Innovative Pavement Design: Are Solar Roads Feasible?

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1.0 Abstract

Sustainability is critical in current engineering designs, particularly in the field of pavement engineering, and is based on having only limited resources while trying to maximize designs for performance. To this end, developing infrastructure that can meet multiple needs is highly beneficial to society's will to live at our current standard of living.

One such project is the proposal to build roads that have been integrated with photovoltaic cells in order to provide a high performance driving surface while generating renewable electricity. This electricity could then be used by local infrastructure, adjacent buildings, or sold to the electrical grid. In order to do this there are many challenges that need to be overcome, as these roads cannot be made from traditional road surface materials, and a thorough analysis of many design aspects needs to be considered.

This paper looks to determine, based on existing pavement materials research, how such a road panel can be constructed and manufactured. Specific elements investigated include the design of each layer of the solar road panel, how the panel can be integrated with photovoltaic electronics, how such a design can be weatherproofed, and how to optimize between solar capture area and structural integrity.

The analysis will be influenced by designing around available materials and engineering calculations of the panel under loading. The end result of this paper is a detailed solar road panel design that will be built and evaluated through physical and finite element testing in future work.

2.0 Solar Road Panels

2.1 Introduction

Sustainable solutions are a requirement to modern design problems due to society's overreliance on natural resources for everything from energy generation to transportation infrastructure. In order to come up with these solutions it is important for creativity to be a focus of design, as clearly the traditional practices are lacking and new ideas are required. One such example of this is the design of solar road panels; a modular road panel that is also a functioning solar photovoltaic panel.

The idea behind solar road panels is quite simple in theory; through the issues associated with urban heat islands it is known that pavements are often exposed to a vast amount of solar radiation throughout the day. If it were possible to extract a portion of this energy, we could begin to simultaneously solve civil and electrical infrastructure issues through the implementation of new sustainable technologies.

Two methods have been developed to accomplish energy generation from roads before; using asphalt pavement as a solar thermal collector and installing piezoelectric generators to collect vibration energy from the traffic load on the pavement. Recent studies have also begun to use thermoelectric systems to extract heat energy from roads and directly convert it to electricity. This project is taking a different approach to the concept as, through photovoltaics, the solar radiation is directly converted into electricity on the surface of the panel without a heat or vibration conversion.

This project is not the only instance where a solar road panel is currently being developed as similar projects are underway at Solar Roadways in the USA [1] and TNO in the Netherlands [2]. Where this project does differ is in the design approach being used; following a methodological research approach backed from experience in civil, mechanical, and electrical disciplines. There is also an end-result focus on examining the issues these panels would face in a Canadian climate; freeze-thaw cycling, snow accumulation and removal, and salt-based winter road maintenance programs.

2.2 Objectives and Scope

The objective of this report is to design a feasible solar road panel that will be able to structurally withstand traffic loading and operate as a test platform for future structural testing. This is accomplished by assessing the overall design requirements of such a panel and working through each major segment of the design. First is the electrical subsystem; while this will not be revolutionary in terms of PV solar modules, it is required as a basis for the rest of the structure. Second will be the structural layers of the module, followed by the transparent layer design and finally the panel housing and weatherproofing mechanisms.

While this paper will be thorough in its analysis there are some elements that will be excluded, the first of which is the surface design of the top transparent layer so that it can provide friction for vehicles while not impairing the conversion efficiency of the module. This report also will not include finite element analysis of the structural or dynamic loading, as the equipment to do so was not available to the authors at the time of writing.

2.3 Design Requirements

The general design of the solar road panel is as shown in Figure 1, where there is a transparent surface made of textured glass that vehicles are driving on, optical layer to transmit the load around the solar cells, and a base to further transmit the load to a pavement, subgrade, or base structure.

