A comparative study of monitoring methods in sustainable pavement management system

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Abstract. Pavement management systems (PMS) have been receiving increasing attention in the attempt to ensure that roads are always in good condition and serving its purpose. Appropriate PMS must be implemented to gather valid and reliable pavement data. Previous studies which attempted to identify methods for monitoring pavements were limited by constraints such as cost, time, safety, data accuracy and sustainability. This study was conducted to review some of the pavement monitoring models introduced in previous studies. After completing a literature review, three models, i.e. manual survey, smart sensor, and optical image processing, were selected for a comparative study to determine which of these models is the most effective model in terms of cost, time, safety, accuracy and sustainability. A data quality guideline was modified to produce a rating system for ranking the models from the worst to the best. The results of this study shows that smart sensor has the highest score in the radar chart, and hence is the best model. In conclusion, the findings of this study could provide a guideline for the government and private sectors in determining the most effective pavement monitoring model to be used in their sustainable PMS strategy despite the constraining factors.

1. Introduction
Pavement management system (PMS) is established by highway agencies to ensure that roads are in good condition and serving its purpose. A pavement condition survey is an important element in the pavement management process. A survey of pavement condition will provide the valuable information needed for pavement performance analysis; it is also crucial in facilitating the forecast of pavement performance, anticipating maintenance and rehabilitation requirements, establishing maintenance priorities, and allocating funds [1]. The network-level pavement asset management system (PAMS) proposed by [2] has become an important tool in helping state highway agencies determine maintenance and rehabilitation schedules and allocating limited resources.

Pavement is one of the most important infrastructures which ensure a safe and comfortable journey. However, pavement is a type of consumable material and must be replaced at an appropriate interval since they deteriorate and are damaged by applied load and the effects of surrounding factors, such as heavy traffic, unpredictable climate, etc. [3]. Pavement maintenance is essential to ensure a safe travel as well as prevent traffic congestion, air pollution, and accidents [4]. Consequently, PMS is becoming increasingly important since it provides information on pavement condition, which in turn helps authorities to schedule pavement maintenance activities [1, 2, 5].

In order to ensure good road system, it is essential to continuously maintain and rehabilitate the existing road network [6]. PMS should be able to facilitate the decision making process regarding which
segments of a pavement network should be preserved, maintained, and rehabilitated despite the budget constraints [7]. Before making a decision on road maintenance, it is important to know the actual condition of pavement in a particular area. Different types of pavement distresses would probably require different treatment [3, 8, 9]. Therefore, data on pavement distress is required before making a decision on the proper rehabilitation treatment to be carried out.

Several pavement monitoring methods can be employed to gather pavement distress data. Conventional method, such as walking survey in figure 1(a) and riding (also known as windshield) survey in figure 1(b) are used to monitor the conditions of pavement surface manually. However, these traditional methods are very costly, time consuming, labour-intensive and subjective, and evaluators conducting these surveys are exposed to hazards [8, 10-13]. These methods typically depend on individual evaluators’ visual inspection, interpretation and judgement of the extent and severity of all distresses observed at each pavement section [14]. Consequently, the disparity in the distress data gathered through manual surveys has always been a contentious issue in PMS.

![Figure 1. (a) Walking survey (b) Riding survey](image)

On the other hand, data collection technology is one of the most rapidly evolving areas in asset management. The methods used to collect distress data range from manual surveys based on visual inspection to automated surveys, which utilized systems, based on photography, video cameras, or sensors. Since the mid-20th century, sensing technologies have been enhanced in terms of sensitivity, functionality, scale, survival rate, and resistance to harsh environment [11]. The development and application of ultrasonic, infrared, laser sensors, and high-speed computer processing have significantly improved the ability of transportation agencies to collect large volumes of pavement data quickly and efficiently. Sensor technologies can be used to gather data automatically, in addition to protecting their workers from exposure to hazards on the road. Technologies and procedures such as these allow agencies to gather data and report on pavement conditions more frequently and are often more cost-effective than the manual techniques [15]. Basically, sensors can be categorized into two types, i.e. wired and wireless. The present study used a wireless sensor which introduced by [16] called the Smart sensor. This sensor was designed with six main features: self-powered, non-volatile storage, small size, wireless communication, ability to withstand harsh loading and environmental conditions, and possibility of network deployment. Smart sensor can be used to automatically gather large amounts of pavement data via a moveable external radio frequency (RF) reader. This method can be implemented either manually or by driving a vehicle over the embedded sensors (figure 2). The use of sensors in PMS would reduce the length of time required to gather distress data and problems related to the safety of evaluators can be eliminated.

