Journal of Engineering and Computer Sciences
Qassim University, Vol. 9, No. 2, pp. 85-99 (July 2016/Ramadan 1437H)

Investigating the Effect of Moving Truck Wheel Load on the Performance of Smart Road Lane Separator

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(Received 9/3/2016, accepted for publication 10/8/2016)

Abstract. Road design has been undergoing incremental upgradation over the past decades. Author developed a new innovative smart road lane separator that can be embedded into the road surface for road illumination and conveying useful information to the road users such as traffic density, sudden stoppage in traffic, road blockage or changes in road geometry. In this regards the presented research work details the numerical modeling and analysis of the proposed device under the action of impact loading generated due to moving truck wheel. This analysis simulates the real-world situation for the newly proposed device. The purpose of analysis was to evaluate the design performance of the proposed device. Three cases of varying support were taken into consideration to simulate real world application, these include fully supported, partially supported and edge supported to simulate the condition when the sub-base material of the road gets eroded owing to gradual wear and tear or due to rains and flooding. Furthermore, analysis was conducted for truck wheel moving along a straight line and in a zig-zag motion along the length of the lane separator. The results indicated that the loading case with minimum support, simulating flooding erosion is the most severe case resulting in cracking of the device. However, no damage was observed in the other cases. Furthermore, a slight uplift of the end of the device was noticed; which can be eradicated using traditional anchoring. From the presented analysis and results it can be concluded that the newly developed smart road lane separator device can be used for real world application in both flexible and rigid pavements.

Keywords: *Impact load, moving load, truck wheel, numerical modeling, smart road system, accident mitigation, road illumination, road design.*

1. Introduction

Modern cars have undergone revolutionary changes over the past few decades resulting in major reduction in driver and passenger deaths. Many of the safety features such as air bags, seat belts, lane keep assist, lane departure warning and accident avoidance systems come as standard in modern cars. However, one piece of the traffic management and safety puzzle; roads, have virtually remained unchanged since last several decades. Much research in the past has been focused on road illumination, cat eyes, use of better material and geometrical design of the road network but till date no revolutionary idea has taken main stage [1-10]. One such recent attempt to gain some fame in the literary society was by solar highway [11]. The vision of the inventor is to replace the entire road structure with hexagonal solar panels which can be used to generate electricity using sunlight and would also give authorities infinite freedom to modify the road geometry by using sophisticated software, as shown in Fig. (1). However, a critical review of the proposed idea reveals that such a solution would be impossible to implement in real world as it has no real-world testing, no literature backing, no strategy for implementation on existing infrastructure and job creation at the cost of downsizing of the existing jobs. Furthermore, if the proposed solution is implemented, the existing theory or philosophy for road design, construction and maintenance would be redundant.

Hence keeping in view, the real-world application problems and challenges associated with the maintenance, upgradation of existing infrastructure, the author invented [12,13] a new type of smart road lane separator using an innovative material to transfer colored light through the road surface. The applications of this material vary from roads, buildings to esthetical application for architectural purposes [14]. This innovative solution was developed to be applicable in real world. The details related to real world testing, prototype development, implementation strategies and challenges associated with implementing such a change are already discussed in earlier research by the author [13]. It is also worth mentioning that the author has done a detailed strengths and weaknesses analysis for the possible solution to the traffic safety problem and chosen the Smart road Lane Separator (SLS) option based on its feasibility for application, maintenance and implementation advantages. One such solution taken into consideration was the use of smart cat-eyes with embedded LED's and wireless controls for data transfer. However, it became evident that cost of production, size, maintenance cost and exposure to harsh environment of such a device would lead to failure of mass adaptation. Furthermore, since the

Fig. (1). A vision of solar highway consisting of hexagonal solar panel for solar highway with strengthened glass top [11]