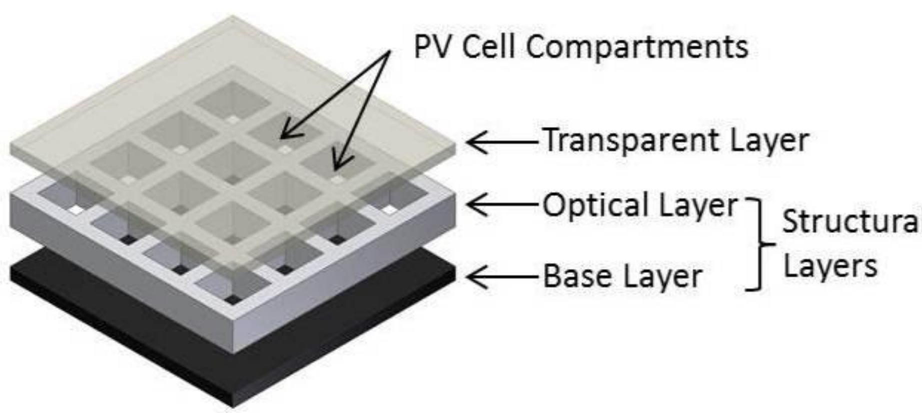

Figure 1: Exploded view of a conceptual solar road panel [3]

The greatest challenge of designing a solar road panel is that the design requirements for pavement structures and solar modules frequently contradict each other. These requirements have been outlined below, divided into the structural and electrical requirements respectively.

2.3.1 Structural Design Requirements

The structural design requirements for a solar road panel are as follows:

- The structure must be able to support the cyclic distributed load from vehicle tires without failing through deformation, fracture, or other means; it is expected that 480 kPa is a typical design stress requirement from tires contacting the panel
- The transparent layer cannot deflect over the cell compartments so much that the layer transmits load to the solar cells
- The structure must be corrosion resistant to salts and other potential contaminants
- The design must be modular and facilitate easy maintenance
- For this prototype's purposes, the panel must be made out of readily available components and materials
- To accommodate construction, testing, and the measurement units of available components, the designed panel should have 0.91 m (3 ft) side lengths and be of sufficient thickness to satisfy the other requirements
- The weight of the panel must be low enough so that two people can maneuver it for testing and installation purposes

2.3.2 Electrical Design Requirements

The electrical design requirements for a solar road panel are as follows:

- The panel should be designed so that no shading of the solar cells occurs
- The interconnection between the cells should be strong enough to withstand potential deflections from the optical layer
- The panel must be weatherproof so that water and other contaminants are not able to interfere with the electronics
- There must be a diode installed on the output electrical line of the panel to block reverse currents, as this would damage the solar cells within the panel

3.0 Electrical System Design

3.1 Component Selection

The most important selection in the design of the electrical system is the selection of the photovoltaic cells. There are a vast array of technologies to choose from for this application including monocrystalline, and polycrystalline silicon cells; dye sensitized cells; thin film; and organic thin film solar cells. Since this project is more focused on the structural design of the panel the monocrystalline silicon cells were chosen as they provide the highest maximum power output of commonly available solar cells today.

The next selection was for the size of these cells; monocrystalline silicon solar cells are available in many shapes and sizes as a result of their use in a wide variety of customized OEM products.

The ones most typically used in utility power generation applications are 150 mm square solar cells as these can be efficiently produced with high end conversion efficiency, but various rectangular and circular options are also available. For this project the decision was made to utilize 125 mm square solar cells, as these will allow for a large area of the solar road panel to be exposed solar cells while also not leaving too large a section of the transparent layer cantilevered over the cell. An image of the solar cell selected is shown in Figure 2, where all of the dimensions provided are in millimetres.

