Integrated Solar Lighting for Pedestrian Crosswalk Visibility

A report written for the Florida Department of Transportation

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Abstract

This report is written for the Florida Department of Transportation (FDOT) to aid in their assessment of the viability of solar-driven lighting of pedestrian crosswalks or other traffic bearing areas to enhance safety. The goal of the solarized crosswalk is to provide power for lighting and/or illumination using integrated lighting to enhance pavement markings and visibility; it should also provide service during power failures and in remote areas without nearby electrical utilities. Other potential traffic bearing areas include parking lots, shared-use/multi-use trails, motor vehicle traffic ways, etc. The FDOT is primarily interested in mature technologies that have the potential to meet these demands.

The primary technology of interest for FDOT is a device that may be integrated directly into the surface of the crosswalk or pavement; this device would include the solar energy harvesting device (e.g. photovoltaic module), the light emitting devices and energy storage. Primary concerns of FDOT include the friction on the surface, the load bearing capacity and the cost. If the viability of utilizing solar panel technologies that are directly integrated into the crosswalk or pavement is low, FDOT is also interested in using solar power at a site external to the crosswalk or pavement to illuminate it from above or with in-pavement lighting. FDOT is ultimately interested in commercially available technologies but would also be interested to learn of technologies being developed at the lab scale.

While the use of photovoltaic modules is ubiquitous for remote power generation applications, the results of this analysis indicate that only a handful of companies are currently developing photovoltaic (PV) modules for direct integration in roadways. These technologies are motivated by using the extensive area available on roadways as power generating potential. Some, such as Solar Roadways® provide the ability to integrate sensors and lighting into roadways surfaces for a multitude of potential applications related to so-called “smart roads”. Nevertheless this technology faces several potential hurdles, as will be discussed, and also are not designed with energy storage in mind; one pre-requisite of the FDOT. Furthermore, this analysis indicates that there are no technologies available today that are commercially available; all companies developing solar roadway technologies are still in there development and demonstration phase. The major concerns that arise when considering these technologies are 1) their mechanical durability and 2) their optical durability, meaning how transparent do the surfaces stay over time after deposition of dust and other debris and scratching of the surface from interaction of vehicles and small particulates. The former is often addressed by the companies but the latter is not.

One alternative possibility that this analysis has uncovered is the use of photo-luminescent stones that may be directly integrated into roadway surfaces. This passive approach has been realized by a Dutch company Heijmans, for lighting bike paths during the nighttime. Because this is a completely passive approach, there are concerns about the duration of lighting, as well as the structural and chemical stability of the materials over long periods of time. Nevertheless, this approach should be considered a very cost effective solution.

Beyond these two possibilities we discuss the feasibility of providing decentralized power for lighting by integrating PV modules off the side of the road or integrating thermo-electric modules directly into the roadway (to meet the original objectives of FDOT). The latter has some distinct

advantages compared to integrating PV modules into roadway surfaces because they do not need to see direct exposure to the sunlight. The total power generation is substantially less but if the goal is only to provide lighting then thermoelectric power generation may be a suitable alternative.

Background and Motivation

According to the National Highway Traffic Safety Administration there were 4,735 pedestrians killed in traffic accidents and another 150,000 treated in emergency departments in the United States [1]. The state of Florida had the second largest number of total pedestrian fatalities, with 501, the second largest fatality rate per 100,000 population at 2.56 [1]. If utilized correctly, pedestrian crosswalks can increase pedestrian safety and thus there is a motivation to build crosswalks that provide reliable safety lighting to alert drivers, even in the absence of power outages.

One possible way to provide grid-disconnected lighting for crosswalks is to integrate photovoltaic (PV) modules directly into the road surface. There are three companies that are actively pursuing this approach (Solar Roadways®, Wattway and SolaRoad) but the PV panels only deliver power to the electrical grid, rather than store the energy for lighting purposes during the nighttime. The technologies are mainly for building so called "solar roads", where the entire road's surface is composed of PV modules. Both Wattway and Solar Roadways® utilize technologies that would enable LED lighting, but because they do not integrate storage (e.g. batteries) it is dependent on grid power. Nevertheless, there is motivation for providing LED lighting for purposes beyond pedestrian safety. For example, there is discussion about lighting lanes with LED's rather than relying on paint. One could even envision a scenario where sensors of various sorts communicate with the cars and thus the road is able to serve as a "smart highway" and talk to other "smart cars", all the while generating the power to drive them.

One interesting approach that may be capable of providing roadway lighting disconnected from the electrical grid is through the utilization of photoluminescent materials. These materials absorb sunlight during the day and slowly emit radiation in a small and controllable visible wavelength range. We believe this is the technology behind a lighted bike path in the Netherlands called "Van Gogh – Roosegaarde Cycle Path", although we could not find many specifics about the technology that was utilized[2]. This was designed by a company called Studio Roosegaarde in collaboration with Heijmans; they propose similar photoluminescent technologies for lighting lanes on highways during the nighttime. Regardless, one of the major drawbacks of this approach is that the energy storage is completely passive and there is a decay of light emitted from the materials with time. These materials are widely available from several companies and are relatively cheap, especially compared to photovoltaic technologies. Materials can be acquired in the form of stones or fine powder. One could envision integrating the stones directly into asphalt or mixing the powder with asphalt in strategic areas to create something akin to warning lanes.