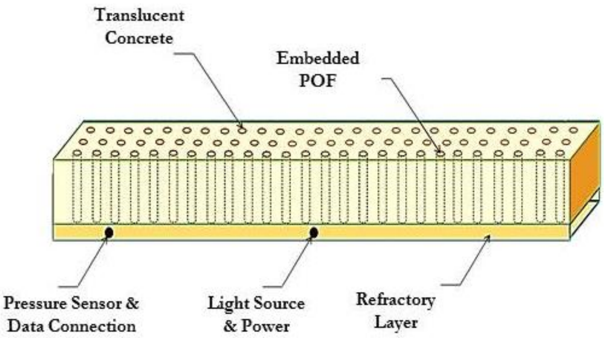

Fig. (2). Functional description of proposed smart lane separator (United States Patent and Trademark Office, Application No. 14/594,509) [12]

size of the cat-eyes would increase, it would lead to a larger number of traffic accidents and could also lead to tire failures. Hence, the presented option of SLS superseded in the Strengths and Weaknesses analysis (see Saleem et. al. [13]). Fig. (2) presents the functional description of the newly proposed smart road lane separator (SLS), which consists of pressure sensing and data collection devices embedded at the base along with the lighting source and refractory layer. The base acts as the nervous center of SLS housing the electrical and sensing equipment in-order to protect it from the environment. The top portion of the SLS consists of optical fiber tendons embedded in special concrete like material which transmits the light without any loss [14-19]. SLS can be embedded into the road surface and can be used to transmit colored light. The color of the light can be changed to convey useful information to the road user such as sudden stoppage of traffic owing to accident, changes in road geometry and other information related to traffic density, lane saturation etc.

In this regards the presented study deals with the numerical modeling and analysis of the proposed smart road lane separator under the action of a moving truck wheel load to estimate its real-world feasibility and to highlight any problems associated with its design. Three types of support systems were analyzed to simulate real world scenarios. These include the case where the base of the SLS is fully supported by the sub-base representing a typical post-construction newly built scenario, second case being that of partial support for SLS representing the condition when some of the support material is eroded with the passage of time either by natural wear and tear or by flushing due to rain and seepage water. The third and most critical condition is case of edge support only; this case represents the worst-case scenario where the base material is completely eroded due to flooding. Furthermore, the movement of truck wheel is simulated in a straight line and in a zig-zag pattern along the length of SLS. These two cases represent the typical movement of traffic on top of the proposed device under real world conditions. From the detailed analysis and presented results it can be concluded that the proposed SLS is suitable for application in real world for flexible and rigid pavements as it performed well under the action of impact load generated due to moving truck wheel.

2. Objectives

The presented research work aims to focus on response of smart lane separator subjected to impact load generated by moving truck wheel under various support conditions to simulate its real-world application and to highlight any problems associated with its design, using numerical modeling and analysis. The objectives of this research study are as explained below:

1. To develop a realistic numerical model for the smart road lane separator and to evaluate its response to the impact load generated by a moving truck wheel.

2. To evaluate the stability of SLS under various support conditions.

3. To highlight shortcomings in its performance, stability and design.

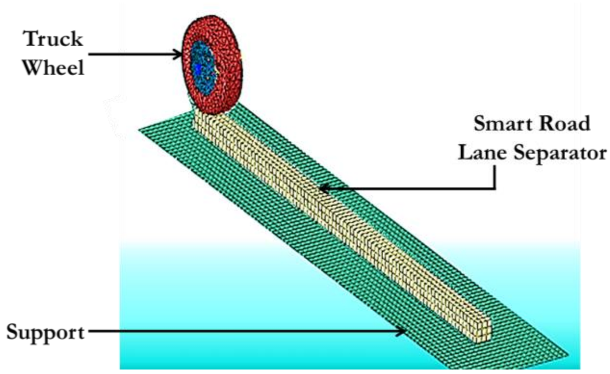

Fig. (3). Numerical model detailing the smart road lane separator with truck wheel