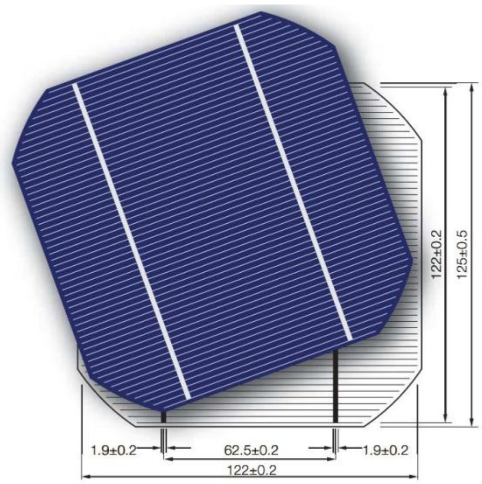

Figure 2: 5" square monocrystalline silicon solar cell [4]

3.2 Cell Interconnections

With the cells chosen, the next step is to connect them together to assemble the panel. Typically strings of solar cells will be connected in series to increase the voltage generated by the collector, as the current output is already reasonable (5 amperes) from each cell. Then the panels would be connected in series or parallel accordingly to boost the voltage and current to meet the end load or inverter requirements. In this case there are 0.91 m (36”) of space in each direction and it was assumed that at least 25 mm (1”) of space was required between each of the cells and between the edge cells and the casing of the solar road panel for structural support. It was also assumed that an extra 12.5 mm (1/2”) was required for the solar cells to allow for the interconnection and shading protection from the structural ledge to be accounted for. As a result, 5 cells can be spaced in each direction along the panel, allowing a total of 25 cells in the whole panel.

In order to connect these together, the routing as shown in Figure 3, where the squares represent the solar cells, the two lines between represent the two power connection lines between the cell bus bars, and the positive and negative signs indicate the input and output lines from the solar road panel respectively.

Traditionally the cells in a solar panel would be connected by soldering a tin-coated copper ribbon across the bus bars of one cell and then soldering these ribbons onto the adjacent cell. One of the disadvantages of this is that the interconnections are one of the most fragile components of the module, and with the loads the solar road panel will be seeing this is not a feasible option. Instead, the ribbon will be soldered only across the bus bar of one cell and then a wire will be soldered to the output of the one cell and to the input of the adjacent cell in the next compartment. Using insulated wires to complete this task should improve the reliability of the system despite the addition of more components and solder points.

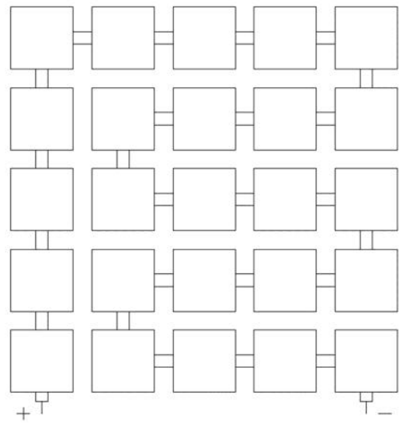

Figure 3: Schematic solar road panel interconnection scheme

3.3 External Hardware

As identified in the requirements, a diode must be installed to protect the solar cells from a damaging reverse current. To simplify the design of the solar road panel, this will be done in an enclosure outside of the panel. This will only require a plastic enclosure large enough to hold a terminal block, the diode, and the input and output wires for the whole panel.

4.0 Structural Layer Design

4.1 Material Selection

Based on an extensive literature review of road and landing mats it was determined that the best materials for use in the structural layers of the solar road panel are steel, aluminum, and fibreglass. Aluminum is one of the most popular materials for use in landing mats, proving that structures made from the material are able to withstand mission critical static and dynamic tire loads [5]. Due to the relative material properties of aluminum and steel it is known that steel should do a better job of withstanding the loading from vehicle tires at a lower cost though also at a higher weight. Lastly, it was found that multiply fibreglass panels are able to withstand repetitive loading on poor sub-bases without failing [6].

Due to the requirements of the prototype design fibreglass was chosen as the ideal structural material. In addition to being low cost and light weight it is also the easiest to build a research prototype for as either the aluminum or steel options would have required a custom casting operation, which is a very expensive and difficult process. Future analysis using structural testing and finite element modelling will be done to ensure that this is the optimal material choice.