In addition to integrated PV/lighting and photoluminescent materials, there are other approaches that may prove to be more suitable. For example, rather than installing PV modules directly into the roadway where they are exposed to severe conditions, it would probably be more practical to install them elsewhere off the side of the road (unless in a dense, urban area where little land is available) where they can work unhindered. This is the approach taken by Kyocera for lighting 73 km of highway in Brazil[3]. Finally, one interesting approach that we consider is the integration of thermoelectric modules that are able to take advantage of the elevated road surface temperatures and lower temperature underneath to produce electricity. With modules such as these, the normal asphalt surface may be constructed above them and thus concerns about dirt deposition or fragility are not as much of an issue. These could be integrated with energy storage and LED lighting to meet the requirements of the FDOT.

Description of Relevant Commercial Technologies

Below is a description of the technologies available from established companies that meet certain aspects of the FDOT's requirements. It should be noted that none of the companies below provide all of the needs of FDOT, namely integrated power generation, storage and lighting. Furthermore, as far as we can tell the technologies are not available to the general public and are largely being promoted by the companies as potential technologies that are currently being tested at relatively small scales.

Solar Roadways®

Solar Roadway's® is a US based company that proposes a modular approach to implementing solar collectors into roadways and walkways[4]. They are currently being funded by in their second Phase II SBIR United States Department of Transportation (USDOT). The company received their first phase of funding in 2009 and two years later was awarded a much larger $750 K phase II grant for developing their modules. Finally, in 2016 they were awarded a second $750 K phase II grant for further developing and refining their modules. Currently their product is not available to the general public.

Each solar collecting module is independent but interconnectable with others (analogous to lighting wired in parallel rather than series). Figure 1 shows an artist's depiction of a single module of the latest proposed design alongside three built prototypes of the same module. Each photovoltaic module is sandwiched between two plates of tempered glass and integrated with the PV module are LED lights that may be configured in a variety of different ways. There is a buffer between the tempered glass and PV cells in order than compressive forces that are incident on the glass are not seen by the sensitive PV cells. The modular design would hypothetically allow for easier maintenance as the modules are not permanently connected to each other - allowing for localized repairs as opposed to traditional asphalts where cracks and deformations easily spread throughout the structure of the road. The modules are designed to replace asphalt in the road.

Perhaps most relevant is that these lights are proposed to eliminate painted lines on roads and highways. They are described to be actively changing with the environment and they state that their newest iteration is reported to have LED lights that are adequately visible throughout the day[4]. Effectively these modules would be controlled by microprocessors and potentially be able to alert drivers with warning messages or change lane displays in an emergency. Unfortunately, there is no specific data available from Solar Roadways® regarding their design that would allow us to assess what the performance of the lights will be during the day. Nevertheless, lighting for a crosswalk is more of an issue during the nighttime and there should be no issues with LED visibility then.

Figure 1. Digital depiction and built prototype of a Solar Roadways® experimental solar road module[4].

On October 2nd, 2016 Solar Roadways® unveiled their first public installation in downtown Sandpoint, Idaho. The installation is monitored via a webcam 24/7 that is available to the public to observe (http://www.sandpointidaho.gov/visiting-sandpoint/solar-roadways#ad-image-5). The unveiling was in general met with great disappointment; 18 of the 30 panels did not work from the start, the LED lights reported to be clearly visible in daylight on their website are very obviously not very visible in clear daylight, this installation does not produce power because of non-defined manufacturing problems, it is NOT waterproof which caused 5 more panels to turn off during the first rain and installation does not have proper surface materials to support vehicular loads.

The company has indicated that their modules will be able to withstand heavy duty vehicles and are quoted as saying that “it will stop vehicles going 80 miles per hour on a wet surface[5]”. They do not give more specifics but do state that this is because the surface of the tempered glass is covered with a macro and micro texture to provide traction. A major issue with using fiber glass or tempered glass as asphalt replacement is the materials’ ability to keep consistent friction between the wheels of a vehicle and the surface at high speeds. A method previously utilized by Solar Roadways was equidistant rough elevations in the top panel that are used as peak pressure points and as such peak friction points[4]. This method seems to have been abandoned in the most recent prototype presented by Solar Roadways. This is of great concern as the company does not publicly disclaim the exact variation of tempered glass that is being used.

Regarding the weight that the modules are able to withstand, their website states that their "goal" is to withstand 250,000lb of weight. The number is based on the limit of refinery equipment up to 230,000lbs on frozen roads. This has been confirmed with actual physical load testing at civil engineering labs and finite element analysis. Further analysis of the mechanical integrity will be discussed later when discussing “Potential Issues”

Their vision as a company is to install these panels on all roads in place of asphalt, effectively turning roadways into electricity generators. Their calculations indicate that if all roadway surfaces were covered with their technology then they would be capable of producing three times the energy demand of the United States. However, it remains unclear that this technology would be economically viable in rural areas where ample land is available to put other forms of solar electricity generating devices. Alternatively, where land is scarcer, such as urban areas, the amount of available sunlight available is also diminished because of shading and increased traffic.

The individual modules do meet many of the demands of the FDOT for pedestrian crosswalks, except for energy storage; this is because these are designed to be directly integrated with the electrical grid. Solar Roadways® proposes that the modules generate power during the day that is delivered to the grid and at nighttime receive power from the grid to light the LED's. Thus, these modules are not capable of functioning in the case of a power outage in their current configuration. Because the company does propose that the modules may be integrated with sensors that light up when animals or pedestrians are crossing the road, we do not see any technical reason why the modules could also not be configured with a small battery for energy storage.