3. Numerical Modeling

Fig. (3) presents the 3D view of the model detailing the smart road lane separator with truck wheel loading. Analysis of impact loading was carried out using a finite element software ABAQUS [20]. The SLS was modeled as a 150 x 150 mm cross section and a length of 4000 mm. A truck wheel with average tire pressure of 100 Psi and a speed of 50 km/hr (13.89 m/s) was selected for analysis. The beam was simulated with solid elements of mesh size 50 x 50 mm. The steel rim and the rubber tire are assigned as solid elements with variable mesh size and a maximum of 50 mm. It is to be noted that the application of the proposed SLS ranges from small residential roads to major highways. Hence, the choice of speed of 50 km/hr was based on the average of 20 km/hr for residential roads and 80 km/hr for highways. Furthermore, the speed of 50 km/hr can be taken as average cruising speed of fully loaded truck.

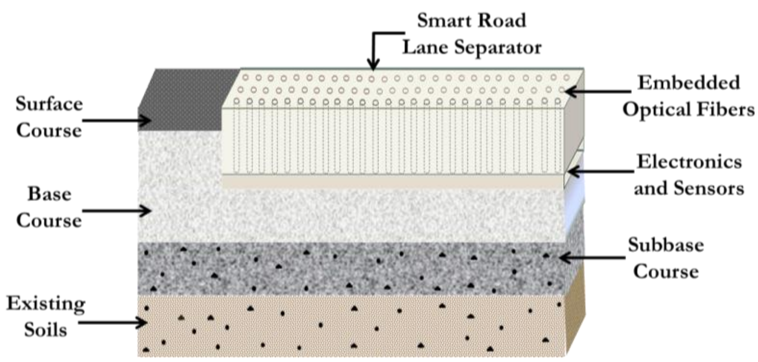

Fig. (4). Schematic cross-section of smart road lane separator with support structure – Case 1

Fig. (5). Numerical model used for simulation to represent case-1

3.1 Case-1

Three boundary conditions were simulated for analysis of beam embedded in the pavement; these were selected to represent the real-world challenges associated with the application of SLS. The first boundary condition was the case when SLS was supported on a rigid surface representing a typical newly built post-construction situation of road. In this case the base of SLS is fully supported by the sub-grade as shown in Fig. (4). For the numerical modeling of this case, the subgrade was considered as a rigid surface and the beam was fully supported on it, as shown in Fig. (5). The materials of base-course and sub-base under the separator beam were considered in FE model as rigid surface fully contacted with the lower side of the beam.

3.2 Case-2

The second and third boundary conditions were designed to simulate the wear and tear and weathering effects on the SLS. The second case as shown in Fig. (6) represents the case when the base material was partially washed away owing to rain fall or seepage. In this case the base of SLS was partially supported on flexible base course. The stiffness of the base course was taken as a factor of bearing capacity above the base course layer. Compression spring elements were used for connecting the lower side of the beam to the base course as shown in Fig. (7). The spring stiffness was taken as the modulus of subgrade reaction (K) obtained using Eq. 1. Where, K is obtained by applying a unit load (P) and measuring the deflection/settlement under the loading plate (Δ).

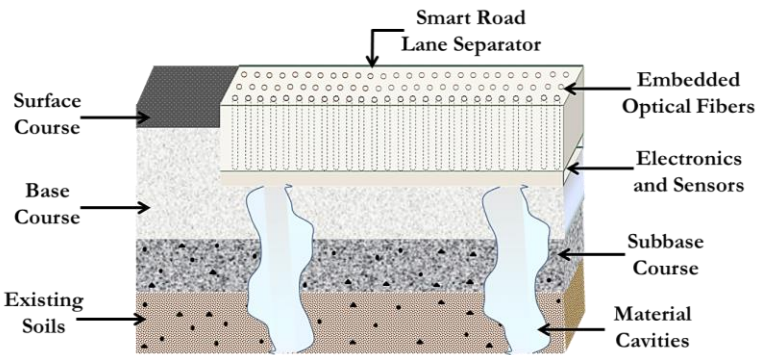

Fig. (6). Schematic cross-section of smart road lane separator with support structure – Case 2