Many systems based on ground-penetrating radar or laser system have been proposed. However, the findings of recent research have shown that the optical image processing (OIP) method is more effective in conducting a non-invasive evaluation of surface degradation [17]. Since the 1990s, evaluation of pavement through digital images has become increasingly popular due to the significant advances in the sciences of computer vision and image processing [11]. OIP is performed using a mobile laboratory (figure 3), where a vehicle is equipped with special cameras to capture the image of pavement surface and record distress data. The data is based on high-speed digital acquisition system, which depends on
the computed digital values and the images captured by the camera. The system is essentially a mobile laboratory, which gathers pavement surface data together with other supporting software such as global positioning system (GPS). Since the data is gathered using an OIP method, further analysis must be conducted, and this could be done using semi-automated or fully automated techniques. The data is processed to convert it into a usable format which provides the distress information of pavements. Fully automated data processing uses computers to interpret, reduce, and analyze the images without human intervention. Semi-automated data processing converts the gathered data using automated collection means, and the images will be viewed and interpreted by evaluators who to identify distress information [10].

![Figure 2. Smart sensor method](image1)

![Figure 3. Optical image processing method](image2)

The objective of this study is to compare the frequently used monitoring methods, including manual survey, smart sensor study, and optical image processing in term of cost, time, safety, accuracy of data, and sustainability.

2. Methodology

After completing a review for three of the models in this study, the information gathered are summarised into a table (table 1). Table 1 presents an overall summary of the three methods. These three methods were chosen due to their outstanding performance in their respective category.

Manual survey is the first model to be considered in this comparative study due to fact that it is the very first pavement monitoring method used in PMS. Manual survey can be used as a basis for comparison of other models. Other automated methods were introduced subsequent to the implementation of the manual data collection survey. The use of sensor is important in an automated data collection in PMS. A wireless smart sensor is chosen for this comparative study due to its superior performance in comparison to that of a wired optical fiber sensor. Finding stated that normal wired sensor in PMS can only be used for short term purpose due to the need to use batteries, which have to be replaced when they run out of power [16]. This results in a higher operational cost. The use of solar power for other normal wireless sensor used to gather data in PMS is not feasible since the sensors are fully embedded under the pavement. Another model taken into account in this comparative study is the OIP model. Since this is an automated pavement image collection model, there is no concern of any data being missed at typical highway speeds.

This comparative study used a rating system table to assign average score to each model. The model with highest cumulative average score for all five indicators is regarded as the most effective pavement monitoring model. At the end of this study, the finding would assist the authorities choose the most effective pavement monitoring method by using valid and reliable data to implement a PMS strategy despite the constraining factors.
Table 1. Summary of comparison of the models