Structural Analysis

There have been several academic studies conducted to evaluate the stresses exerted on hypothetical tempered glass or fiberglass coverings that are proposed to be used by Solar Roadways [6, 7]. The studies concluded that fiberglass[7] and tempered glass[6] are feasible choices for the structural panels of the construction and can withstand the loads supplied by daily traffic. However, it should be noted that both studies only simulated compressive loads onto the construction of the module. While this is indicative of usual traffic on highways where sudden stops of vehicles are not often necessary, it is not a very accurate to consider only this in an urban environment where shear forces due to braking is commonplace. These shear forces are likely to be substantial in cases of near-legal-weight limit vehicles. Shear testing data to simulate breaking forces are not available in the literature.

Stresses were evaluated for static and fatigue loads[7]. The static load was based on the maximum single wheel load under Canadian regulations (CSA 2006), while the fatigue load was an equivalent single axle load. The contact area for the fatigue load was determined using the geometric relations to convert dual tire loads to singles for concrete pavement section analysis and an assumed tire pressure of 600 kPa[7] .It was assumed that these correlations were relevant to solar road panels due to the similarity of their material properties to concrete. Both loads were applied as pressures on the panel surface with an even distribution of the total force[7]. Glass specimens fail through fracture methods which were well documented for varying glass chemistries citation. With tempered glass, any cracks that develop past the tempered layer would propagate rapidly and cause the glass to fail. Therefore, it is important for the fatigue life of the panel to keep tensile strain in the transparent layer below the 69-MPa compressive stress developed on the faces of the glass panes through the tempering process.[7]

Figure 2 shows a summary of stresses experienced by the transparent layer of the structure under static and fatigue stresses for various locations on the module (PCC refers to concrete, HMA refers to Asphalt, Granular and Subgrade refer to different types of tempered glass). As seen, for all locations, the tempered glasses do not see stresses greater than their endurance limit. Thus, under the loads simulated it is suggested that the panel design assumed by Eljavaru et al. would have "infinite life" – meaning that the stresses would never exceed maximum allowable stresses in ideal conditions[7]. This is, of course, impossible but from this data, the authors conclude that the glass layer of the panel will not fail due to loads under described conditions.

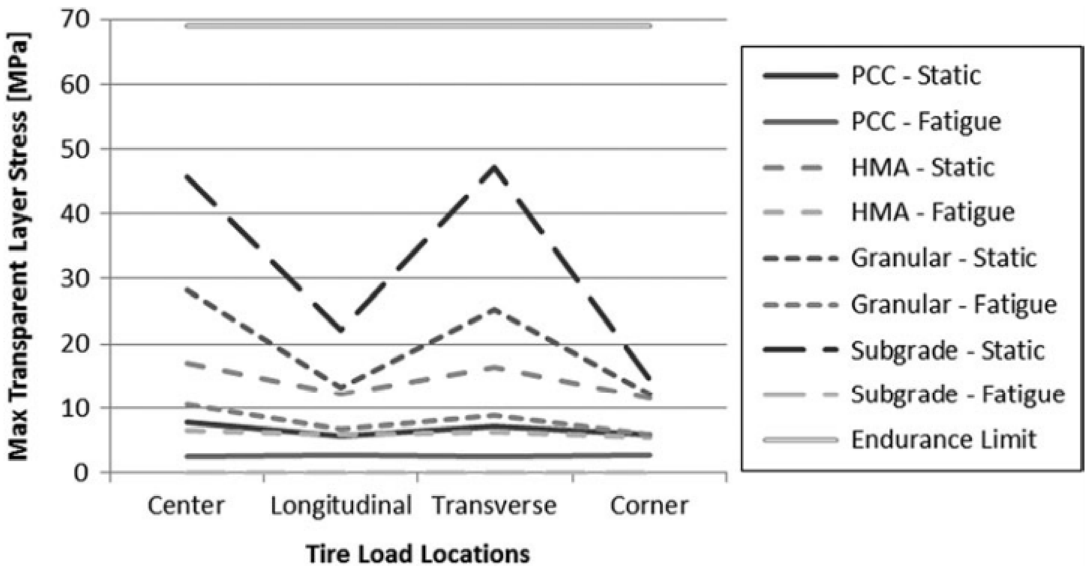

Figure 2. Maximum stresses seen by two grades of tempered glass (granular and subgrade) under conditions assumed to replicate loads seen on roadways and a design assumed to be representative of Solar Roadways modules[7].

<u>Wattway</u>

Wattway is a concept by a French transportation infrastructure company, Colas, to replace highways made of asphalt with solar panels that cars and trucks can drive on. The technology is based on thin solar modules designed to be placed directly on top of the road surface, in contrast to the modules of Solar Roadways® that replace asphalt[8]. Like Solar Roadways®, the major goal of this company is providing solar electricity directly to the grid. The modules appear to only be capable of providing power and are not capable of lighting or storage, although the company does state that

> "Other technologies can be added into Wattway panels because a road that produces electricity is a connected road. For example, integrated sensors can provide us with real time information on traffic conditions, help us manage traffic dynamically and allow the road to self-diagnose potential maintenance issues. It could also be possible to charge electric vehicles using induction."

Overall, the modules appear to be much more streamlined than the modules of Solar Roadways®. We could find no specific information given about how the PV modules are protected, but it does appear that there is a durable transparent layer coated onto the modules, as seen in Figure 3. Thus, unlike Solar Roadways® the modules and protective cover appear to be in contact with one another which should increase the stresses on the PV cells when vehicles drive over them. Nevertheless, the company states that their major advantage compared to competitors is the fact that "Wattway panels are sturdier than their competitors. Tests have shown that they can bear one million truck tire passes without damage". Unlike Solar Roadway's however there is no indication of how much weight these modules are capable of absorbing without being damaged.