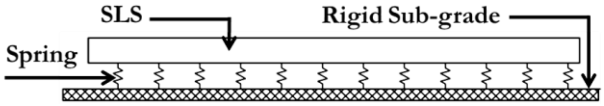

Fig. (7). Numerical model used for simulation to represent case-2

$$K = P/\Delta \tag{1}$$

However, since no experimental testing was conducted to measure the properties of a specific sub-soil structure, the spring stiffness was considered as an average value of 40000 kN/m^2/m for a well compacted base-course and sub-base layer.

3.3 Case-3

The third boundary condition was used to simulate the worst possible case when the base material is fully washed away by the flooding and the base of SLS is not supported at all, while only the ends are supported as shown in Fig. (9). This case was modeled using a beam that was simply supported at both ends which simulate the case of flushing away of the base material under the SLS, as shown in Fig. (8). This case represents the worst-case scenario which might occur during the life cycle of the proposed SLS.

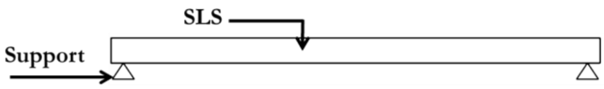

Fig. (8). Numerical model used for simulation to represent case-3

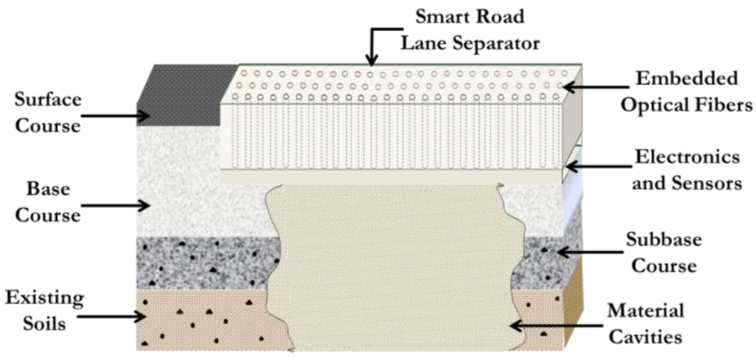

Fig. (9). Schematic cross-section of smart road lane separator with support structure – Case 3

Table (1). Loading and material input details

Sr. No.	Parameters	Inputs / Assumptions
1	Mesh Size	50 x 50 mm
2	Size of Smart Lane Separator Beam	50 x 50 x 4000 mm
3	Wheel Load	100 Psi
4	Wheel Mesh	Variable with Max. 50 mm
5	Material Strength	25 MPa
6	Failure Criterion	Von-Mises
7	Support Condition	03
8	Average Speed	50 km/hr (13.98 m/s)

4. Modeling Details

The material used for the modelling of smart road lane separator is taken as concrete with ultimate compressive strength of 25 MPa. However, it is to be highlighted that the lab experimentation showed that the special concrete like material developed was able to produce a maximum compressive strength of 35 MPa, hence the assumption made for the analysis is on the conservative side. For prototype development, experimentation and testing see Saleem et. al. [13]. Furthermore, the reduced value of the material compressive strength was applied for analysis to simulate lower quality construction of SLS. This approach was adopted to highlight any design flaws of the proposed model. The parameters used for modeling smart road lane separator are summarized in Table (1).

5. Results and Discussion

The proceeding section describes the detailed findings from the numerical analysis. It was observed from the analysis that the most critical case was the third one at which the beam cracked with very large deformation. The second case was more realistic since it presented a sensible deformations and stress distribution in the separator with a maximum stress component in the vertical direction at the point of contact between the road separator and the base course as shown in Fig. (10).

