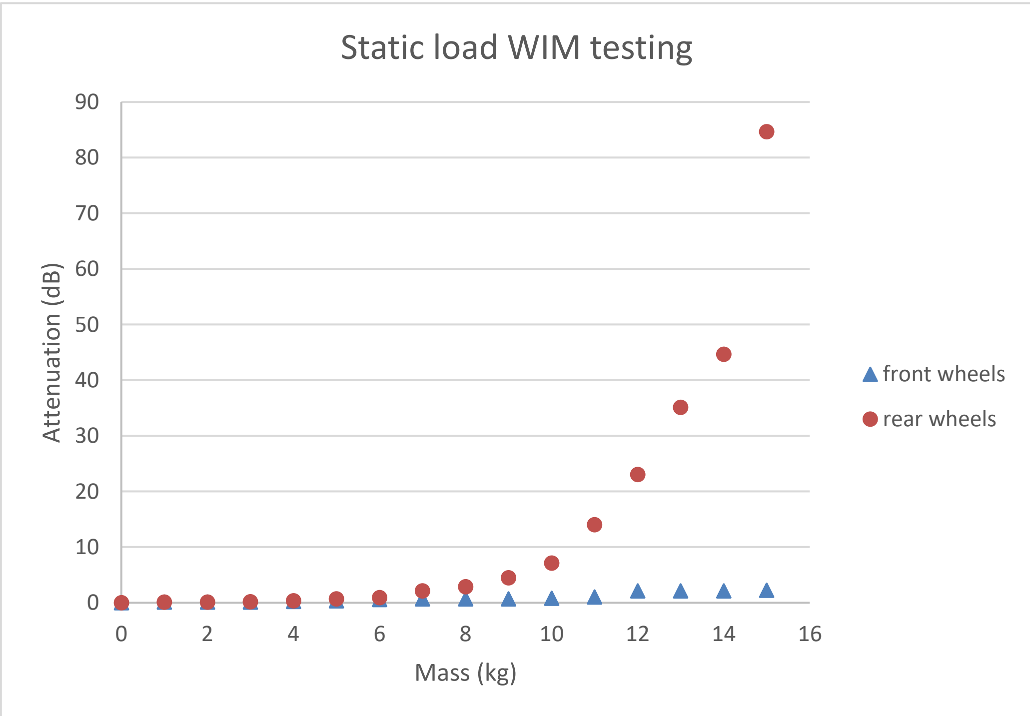
$$\Sigma V \sim \Sigma E \tag{4}$$

where ΣV represents the total voltage pulses and ΣE denotes the cumulative photon current received by the photodiode.

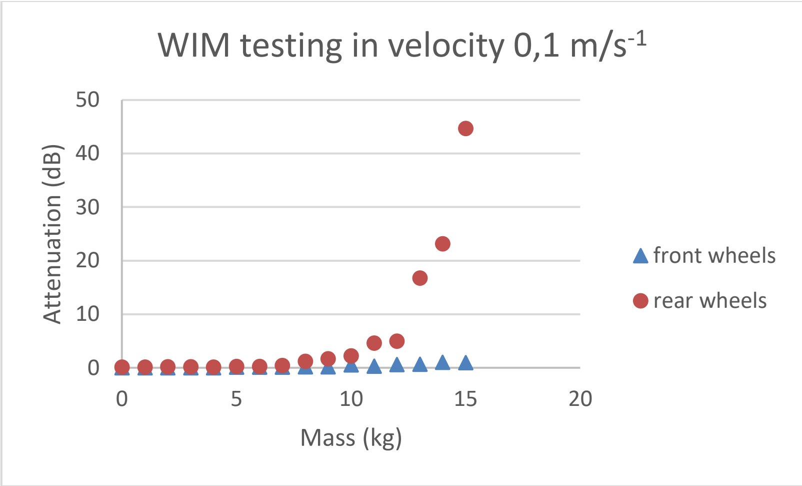
In the course of this study, an investigation was conducted involving a dynamic load applied to the path of the Weigh-In-Motion (WIM) field, wherein an optical fiber winding is present. The imposition of the load induces deformation in the fiber optic coil. Concurrently, deformation is also observed in the optical fiber when the winding coil undergoes deformation. The resultant deformation in the optical fiber leads to a weakening of light intensity[14-15]. The occurrence of this phenomenon signifies a reduction in the photon current received by the photodiode. A decline in light intensity results in the generation of fewer voltage pulses. The correlation between light intensity (ΣI) and pulse voltage (ΣV) can be articulated as follows:

$$\Sigma I \sim \Sigma V \tag{5}$$

The presentation of this research data can be seen in Figure 6.