Figure 3. Wattway's solar module that is designed to be placed directly on top of asphalt[8]. The design is streamlined as indicated by the thickness relative to the coin on the right.

Figure 4. Wattway's solar modules integrated to serve as a roadway surface[8].

Like Solar Roadways®, these modules are not available to the general public but the company does state that they expect them to be released in 2-3 years. There is currently an ambitious demonstration project underway in France to build a 621 mile stretch of road with Wattway's panels[9]. This was signed in 2016 by the French Minister of Ecology and Energy and is expected to take up to five years to complete. Overall, there is little to no scientific data provided by Wattway for us to provide a reasonable technical or economic analysis of their panels. It is also stated by Popular Mechanics that "What we don't know now is how much the solar road surface will cost, how it will stand up to inclement weather, and how long it will last until stretches of road need to be replaced.[9]"

<u>SolaRoad</u>

SolaRoad[10] is concept by a consortium of Dutch institutions to replace roadway surfaces with prefabricated solar electricity generating modules. The consortium consists of the research institution TMO, Ooms Civiel, Imtech and the province of Noord-Holland[11]. Similar to Wattway, the technology is only aimed to generate electricity and is not integrated with lighting as the Solar Roadway's panels are. In contrast to Wattway however, the panels are designed to replace asphalt rather than be placed on top of it; they are relatively bulky, and in that way similar to the Solar Roadway's panels. The modules are 2.5 by 3.5 meters with a top layer made of translucent tempered glass that is 1 cm thick, as seen below in Figure 5[10]. Furthermore, it can be seen that the tempered glass surface can be roughened, as indicated by the contrast in the left and right hand sides of the panel. Creating this textured surface has been one of the major challenges of the company[10].

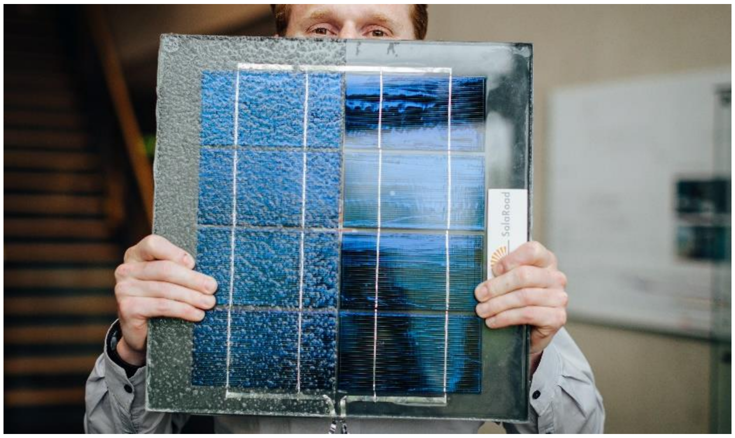

Figure 5. Representative module being used for the SolaRoad project.

Figure 6. Pre-fabricated concrete modules with the PV module placed on the surface. The PV module is placed between two slaps of tempered glass.

The large size of the modules can be seen in the figure below and we anticipate that the installation costs could be substantially higher for these than Solar Roadway or Wattway, simply due to their large size. In 2014, the consortium completed construction of a 70 meter bike path to test the technology[12]. It was reported 6 months later that the surface was still producing power and in good working order but that the anti-slip coating that was used on the surface saw some deterioration. It was reported that “The anti-slip coating began to peel away thanks to long-term sun exposure and temperature fluctuations, but researchers told Al Jazeera they are already at work developing an improved version.”[12] This is a major concern for roadway applications as any decrease in the friction of the surface would constitute a safety hazard, especially in rain conditions. This was reported in May 2015 and we have not been able to find any more current updates of the performance to date. It should also be noted that this company recognizes that energy storage is not possible with its current configuration but they are working on the development of batteries for energy storage, but it is not clear if they plan on integrating them directly within the modules or not[11]. The total cost for the 70 meter project was $3.7 million.

Hejimans - Studio Roosegaarde

Hejimans is a Dutch transportation company that has been involved in the design of Solar Roadways® and bike paths. In collaboration with Studio Roosegaarde, they have developed a lighted bike path entitled the "Van Gogh – Roosegaarde Cycle Path"[13]. An image during the nighttime can be seen below in Figure 7[13]. In contrast to the previous three companies, Hejimans takes advantage of the photoluminescent effect and uses stones that absorb sunlight during the day and emit light slowly during the nighttime. Thus, this technology is not capable of generating electricity like the modules of Solar Roadways®, Wattway and SolaRoad. In this case they have integrated photoluminescent stones directly into the concrete but the companies have also proposed other options such as photoluminescent paints for making lanes more visible during nighttime. The Hejimans - Studio Roosegaarde collaboration also proposes other mechanisms for increasing driver safety and awareness using LED lighting within roads but as far as we can tell do not give any specifics about how they plan to integrate them with either electricity from the grid or solar energy.

Figure 7. Nighttime photographs of the photoluminescent Van Gogh – Roosegaarde Cycle Path. On the left is a zoomed in image showing the stones with various colors and on the right is a broader picture of the bike path lighting.