| No. | Comparative Items       | Manual Survey                  | Smart Sensor                                          | Optical Image Processing                                      |
|-----|-------------------------|--------------------------------|-------------------------------------------------------|---------------------------------------------------------------|
|     |                         | Walking                       | Riding                                                |                                                               |
|     |                         | Handheld tools or devices, data sheet | Computer, vehicle                                      | Sensor, RF transponder and RF reader                           |
| 1   | Cost                    | - Trained evaluators          | - Experienced evaluators                             | - No labour cost                                              |
|     |                         | - Trained for more than 6 months | - Training required                                  | - No training required                                        |
|     |                         | - No operating cost           | - Low operating cost                                 | - First time installation                                     |
|     |                         | - No maintenance fee           | - Low maintenance cost                                | - Less maintenance due to high robustness                    |
|     | Labour & Training       |                                |                                                      |                                                               |
| 2   | Time                    | Very slow, 4 km per day        | 6000 km completed in 3 weeks                         | Very fast, continuous                                         |
|     |                         | Dangerous, higher risk when gathering data | Safe, no risk                                        |                                                               |
|     | Safety                  | Subjective, based on evaluator’s experience | - May miss some data when the vehicle moves too fast | Real time data, record and long term data storage              |
|     |                         | - Use of paper, record on data sheet | - Emission of carbon monoxide gas by vehicle will cause air pollution | - Data can be read by RF reader either manually or by using a vehicle |
|     | Accuracy                | - Emission of carbon monoxide gas by vehicle will cause air pollution | - Real time data, record and long term data storage |                                                               |
|     |                         | - More objective measurement  | - Repeatability                                       |                                                               |
|     |                         | - Repeatability               |                                                      |                                                               |

The components of the rating system are introduced through data quality guidelines [18 & 19]. The table was modified to suit the aims of this comparative study. The rank for each comparative item is arranged from worst to best. The worst rank is assigned a value of 1 and the best rank is assigned a value of 5. The rating system shown in Table 2 explains the comparative items in each rank. Each model will be given score based on the behaviour of the model. In the final stage, the score for each comparative item was summed up to compare the ranking of the models.
Table 2. Rating system for comparison items

| Compared Item | Rating System |
|---------------|---------------|
|               | WORSE TO BEST SCORE |
| **Cost**      |               |
| (For 1 km)    | RM 400 and above | RM 301-RM 400 | RM 201-RM 300 | RM 101-RM 200 | Below RM 100 |
| **Time**      |                |
| (For 6000 km) | More than 1 month | 2 weeks to 1 month | 1 to 2 weeks | 1 to 6 days | Less than 1 day |
| **Safety**    |                |
|                | Very dangerous, may cause accident | Dangerous, exposure to hazard | Lower risk, safe | Safe to conduct on road | Very safe, no direct contact with traffic |
| **Accuracy**  |                |
|                | Inaccurate or wrong data | Low accuracy, some unfitting and missing data | Accurate, data considered acceptable | Accurate, most of the required data is retrieved | High accuracy with real-time data |
| **Sustainability** | Not related to any sustainability practices | Sustainable practice, cause certain damage to environment | Sustainable practices, effort to reduce pollution | Support overall sustainable practice, environmentally friendly |

The first compared item in the rating system (table 2) is cost indicator, which explained the budget rates for 1 km pavement are arranged from scale 1 to 5. The model that conducted with lowest cost will gain highest score of 5. Scores for the time indicator shows where the ranking is from the slowest to the fastest. The model which completes the monitoring of pavement condition in the shortest period of time is ranked as the best mode. In the rating system table also shows the ranking used for the danger and hazard exposure in the safety indicator. The fourth item compared in this study is accuracy of data collected. This is an important factor which is taken into account by most agencies when choosing the best pavement monitoring model. The availability of a more accurate data would allow agencies to make better decision with regard to their PMS strategy. In order to improve sustainability, pavement asset management systems should be able to account for sustainability indicators. Such as user time delay caused by preservation activities, additional fuel consumption caused by deterioration of pavement surface and other environmental impacts [2 & 20]. A compared item about sustainability is therefore also listed in the rating system table.

In the present study, a new rating system was introduced for the cost indicator to give a more specific and detail explanation about cost allocation. Similar with the concept in present rating system, the details in Table 3 is ranked from worst to best with the score ranging from 1 to 5. Since each model has been assigned with different types of cost, the cost indicator was divided into three categories, i.e. price of equipment, labour and training costs, and operating and maintenance cost.