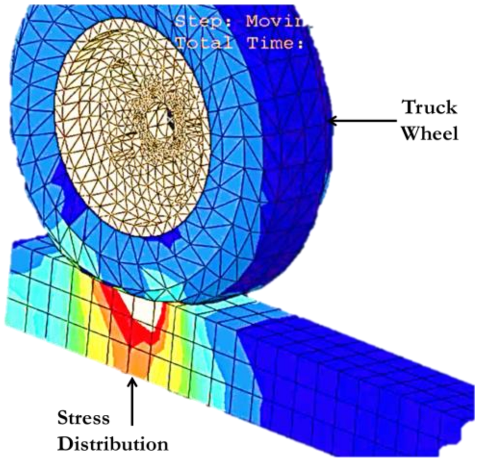

Fig. (10). Numerical simulation depicting the peak stress distribution at the point of contact between the truck wheel and the Smart Road Lane Separator

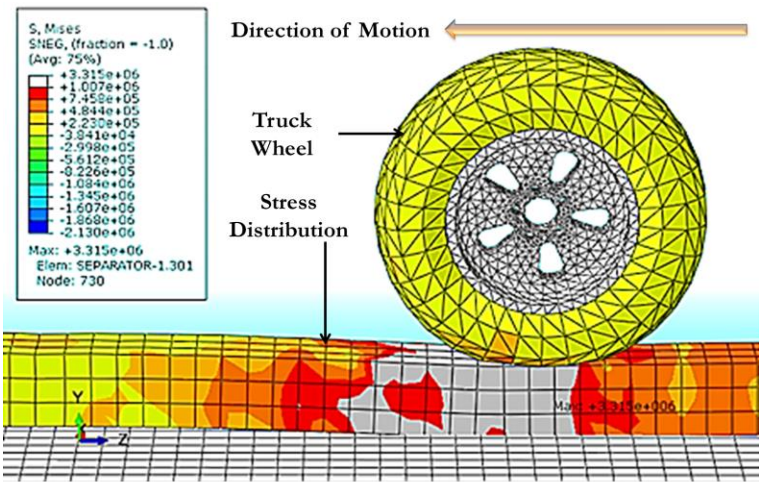

Fig. (11). Numerical simulation depicting the stress distribution along the length of Smart Road Lane Separator

However, it is worth mentioning that although the vertical stress component was maximum under the tire contact, it was still less than the failure requirement, allowing for a smooth motion of the wheel. Fig. (11) depicts the variation in stress distribution along the length of the SLS as the wheel moved over the surface. It is also to be highlighted that the presented analysis results represent the motion of the wheel along a straight line on the top of smart road lane separator,

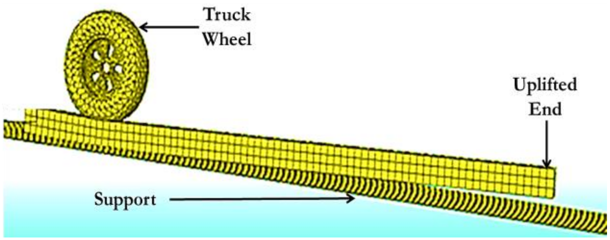

Fig. (12). Numerical model depicting the uplifted end owing to wheel loading

Table (2). SLS uplift history

Sr. No.	Distance along SLS (m)	Vertical Uplift (m)
1	0.00	0.02
2	0.12	0.03
3	0.33	0.06
4	0.43	0.08
5	0.72	0.12
6	0.83	0.13
7	1.01	0.13
8	1.43	0.11
9	1.46	0.10
10	1.57	0.08
11	1.81	0.02
12	1.89	0.00
13	1.95	0.01
14	2.12	0.03
15	2.20	0.05
16	2.32	0.06
17	2.50	0.06
18	2.85	0.04
19	3.00	0.03
20	3.70	0.00