Because this company utilizes photoluminescent materials, the integration of lighting into asphalt or concrete is fundamentally different than the aforementioned solar roadway companies. The photoluminescent materials are effectively stones that do not have the same fragility as PV modules; their photoluminescent behavior does not change if the materials crack or degrade over time. This type of technology is one that involves no electricity, for it relies on the photons of light from the sun to excite the luminescent material whenever there are no longer any photons present. These stones generally take 1-2 hours to "charge" and give off light for roughly 8-10 hours. The intensity of the light degrades over time however, as discussed further below [5]. This technology may be embedded into driveways and sidewalks and companies such as Core GLOW™ [14]and Ambient Glow Technologies™ [15] claim that the structural integrity of these stones is roughly equivalent to the integrity of the concrete or gravel that it is embedded in (personal communication with Core GLOW™).

We could not find specifics of the photoluminescent materials that are used by Hejimans, but believe they are fundamentally similar to the materials offered by Core GLOW™ and Ambient Glow Technologies™, Both companies sell photoluminescent stones of various sizes and colors. There are several different combinations of elements that can produce the same effect, but Strontium Aluminate (SrAl) is the combination that has provided the highest amount of luminescent yield. SrAl is usually composed of 20% w/v strontium, and is doped with another element, europium, in order to activate the material's luminescent properties[2]. The SrAl's concentration can be increased by manufacturers (in order to increase the luminous intensity) at the request of their customer. This type of material is nonflammable, nonradioactive, and both chemically and biologically inert, which makes it a perfect candidate material to embed into roadways. This material can be made to expose different types of colors, which include: green, blue, aqua, and red. Each color is emitted with a certain wavelength; for example, green, aqua, and blue emits 520nm, 480nm, and 400nm, respectively; green stones have the highest luminance and are therefore most ideal for providing visibility in roadways.

The material can be made into either a powder or solid stones, as shown below in Figure 8. When taking these stones and embedding them into gravel or concrete, the overall maximum load of the structure will not decrease. When taking the powder and embedding it into gravel or concrete the same effect can be achieved, but one must be aware of the fact that the crystal structure could be compromised due to long exposure to liquids. In order to combat this issue, a sealant is recommended.

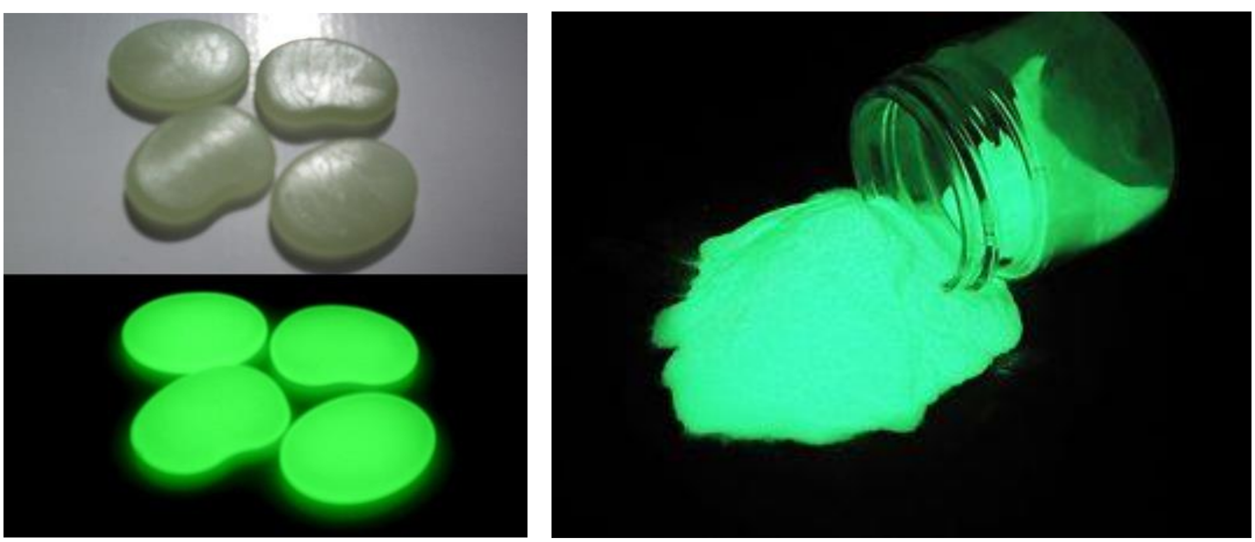

Figure 8. Left top) Green stones of roughly 1 cm diameter before charging and left bottom) green stones of roughly 1 cm diameter after charging. Right) The same green photoluminescent material in powder form. Courtesy of Core GLOW™.

Since this technology is completely absent from the usage of electronic components, any electromagnetic anomaly (i.e. an EMP or power outage) will not affect its performance. The only main concern with this technology is the fact that it is completely reliant on photons from the sun, and there is no way to control the output of it with time. Generally, this luminescent material contains the highest intensity of bright light for approximately 30 minutes, and then starts to degrade in intensity over time. The technology also has no way of intelligently storing energy for times when it is exposed to less sunlight than on average, and so this could cause a problem for times when there are long periods of time where there is no exposure to sunlight (e.g. during a long, stormy day). Core GLOW™ states that light would be given off from it for roughly 8-10 hours, but the intensity of light degrades substantially over time until it is "recharged". Figure 9 shows the anticipated luminance verses time; after 1000 minutes (~16 hours) the luminance decreases from about 2000 mcd/m^2 to about 5 mcd/m^2, a factor about 400 times. For reference, the standard LED in a high definition television has a luminance on the order of 300 cd/m^2, or about 300 times the maximum luminance of these luminescent stones.