Table 3. Rating system for cost indicator

| Cost Indicator                      | Rating System |
|------------------------------------|---------------|
|                                    | WORSE TO BEST SCORE |
| **Equipment**                      |               |
| High lab and training costs        | Very expensive | Expensive | Affordable | Cheap | Very cheap |
| Medium lab and training costs      |               |
| Low labour and training costs      |               |
| **Labour + Training**              |               |
| High conducting / operating costs  |               |
| Medium conducting / operating costs|               |
| **Operating + Maintenance**        |               |
| High conducting / operating costs  |               |
| Medium conducting / operating costs|               |

After prepared the rating system table as above (Table 2 & Table 3), the scoring process is able to proceed together with the finding listed in summary table.
3. Results and discussion

Following the tabulation of the rating system, the ranking process can be commenced by giving a score to each of the monitoring models. The scores are assigned based on the information provided by previous researches and studies, along with additional self-justification when the criteria are not considered in those studies. The comparative items begin with cost, time, safety, accuracy, and end with sustainability. Table 4 below shows the scores of average costs for all three pavement monitoring methods. Score 1 indicates the worst rank, which is given to the method that use the most expensive equipment; or highest labour charge and training; or highest operation and maintenance cost. For example, smart sensor study is having score 1 in the cost indicator of equipment because the material of sensor used is the highest among other methods.

Table 4. Average cost score ranking system

| Models            | Cost Indicator | Cost Average Score |
|-------------------|----------------|--------------------|
|                   | Equipment      | Labour + Training  | Operation + Maintenance |
| Manual Survey     | 5              | 1                  | 5                      | 3.67 |
| Riding            | 3              | 2                  | 3                      | 2.67 |
| Smart Sensor      | 1              | 5                  | 1                      | 2.33 |
| Optical Image Processing | 2          | 4                  | 2                      | 2.67 |

On the other hand, manual walking survey obtained score 5 in both equipment and operation and maintenance indicator. The reason was come from cheap handheld tools or devices used while conducting the survey and there are no any operation cost and maintenance fee needed.

Based on the summary of the costs and average score for all models in table 4, a model with the highest average cost score is considered as the best model. Manual walking survey has the highest average cost score of 3.67, which means that it has the lowest cost in comparison with other models in this study. The smart sensor model has the lowest cost average score of 2.33, which means that it is the most expensive method for PMS. The manual riding survey and optical image processing models have the same average cost score, which means that the cost for data collection in the two models are the same. Therefore, the models have to be compared based on other items to determine which the better model is. Table 5 presents the average cost scores for all models vis-à-vis other factors for a more comprehensive comparison.

Table 5. Average score of the five indicators

| MODEL                | Rating Comparison Item | Average Score |
|----------------------|------------------------|---------------|
|                      | Cost | Time | Safety | Accuracy | Sustainability |               |
| Manual Survey        | 3.67 | 1    | 2      | 3        | 3              | 2.53          |
| Riding               | 2.67 | 2    | 3      | 2        | 4              | 2.73          |
| Smart Sensor         | 2.33 | 5    | 4      | 5        | 5              | 4.27          |
| Optical Image        | 2.67 | 4    | 4      | 4        | 3              | 3.53          |

Through the time indicator’s results shown above, manual survey apparently took the longest time to be completed, as have been shown in previous studies, such as the study conducted by the Arizona Department of Transportation (ADOT) [1]. But, the riding survey was able to cover a longer segment, in less time [1]. This survey was conducted using a very slow-moving vehicle [14]. Therefore, manual riding survey can obtain score of 2 in the time indicator.

For the safety indicator in this study, smart sensor model does not expose evaluators to any kind of hazard. This method does not require any human involvement subsequent to its installation. Smart sensors will automatically record and store pavement data independently and data is retrieved...
periodically via a wireless RF reader. Hence there is no need to gather pavement data on site. The scanning of RF transponder in the sensor to the reader can be done either manually or by mounting the reader on a moving vehicle. This process can be carried out fairly quickly without exposing anyone to any kind of hazard. Hence, the smart sensor model is given a score of 4 in safety indicator.