4.2 Base Structure

The base structure is straight forward while using multiply fibreglass as the bulk of the structure is simply layers of fibreglass adhered together. While some accommodations will need to be made for the cell compartments, interconnection routing, and panel housing, the main challenge of this section is determining the thickness required in order to withstand the desired loads.

As the overall design of the solar road panel is a composite material, between glass and fibreglass, it is important to make this thickness decision while bearing in mind the performance of the glass layer. It is known that glass is a very rigid material that, in compression, behaves very similarly to steel. As a result the design incorporates a very rigid glass layer over a, comparatively, very elastic fibreglass structure. Since the panel will be contained by a housing it is assumed that the glass' performance will govern the deflections within the panel with the fibreglass layer providing resistance to ensure the glass does not fail in tensile loading.

To this end, it is known from literature that the multiply fibreglass panel that can resist traffic loading on sand consisted of 4-ply fibreglass [6]. For this structure that will be the lower limit for the number of whole fibreglass ply layers that must be in the design. While the appropriate upper limit is unknown, the design requirements specify that the panel must be made from readily available material, so the maximum available size of the housing will govern the number of layers of fibreglass used in the design.

4.3 Cell Compartments

In order to accommodate the solar cells within the panel, cut-outs need to be made from several of the fibreglass layers in order to allow light to reach the cells embedded in the structure. With a multi-ply fibreglass structure this is simple, as square sections can be cut from the fibreglass sheet prior to adhering the layers together. The challenge comes in determining the geometry of the sheet and the number of fibreglass layers available to support the glass above the base layer.

While maintaining the 140 mm spacing for the solar cells that was determined in the electrical system design portion of this paper, the design was completed as shown in Figure 4. This is the basis of the design for the top layers of fibreglass, some of which will be modified as demonstrated in the following section for cell interconnection.

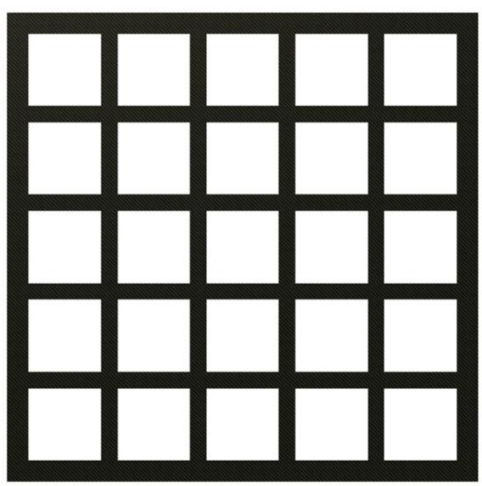

Figure 4: Cell compartment accommodation in fibreglass structural layers

4.4 Interconnection Routing

The last consideration to be taken here is for the interconnection routing between the cell compartments. The objective of the routing is to supply only enough space to route the interconnection wires through and nothing more, as any extra space would degrade the structural integrity of the panel with no additional benefit. The spacing also has to be manufacturable.

In order to follow the routing plan detailed in Figure 3, it was determined that the cut-outs from the structural layers for the cell interconnections would need to be located at the center of the cell walls. Two layers of fibreglass with this configuration would be required to safely and easily route the wires through the sectioning. Similar cuts will also be made in the edge walls to allow wires to deliver the electricity from the cells inside the panel to whatever external load is applied.

5.0 Transparent Layer Design

The key parameter in designing the transparent layer is determining the thickness of glass required on the surface. Cantilevered glass panes in floors are very common, and are heavily overdesigned to typically reduce the anxiety of people walking over them, however they also span much greater gaps than the glass in this solar road panel will need to. One of the main elements of their design is that they consist of multiple glass layers, with the objective being that should any one layer fail the others would still be able to support the design load for the structure.