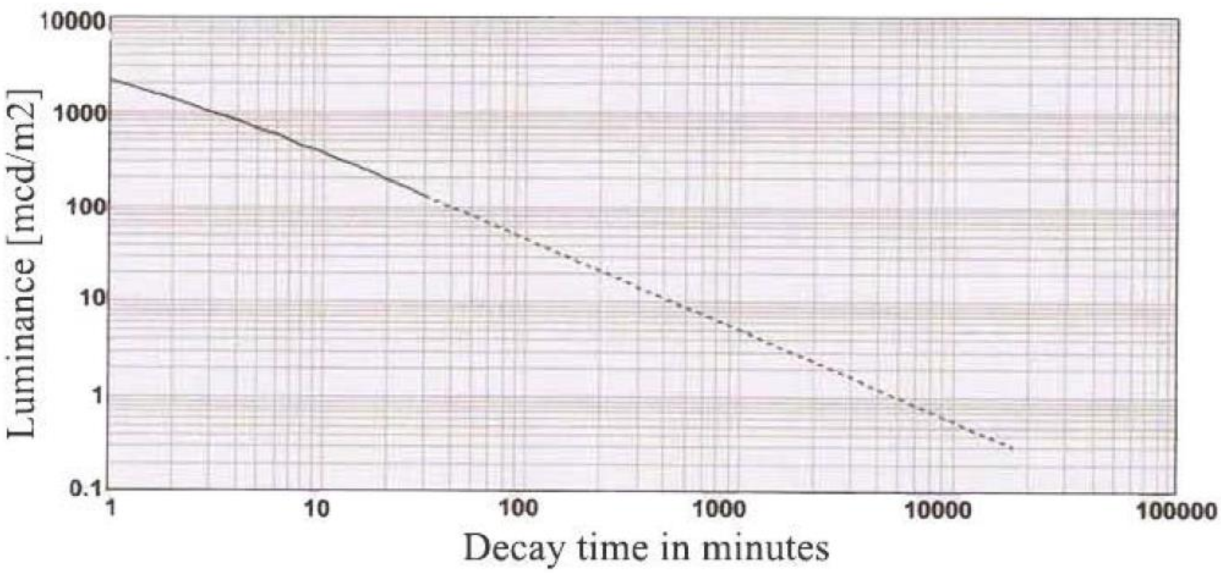

Figure 9. Luminance verses time for Core GLOW™ luminescent stones. For reference, a standard LED in a high definition television has a luminance on the order of 300 cd/m^2.

Other minor concerns related to this material are its performance over extended periods of time in the humid Florida environment, but we were unable to find any stability studies of this material. We have spoken with representatives from Core GLOW™ and they do state that the material may degrade over time when exposed to liquid water or water vapor. This would be relatively easy to test in an accelerated fashion in our laboratory if necessary. Overall, the materials should be chemically stable according to their MSDS datasheet and the Core GLOW™ states that they have a lifetime of 20 years (however, their degradation over that time is not quantified in any way).

Overall the cost of these materials is almost negligible. Core GLOW™ has offered these to the University of Florida at $21 per pound. For example, Figure 10 below shows relative densities for 0.12 pounds to 1 pound per a 16 ft^2 area using 8-15 mm stones. For all of the densities the cost is minimal and thus we estimate the cost increase if implementing these in a crosswalk to be on the order of hundreds of dollars.

Figure 10. Estimation of wight of stones required for different densities. Top left) Low density – 0.12 lbs per 16 ft^2. Top right) Low – Medium density – 0.25 lbs per 16 ft^2. Bottom left) Medium density – 0.50 lbs per 16 ft^2. Bottom right) High density – 1.0 lbs per 16 ft^2

Other Possible Solutions

Technically speaking, probably the easiest way to meet the FDOT's requirements would be to build a small solar charging and energy storage module to the side of a crosswalk or area of interest, rather than directly into its surface. The footprint of such a module would be extremely small if the only intent is to power LED lights and microcontrollers. Integrating LED lighting into the road surface has been accomplished successfully by Hejimans, in this case for alerting cars to bike crossing a bike path. Additionally, similar projects have been involved in the state of Florida (https://fdotwp1.dot.state.fl.us/ApprovedProductList/ProductTypes/Index/493). Because the LED's do not need access to the sun, they can be shielded with heavy duty covers that protect them from vehicles. In the case of Hejimans, they implement sensors that detect the occurrence of pedestrians or bikers before they enter the crosswalk and pro-actively alert drivers with flashing lights. A video about their project, titled BikeScout, can be seen here: https://www.youtube.com/watch?v=-kYJCE1W7co&feature=youtu.be. The company states that the "BikeScout system increases traffic safety by giving timely warnings of cyclists crossing the road. Highly robust, dimmable LEDs, which can be fitted flush with the road surface, can provide signals in various configurations and are more effective and visually attractive than other safety measures. Via mobile Internet and an online Web application, local traffic control can view the Heijmans BikeScout's availability and the traffic flow. This makes Heijmans BikeScout a valuable management tool as well as making our city streets safer." A picture of the BikeScout project can be seen below in Figure 11. The green arcs represent a sensor that can detect oncoming bikers or pedestrians. Upon detection, flashing LED lights shine in the direction of oncoming traffic. One could easily envision a project such as this where the power is delivered from a battery that is powered by a solar photovoltaic module.