(a)



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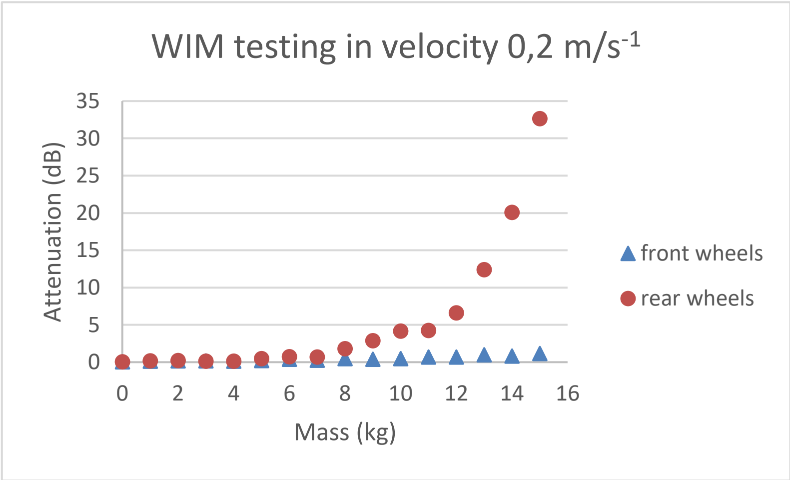

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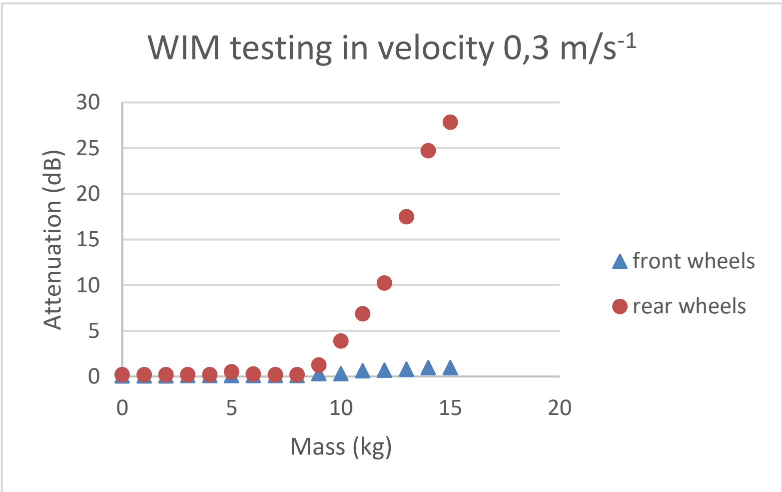


(d)

Figure 6. Chart of Loading on the WIM system: (a) Static; (b) Moving at a speed 0,1 m/s; (c) Moving at a speed 0,2 m/s; (d) Moving at a speed 0,3 m/s

The trendline graph depicted in Figure 8 illustrates the behavior of the front wheel of the simulated dump truck. It reveals a distinctive pattern resembling a horizontal asymptote, approaching or reaching 0 dB. This pattern suggests that the front wheels exhibit minimal variation in the coil's diameter as they traverse the Weigh-in-Motion (WIM) plane. When the coil's diameter remains relatively constant, the light loss (attenuation) recorded by the optical fiber approaches 0 dB. The optical fiber core captures a level of light intensity that surpasses what is either transmitted or absorbed.

This data elucidates the phenomenon wherein the fiber optic core can effectively reflect light even when subjected to both stationary (static) and moving (dynamic) loads. The implication is that under these conditions, the optical fiber core maintains its reflective properties, highlighting its resilience to changes in load dynamics.

The rear wheel trendline graph reveals discernible alterations in attenuation patterns at a load of 8 kg. Simultaneously, the loading trendline graph progresses at speeds of 0.1 m/s, 0.2 m/s, and 0.3 m/s, corresponding to loads of 10 kg, 7 kg, and 8 kg, respectively. This load threshold marks the initiation of changes in attenuation values. Additionally, there is a noteworthy escalation in attenuation values with increasing loads. This information can serve as a valuable reference in the Weigh-In-Motion (WIM) system to identify overload vehicles.