however, the second case considered for analysis was the one in which the wheel moves along a zig-zag path on top of the SLS. During analysis, it was evident that the effect of motion of the wheel along a straight line and along a zig-zag path would not result in much variation as during the zig-zag motion half of the wheel would be in contact with the road surface and hence would lead to lower stresses in SLS. Hence, only the results related to motion of wheel along a straight line are presented in the current manuscript. From the analysis it was found that the SLS experienced uplift movement of the far end of the beam as the truck wheel load moves along the length of SLS as shown in Fig. (12). Table (2) represents the uplift history as the wheel load moves along the length of SLS and Fig. (13) depicts the graphical representation of the uplift. From the figure, it can be seen that peak uplift, approximately 0.13 m, of the end is experienced when the wheel load is about a quarter of the length along SLS, which gradually reduces to zero as the wheel reaches the end of SLS. This behaviour requires the beam to be fastened with anchor bolts to the ground at the ends and the middle part.

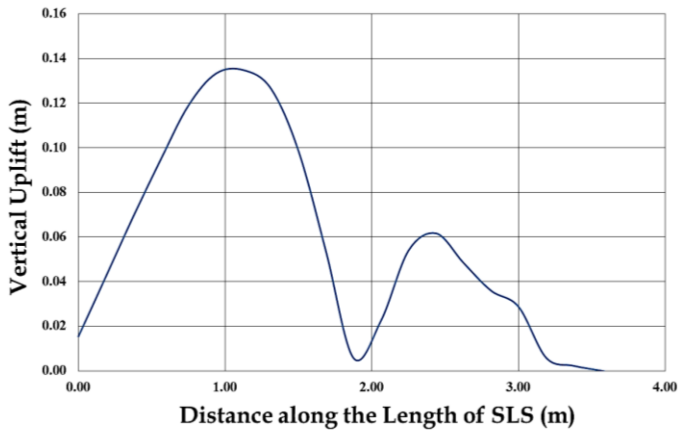

Fig. (13). Vertical end uplift with respect to motion of wheel along the length of Smart Road Lane Separator

The third case developed for numerical modelling was considering that the base course washed away owing to flooding. During analysis it was noted that as predicted the simply supported beam as shown in Fig. (8) and Fig. (9) cracked with large deformations when the wheel load reached the middle of the beam. However, it is to be highlighted that this scenario is the worst-case situation which might occur once during the life cycle of smart lane separator and hence does not govern the design of SLS. Also, it is to be noted that the replacement strategy outlined in

Saleem et. al. [13] would allow for the replacement of smart road lane separator in a matter of hours, hence leading to fully functional road. Furthermore, it was noted that the maximum Von Mises stress value in the separator section reached 3.241 MPa which is far less than the compressive strength of concrete used for manufacturing of the SLS's body. However, the tensile stresses exceeded the allowable stresses which require the separator beam design to be modified by introducing steel reinforcement to resist tensile stress. Table (3) presents the maximum and minimum stresses in the separator beam in vertical direction in addition to Von-Mises stresses. These can be used to modify the design of smart road lane separator for better application in the real world.

Table (3). Von-Mises stress variation

Distance (m)	Maximum Stress (MPa)		
	Vertical		Von Mises
1	1.593	-2.208	3.24/-2.13
2	1.007	-2.185	3.42
3	1.007	-3.019	3.315

6. Conclusions

An exploratory study to evaluate the design and real world performance of the newly proposed innovative smart road lane separator was conducted. Smart road lane separator was modeled under three boundary conditions to evaluate its real-world performance under the application of impact loading generated owing to a moving truck wheel. The boundary conditions were designed to closely simulate the real-world conditions. From the detailed analysis, the following conclusions can be drawn;

1. It is evident from the presented results that the proposed smart road lane separator can be used for application in the rigid and flexible pavements.