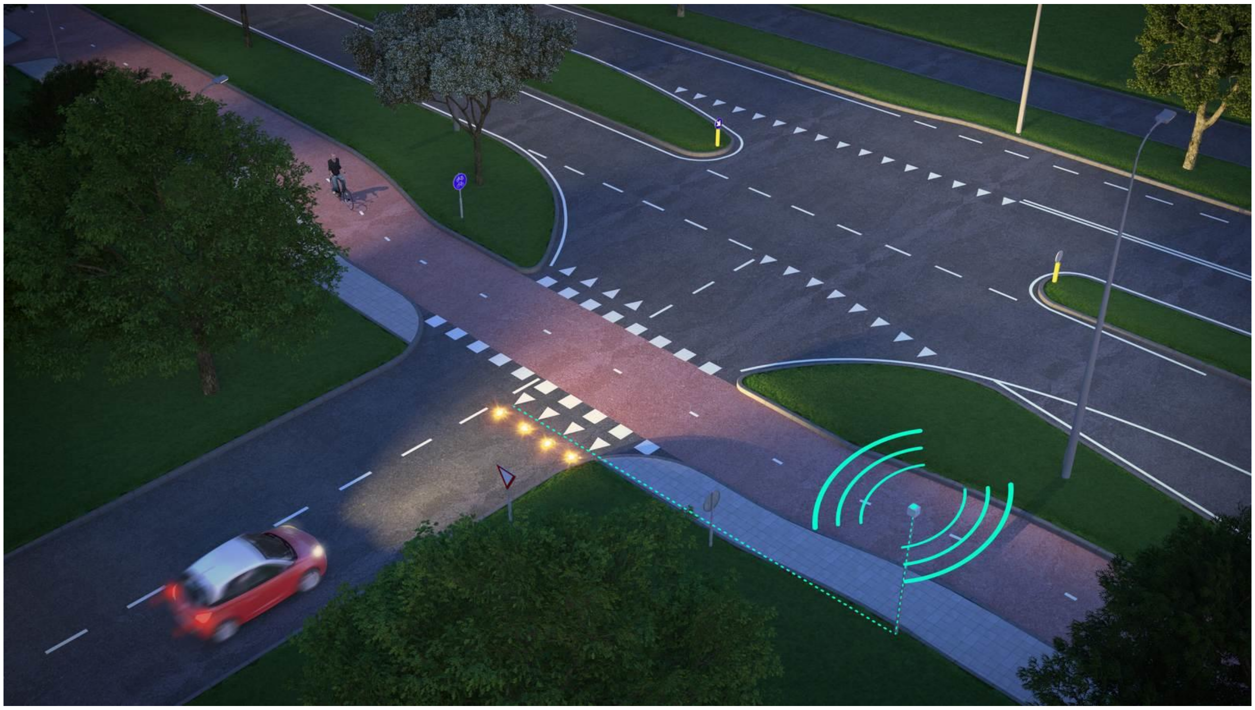

Figure 11. An aerial photograph of Hejiman's BikeScout project. Major components include a sensor to detect bikers or pedestrians. Upon detections, LED lights begin flashing to alert oncoming traffic[16].

Adjacent power generation and storage has also been utilized in initiative led by Kyocera of Japan to light 73 km of highway in Brazil. Lighting, power generation and battery storage are all encompassed in a "solar streetlight" developed by Kyocera. Each streetlight has a 150 W LED lamp, three Kyocera KD250 solar modules and four 240A/12V lead acid batteries. These modules are available as kits and can be purchased from Kyocera (http://www.kyocerasolar.eu/index/products/Industry_Markets/rural_electrification/street_lighting_stand-alone.html).

Finally, there is a fair amount of discussion in the literature regarding the possibility of implementing thermoelectric elements into the roadway surface to generate power[17]. The devices are effectively solid state heat engines that directly convert heat into electricity. The only requirement is that a reasonable temperature gradient exist. Such is the case with roadways; on sunny days surface temperatures are on the order of 50 °C to 60 °C and below the surface cooler temperatures on the order of 15 °C are present[18]. If the power generating device is to be integrated in the roadway, thermoelectric generators have a distinct advantage from photovoltaic modules; namely, they do not have to see the photons from the sun and thus there is no need for an optically transparent surface. Therefore, thermoelectric modules could be placed below the near surface of the asphalt and the traditional asphalt surface would not be compromised. Thus, the durability devices is expected to be superior as well as the ability to mitigate dangers associated with artificial surfaces such as tempered glass. The main disadvantage of thermoelectric generators is their low efficiency, on the order of 1-7 %, compared to higher efficiencies of photovoltaic modules. However, because the FDOT's main objective is to provide roadway lighting rather than distributed power, the expected amount of energy required is low. Therefore, energy efficiency is expected to be a small component of the cost of this technology. We could envision integrating a thermoelectric generator coupled with battery storage all below the roadway surface, coupled with a controller to power LED lights. One major uncertainty with this technology is the amount of power that would be developed on cold cloudy days when the temperature gradient in the asphalt is minimal. To account for this, the energy storage and power generation would have to be scaled sufficiently to store power for several days. A sizing analysis based on a realistic heat transfer model could be performed relatively straightforwardly.

Comparison of Different Technologies

Below is a tabulated overview of all of the technologies discussed above and their ability to meet the requirements of the FDOT. To summarize, only the Solar Roadways modules, photo-luminescent stones and thermoelectric power generation have the ability to meet all FDOT's requirements. Regarding Solar Roadways, this is predicated on the fact that battery storage can be integrated with the modules; currently this is not the case. Regarding the photoluminescent stones the major question is their lighting duration and their major limitation is that they are completely passive; there is no way to control the lighting (e.g. flashing, intermittant). Only the thermoelectric energy generation scenario will likely meet all of the demands of FDOT, but this is something that would have to be developed in house as a commercial product is not available. Finally, generating power and implementing storage adjacent to the road is a viable pathway that meets all of the FDOT's demands except for being integrated into the roadway surface. This is probably the most cost effective solution after the photoluminescent stones.