In the presented trendline graph depicting an elevated attenuation value, observable is a correspondingly limited variation in the diameter of the fiber optic winding coil. This occurrence manifests as imperfect reflection within the optical fiber core, signifying heightened light loss. Essentially, the intensity of light reflected by the optical fiber core is discernibly inferior to that which is transmitted or absorbed. The sensitivity of the research outcomes is ascertained by computing the mass increase value, where the level of attenuation that remains readable is considered. This can be expressed mathematically through the following equation:

$$tg\ \alpha = \frac{\Delta\ attenuation}{\Delta\ mass} \tag{6}$$

$Tg\ \alpha$: angle between rated load and attenuation

$\Delta\ atenuasi$: difference in attenuation value

$\Delta\ massa$: difference in load value

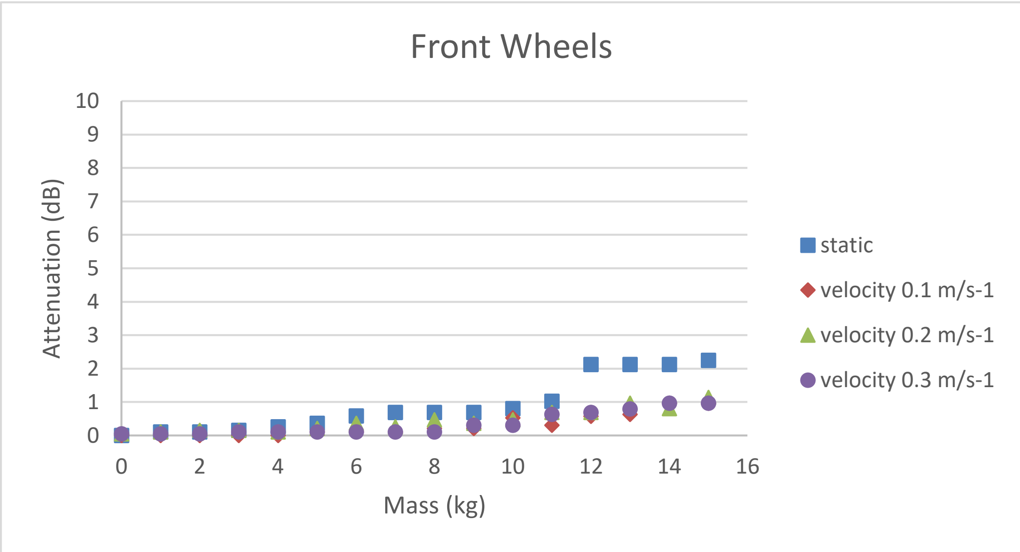
In this equation, the Mass Increase Value represents the measurable change in mass, and the sensitivity is indicative of the extent to which the research results can be reliably interpreted despite attenuation. The tabulation of sensitivity data pertaining to both static and dynamic loading in the Fiber Optic Sensor-based Weigh-in-Motion (WIM) system is presented in Table 1.

Table 1. Sensitivity of Static Loading and Moving Loading on the WIM System

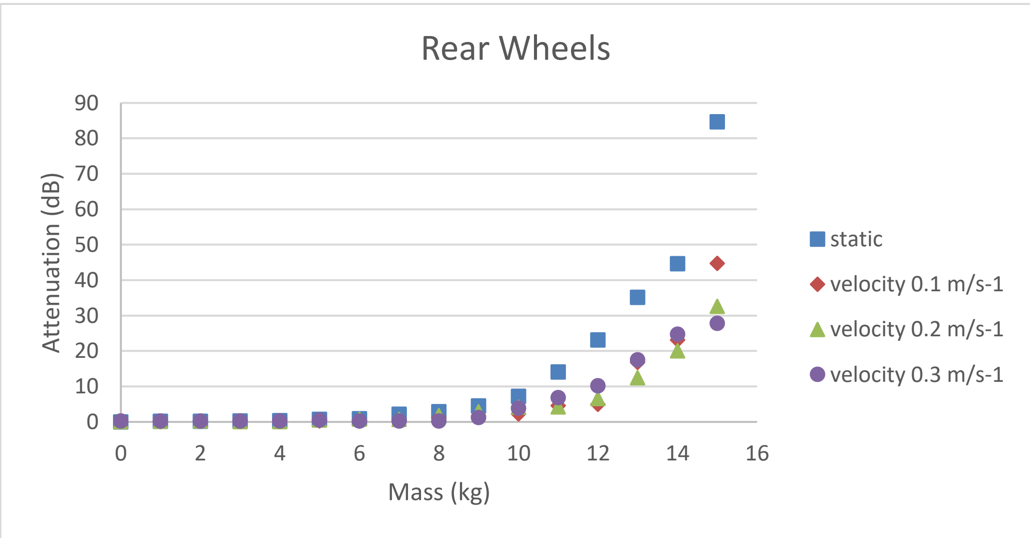
No	Type of Loading	Mass (kg)		Δm	Attenuation (dB)		ΔdB	tg α
		m_2	m_1		dB_1	dB_2		
1	Statis	9	8	1	4,487	2,86	1,627	1,627
2	v = 0,1 m/s	10	9	1	2,233	0,204	2,029	2,029
3	v = 0,2 m/s	8	7	1	1,799	0,687	1,112	1,112
4	v = 0,3 m/s	9	8	1	1,246	0,204	1,042	1,042