Through calculations it is possible to determine the stress development and induced deflection in the glass over the cell compartments, which must be kept under a threshold defined by the glass used and is a function of the glass thickness, shape of the cantilevered section, and load applied over the unsupported glass. Guidelines provided for tempered glass indicate that the design stress for medium term loading on tempered glass is 53 MPa [7]. Stress relation equations provided by Roark and Young [8] allow the maximum bending stress at the center of the unsupported glass section to be found for a tire pressure of 480 kPa, 140 mm square cantilevered glass section, and varying glass plate thickness as shown in Table 1.

Table 1: Maximum bending stress in the transparent layer as a function of glass pane thickness

Thickness (mm)[in]	6.35 [1/4]	9.53 [3/8]	12.7 [1/2]	15.9 [5/8]	19.0 [3/4]
Maximum Bending Stress (MPa)	67.13	29.83	16.78	10.74	7.459
Maximum Deflection (mm)	1.60	0.4842	0.203	0.102	0.0508

With the standard glass thickness used in Table 1 it is shown that any single pane of glass from 9.53 mm and thicker will be able to support the load applied from a 480 kPa tire passing over the solar road panel. There is a slight variation in performance when two laminated panes are used instead of a single pane of the same combined thickness, as the design stress drops to 42 MPa [7].

The glass deflections found in Table 1 indicate that there will be minimal deflection of the glass under the expected loading. This was the expected result as glass is a rigid material and is being cantilevered over a small section of solar cell space. These calculations do, however, confirm that using the low bending theory assumptions that are required for the bending stress equation used are valid.

6.0 Panel Housing and Weatherproofing

6.1 Panel Housing

As the solar road panel being designed is made of several different materials it is important to ensure they will be held together firmly during testing and operation. One of the key design requirements was that the panel should allow easy maintenance, so the housing used must be removable so that the inside of the structure can be maintained during operation and instrumented during testing.

In order to accomplish this it was determined that a metal enclosure was required. In order to contain the layers it would need to overlap the transparent and structural layers, on the top and bottom of the panel respectively, while also covering the sides of the panel to stop layers from slipping at the interface. To accomplish this, the most logical option is to customize a stock aluminum channel to fit around the layers and use coated bolts and nuts to hold the housing to the fibreglass structure.

6.2 Panel Weatherproofing

The design of the housing, and how the other layers are integrated with it, is limited by the design of the weatherproofing system for the panel. In an optimal solar module this would be done using an epoxy, however this is not possible due to the maintenance requirements on a solar road panel. To accommodate this then, various edge sealing and rubber interfaces need to be used to stop water transport into the panel.

7.0 Conclusions

This report found that it is indeed structurally feasible to design a solar road panel to the requirements outlined in Section 2.3. The final design for this project, as shown in Figure 5, consists of a panel that is 0.91 m (3 ft) square; 50.8 mm (2") tall; contains 25, 122 mm square photovoltaic cells; and weighs 48.35 kg (106.6 lb).

Figure 5: Final solar road panel design

8.0 Recommendations/Future Research

The main goal of this prototype is to perform a structural analysis on it, build a finite element model that duplicates the structural results, and then apply the model to various subgrade, pavement, and structural base models to determine the optimal characteristics of a solar road panel for use in roads, parking lots, and similar infrastructure. This would refine the specific glass thickness requirements, solar cell spacing, interconnection routing, and other design parameters discussed in this report and also determine the service life of a solar road panel.

In addition to this work for the fibreglass structural model, analysis should be performed on the material selection to ensure that fibreglass is the optimal material selection. Other metals and polymers should be analyzed and compared for static and fatigue performance.

The sustainability benefits of solar road panels should also be investigated. The initial cost of such a panel will be higher than that of a traditional road structure, however the additional benefit of generating clean and renewable energy and being made of different materials could help this to improve the sustainability aspects of civil infrastructure. One of the challenges of this analysis is determining the lifetime maintenance requirements of such a panel to appropriately determine lifetime costs.

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