2. During analysis it was found that smart road lane separator experiences uplift at the end owing to wheel motion, this can be eradicated by use of anchor bolts for anchoring the SLS to the base.

3. Analysis revealed that the SLS performed exceptionally well in case-1 which is the true as build condition in real world application, while experiences uplift in case-2 which can be eradicated and cracked in case-3, which is the worst-case scenario.

4. Analysis showed that the compressive stresses in the SLS are much lower than the compressive strength of the newly developed concrete material; however, the tensile stresses exceed the desired limit.

Furthermore, it can be deduced from the presented research and discussion that the implementation of the proposed technology can lead to a reduction in traffic accidents by providing real time feedback to the road users by making them aware of their surroundings.

7. Recommendations

From the detailed numerical modeling, analysis and discussion the following recommendations can be drawn;

1. It is recommended to improve the design of SLS by introducing steel bars at the base of newly developed concrete material which will help in the uniform stress distribution and will support the tensile stress. This will lead to a more stable design and will also result in better performance during the case-3, worst case scenario.

8. Acknowledgement

The author is grateful to the Deanship of Scientific Research (DSR-UoD), University of Dammam, Kingdom of Saudi Arabia for the encouragement.

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دراسة تأثير الاحمال القادمة من شاحنة متحركة على أداء فاصل الطريق الذكي

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(قدم للنشر في ٢٠١٦/٣/٩؛ وقبل للنشر في ٢٠١٦/٨/١٠)

ملخص البحث. يشهد تصميم الطرق على مدى العقود الماضية تطور تدريجي لرفع كفاءتها. و قد وضع المؤلف فاصل طريق ذكي بطريقة مبتكرة جديدة التي يمكن أن تكون جزءا لا يتجزأ من سطح الطريق لإنارة الطريق ونقل معلومات مفيدة لمستخدمي الطرق مثل كثافة حركة المرور، والتوقف المفاجئ في حركة المرور، وانسداد الطريق أو التغييرات في طوبغرافية الطرق. وبناء على هذا تم اعتبار العمل البحثي المقدم من النمذجة العددية وتحليل الجهاز المقترح تحت تأثير الاحمال المتولدة بسبب عجلة شاحنة نقل. يحاكي هذا التحليل الحالة في العالم الحقيقي للجهاز الجديد المقترح. وكان الغرض من التحليل هو تقييم أداء الجهاز المقترح. ثلاث حالات لدعم متفاوتة أخذت في الاعتبار لمحاكاة التطبيقات الحقيقية في الطرق ، و هي الفاصل المثبت بشكل كامل و اخر بشكل جزئي و الاخيرة المثبت من الجنب لمحاكاة الحالة عندما يحصل تآكل المادة الفرعية الأساسية للطريق سبب البلى التدريجي أو بسبب الأمطار والفيضانات. وعلاوة على ذلك، أجرى تحليل لعجلة شاحنة تتحرك على طول خط مستقيم، وفي حركة متعرجة على طول الممر الفاصل. أشارت النتائج إلى أن حالة التحميل مع الحد الأدنى من الدعم، هي تحاكى التأكل بسبب الفيضانات و هذه هي أسوء الحالات التي تؤدى الى تكسير للجهاز. ومع ذلك، لوحظ عدم وجود أي ضرر في الحالات الأخرى. وعلاوة على ذلك، لوحظ رفع طفيف لنهاية الجهاز؛ التي يمكن القضاء عليها باستخدام طرق الربط التقليدية. من عرض التحليل والنتائج يمكن استنتاج أنه يمكن استخدام الجهاز فاصل الطريق الذكي للتطبيق الحقيقي في انظمة الرصف المرنة والصلبة على حد سواء.

ملخص الكلمات: حمل التصادم ، الحمل المتحرك ، عجلة شاحنة، النمذجة العددية، ونظام الطرق الذكية، والتخفيف من آثار الحادث، وإنارة الطريق، تصميم الطرق.