Table 1 illustrates that the fiber optic sensor exhibits optimal sensitivity, with a value of 2.029, when detecting a speed of 0.1 m/s. This finding serves as a benchmark for the recommended speed when a laden vehicle traverses the Weigh-in-Motion (WIM) system. This data is deemed suitable for application in fiber optic sensors, as even a minor alteration in the weight parameter leads to a discernible change in the attenuation parameter. Furthermore, Table 1 reveals a trend wherein the sensitivity performance of the fiber optic sensor diminishes as the speed of the loaded vehicle increases. Therefore, the data suggests that higher vehicle speeds correspond to reduced sensitivity in the fiber optic sensor.

The graphical representation in Figure 8 illustrates the trendline characteristics observed in the comparison graph of the front and rear wheels of the dummy dump truck as it traverses the Weigh-in-Motion (WIM) plane.



(a)



(b)

Figure 8. Characteristics of changes in attenuation values when the dummy dump truck crosses the WIM plane: (a) Front wheels; (b) Rear wheels.

Figure 8 (a) illustrates that the augmentation of the moving load imparted by the front wheels exhibits negligible impact on alterations in the attenuation value. This is attributed to the front wheels solely supporting the head of the dummy dump truck, resulting in minimal fluctuations in the diameter of the fiber optic winding coil. The gradual changes in coil diameter give rise to macro bending, which, in turn, causes a gradual shift in the attenuation value. Macro bending, characterized by the bending of the optical fiber, contributes to the reduction in light intensity. Consequently, the decrease in fiber optic light intensity leads to an increase in the attenuation value.

In the interim, Figure 8(b) illustrates that the escalating magnitude of the dynamic load exerted by the rear wheels distinctly influences alterations in the attenuation value. This is attributable to the fact that the rear wheels bear the load of the dump body, leading to marginal adjustments in diameter. The variation in coil diameter, in turn, gives rise to pronounced macro bending, thus contributing to substantial alterations.

The findings are consistent with prior research, affirming that displacement has a discernible impact on the light intensity of optical fibers. Specifically, as the displacement value increases, there is a corresponding decrease in the generated light intensity[5],[16-17]. In this study, displacement is observed as a result of variations in the diameter of the fiber optic winding coil. A reduction in the coil diameter corresponds to a decrease in light intensity. As the coil diameter diminishes, the light intensity values proportionally decrease. Consequently, the reduction in light intensity amplifies light loss.

This study investigates the impact of load on the attenuation characteristics of optical fibers. The intervention involves applying a load to the optical fiber, inducing a refractive angle of less than 90°. Subsequently, when the angle of refraction is below 90°, complete reflection does not transpire. This non-ideal condition leads to light loss from the core of the fiber optic, consequently causing a reduction in light intensity. The decline in the modulation voltage of the optical fiber signifies a corresponding decrease in the light intensity value.

The research findings indicate that a speed variation of 0.1 m/s is optimal for loaded vehicles traversing the Weigh-in-Motion (WIM) track area. This observation is attributed to fluctuations in the diameter of the fiber optic winding coil, resulting in a gradual and negligible increase in the attenuation value. This data proves relatively favorable for implementing Optical Detection of Overloaded Vehicles (ODOL) within a WIM system. Moreover, when the loaded vehicle experiences a marginal overload, the system exhibits a notable detection capability, as evidenced by a significant rise in the attenuation value.

In reality, vehicles passing along major roads have different speeds. Based on the research conducted by Malla[18], the mass of a vehicle is directly proportional to its vertical displacement. As the mass of the moving vehicle increases, so does the vertical displacement. Moreover, as the vertical displacement increases, the compression of light intensity values in the optical fiber core decreases. Consequently, as the light intensity values decrease, the voltage values recorded by the ADC also decrease, as described by Equation 5. According to Equation 3, a lower voltage value corresponds to a higher attenuation value. According to research by Nedoma[20], speed is directly proportional to displacement. Thus, it can be inferred that the determination of attenuation value is based on the vertical displacement of the moving vehicle.

CONCLUSION

The sensitivity analysis of the Fiber Optic Sensor-based Weigh-In-Motion (WIM) system reveals respective values of 2.029, 1.112, and 1.042 for various speed differentials. Notably, a speed variation of 0.1 m/s emerges as the optimal speed for loaded vehicles traversing the WIM track. This recommendation stems from the observed alterations in the diameter of the fiber optic winding coil, leading to a gradual and insignificant increase in the attenuation value. The data obtained proves relatively robust for implementing overloaded vehicles within the WIM system. In instances of a marginal overload on loaded vehicles, the system exhibits the capability to detect a substantial rise in the attenuation value

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