The fourth item compared in this study is accuracy. This is an important factor which is taken into account by most agencies when choosing the best pavement monitoring model. The availability of a more accurate data would allow agencies to make better decision with regard to their PMS strategy. [12] indicated that the data collected through manual walking survey tend to more subjective and less accurate since it is influenced by evaluators’ experience. Even though evaluators must undergo training prior to working in the field, the data that produced by experienced and inexperienced evaluators will invariably be different. The researchers asserted that training programs can help evaluators to improve their evaluation skill, especially if focus is given to provide extra training to the types of distresses that are most likely to be interpreted differently. Thus, the accuracy of walking survey can actually be improved if evaluators are well-trained and are experienced. It should be noted that manual walking survey is sometimes limited to a certain segment of the road [15]. Humans have limited ability and it is not possible for any evaluator to survey the entire route if the distance is too long. Hence, walking survey is given a score of 3, which means that the data is considered acceptable.

There are two factors in manual walking survey could have positive/negative influence on sustainability. Since this is the only model which requires walking in the data collection stage, it is considered as an environmentally friendly method. It does not cause air pollution or release harmful carbon emission into the environment. On the other hand, the use of paper data sheets (to record the pavement distress data) makes this method less sustainable when compared with digital data storage. Unlike the walking survey, the other three method in this study do required the usage of vehicle during collect the pavement data. Manual riding survey and OIP methods both are marked with lower score in term of sustainability compare to smart sensor. The reason behind these scores is relied on the repeatability and frequently to the operation of vehicle on each method. The use of automatic and self-powered from smart sensor has eliminated the need to use vehicles during the data collection process. This also means that there is no gas emission. Vehicles are only used periodically to retrieve data via wireless communication from the RF reader. Data retrieval can also be done manually if the distance for data retrieval is not too far.

Once the scoring process for each of the models in five comparison items has been completed, the average scores were computed, and the results are formed. The model with the highest average score is considered as the most effective pavement monitoring model. The smart sensor model has the highest average score of 4.27. The optical image processing model has the next highest score of 3.53. The scores for walking and riding methods are almost similar, with the riding survey showing a slightly better score than walking survey. Both manual surveys (walking and riding) are ranked the lowest, with the walking survey having a score of 2.73 and riding survey a score of 2.53. In addition, a radar chart (Figure 4) was produced to summarize the results of the comparison.
Figure 4. Radar chart for the comparative study

The radar chart above presents the results of the study in a graphical form. There are four polygons with each polygon representing one model in this comparative study. The red polygon represents the manual walking survey model, the yellow represents the manual riding survey model, the green represents the smart sensor model, and the blue represents the optical image processing model. The score value of the models expands from center of chart to the outer range. The maximum value for this rating system is 5. In this study, the polygon with the largest area is ranked as the best monitoring model. It can be seen that the smart sensor model has the largest polygon area; it has a very high score for four indicators, i.e. time, safety, accuracy, and sustainability. The manual walking survey has the highest score for cost indicator although its scores for other indicators are extremely weak in comparison with other models. Although the polygon for the optical image processing model is quite balanced, it does not have a good overall score value when compared with the smart sensor model. It should be noted that although the manual riding survey has a weak accuracy indicator, it is still better than the walking survey in terms of time, safety and sustainability. The radar chart in Figure 4 above has presents a clear picture of the overall findings of the study.

4. Conclusions
Three models were chosen for a comparative study, i.e. manual survey (comprising walking and riding surveys), smart sensor, and optical image processing. Comparison was done base on five indicators, i.e. cost, time, safety, accuracy and sustainability, to determine which model is the most effective in performing pavement monitoring functions. Results show that the smart sensor method is the best overall model for pavement monitoring. As a conclusion, it is hoped that the findings of this study would help relevant agencies make a decision with regard to the most effective pavement monitoring model for their PMS strategy relative to the constraining factors they may have.

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