	Solar Roadways®	**Wattway**	**SolaRoad**	**Photo-luminescent Stones**	**Adjacent Electricity Generation**	**Thermoelectric energy generation**
Mechanical Durability	High	High (no data)	No data	High (no data)	Not applicable	High (theoretical)
Optical Durability	Uncertain	Uncertain	Uncertain	Not applicable	High	Not applicable
Surface Roughness	High (not quantified or studied long term)	Uncertain	High but wear due to weathering noticeable after 6 months	High/Not applicable	High/Not applicable	High/Not applicable
Lighting Capability	Yes	No	Yes but only theoretically	Yes but duration is questionable	Yes	Yes
Cost	High (not quantified)	Equivalent to standard PV (analysis not discussed)	High ($3.7 million for 70 meter bike path)	Low, on the order of hundreds of dollars	Medium	Medium

Energy Storage	No, but possible	No	No	Stones naturally store photons during daytime and slowly re-emit at night	Yes, see Kyocera's highway-lighting project	Yes, prototype would have to be constructed
Roadway Integration	Yes	Yes	Yes	Yes	No	Yes
Maintenance	High	Medium	High	Low	Low	Medium (entire surface would have to be uprooted to perform any maintanance)

Recommendations Going Forward

1) If the SolarRoadway modules are available for purchase in the near future then this is probably closest to meeting most of the goals of FDOT in the shortest amount of time (menus energy storage which means that the modules would need to be integrated with the grid). Since grid independence is a major target of the FDOT however, the ability to integrate battery storage with the modules should be investigated. It is not clear what the possible complexities of this would be however. Mechanical testing of the modules under realistic roadway conditions, especially braking that would induce shear stresses should be investigated.
    a. **Edit on 10/31/2016** - based on recent concerns with their deployment these modules are far from being dependable and capable of being integrated into a roadway. **Do not pursue.**
2) Wattway modules –Relative to Solar Roadways, these modules are less complex and simpler to install. It could make sense to discuss cost in more detail with Colas and consider this as a viable option. Battery storage and lighting would need to be integrated. Closely follow future deployment on a French Highway.
3) SolaRoad - These have been successfully used for two years on a Dutch Bikepathbut the surface roughness has been compromised. Installation is a major endeavor compared to Wattway modules and will probably dominate cost. There do not appear to be any advantages to using these over Wattwaymodules – **do not pursue**
4) Depending on the demands of the FDOT for controlling the emitted light on the traffic bearing area, the photoluminescent stones may be a cost effective solution. The major uncertainties of these materials is their luminance after long periods of time and their chemical stability in humid environments. Thus, we recommend studying their luminance verses time where day/night is simulated, especially while subjected to moisture. Furthermore, while we do not expect that mechanical wear due to traffic is an issue, this should be validated with experiments.
    a. **Further testing warranted**

i. **test brightness from different manufacturers**
ii. **test prototype with different recipes to study durability**

5) "Solar Streetlight" or off-road solar installation –relatively straightforward solution, especially if lighting not integrated into roadway. Lighting integration into roadway provides nice compromise (BikeScout, or similar FDOT solutions https://fdotwp1.dot.state.fl.us/ApprovedProductList/ProductTypes/Index/493) – **probably most immediate solution**
6) Finally, we believe that thermoelectric modules integrated directly into the roadway surface are probably the most viable approach to meeting all of the demands of the FDOT. If this is of interest to the FDOT the first thing to be completed is a heat transfer analysis of commercially available thermoelectric modules that may be suitable for this purpose. The heat transfer analysis would consider the effect of seasonal variations and daily variations of the solar resource and its impact on the temperature gradient experienced in the asphalt. This should then be integrated with an energy storage analysis to help develop a prototype design. Following the design, the module should be constructed and tested under realistic traffic and weather conditions.

For all of these technologies, a detailed cost analysis should be performed. We expect that the photoluminescent stones are substantially cheaper than either of the aforementioned solutions, followed by the thermoelectric generator and Solar Roadway module.

Summary of Discussion with UF Pavement Expert, Prof. Reynaldo Roque

Prof. Roque does not believe there is anything technically limiting the feasibility of any of the aforementioned technologies. However, he stresses that all of these materials will be subjected to a "very, very tough environment. Durability is the biggest issue. This is even more true at intersections where vehicles are stopping, starting and turning continuously"

- Regarding Wattway modules, Prof. Roque believes the biggest concern will be related to "gluing" the modules to the pavement surface. By doing so this will cause secondary stresses to the modules because of the expansion and contraction of the pavement during day/night. This will increase the stresses the modules are subjected to and could lead to cracking
- Regarding phosphorescent stones, Prof. Roque emphasizes that the asphalt mixture is very sensitive and any new ingredients may cause it to underperform. The artificial ingredients may not adhere well to the solution, especially in the presence of water. One may have to look into different aggregates to blend with to find the optimal recipe. This should be able to be studies using a well thought out study where various ingredients are studied and different binder contents are used. Should be straightforward.
- Regarding friction of tempered glass, Prof. Roque does not believe this is a concern at low speeds where micro-friction is the dominant stopping mechanism. However, at higher speeds where macro-friction is important to remove liquids, this is more of a concern.

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