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Poly Segment Monorail, a conductive method as an alternative for highway electrification.

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Abstract

Vehicles driven on alternative fuels, such as electric vehicles (EVs), are becoming more common while awareness of a diminishing oil supply, oil prices and environmental pollution are increasing. Despite technical breakthroughs, the low energy density in the battery is a problem that limits long distance travel, especially for heavy-duty vehicles (HDV). The low energy density combined with the high cost and the uncertain predictable lifetime of the battery could be estimated to hamper the expansion of the long distance EVs. Electrified highways connecting cities could be one solution to reduce the battery and fuel dependency by supplying electricity continuously to the vehicles. Different technical solutions of electric roads, both conductive and inductive, have been proven functional but are today mainly used in the tram and train industry. Despite the inductive system's major benefit of not relying on a physical contact, an inductive system is not necessarily the best option due to high costs and questionable efficiency. This said, also a conductive system intended for highway transport, despite the mature technology used, is far from problem free. This paper presents the new concept Poly segment monorail (PSM), intended to reduce the drawbacks of the general conductive system for highways. PSM utilizes segments alternating each other at road level, in contrast to traditionally being parallel and sometimes partially buried. With the new design and segments that are galvanically insulated, reduced losses and increase safety could be achieved. The paper also highlights the complexity for the new technology, involving several stakeholder markets, to achieve an international standard, which could be estimated a requirement for such a system to be beneficial and reasonable.

Keywords: Highway electrification, Poly segment monorail, Conductive electricity transfer, Electric vehicle

1 Introduction

With *Peak-oil* approaching or possibly even reached [1] new means of transport, non-dependent on fossil fuels, are making their way into the market. The huge power capacity, enabled by the energy density in the oil, has accustomed and spoiled the automotive-world and raised the competition for new competing technologies, such as the Electric Vehicle (EV) to what is almost seen as a David-Goliath scenario. Exchanging a functional habit for another with lower capacity and a higher price, but better for the common is not within the human nature [2]. Lately, much discussion and development have been focused on increasing the capacity and abilities of the EV to compete with the Goliath. The high efficiency of the electric engine and the possibility to harness the breaking energy are reasons why battery-powered vehicles today mainly are suitable for shorter routes with many starts and stops. However, proposed solutions for long distance travel, both for passenger cars and heavy-duty vehicles (HDV), are often Hybrid EV (HEV) largely due to the EVs Achilles heel, namely, cost and energy storage capacity of the

battery, Table 1. Batteries are estimated to make up as much as 30-50% of the total EV cost with a price between $800-1000/kWh [3]. With a smaller battery the vehicle will not only be made cheaper but also with less weight.

Table 1: Battery capabilities and limitations for short and long distance EVs and HDVs. [5]

EV type	Battery weight	Capability
EV	40kg / 10km	Possible
Long distance EV	1,5tons / 1000km	Not Possible
HDV	200kg / 10km	Possible
Long distance HDV	20tons / 1000km	Not Possible

The supply of electric energy to vehicles, and in particular to the long distance HDV, needs to be maintained at comparable oil levels in order to convert the majority to accept environmentally friendly transport solutions. Without an environmentally friendly option, performance-wise equivalent to the oil-based solutions, a sufficient change in the destructive behavior will be hard to reach. Thereby, targets such as a reduction of green house gases to 80-95 % below 1990 levels by 2050 which is estimated to limit the climate change below 2°C [4] will be hard to reach. With insufficient battery capability, a transfer of energy continuously to the vehicles through the road could be a real alternative (maybe the only one) to fossil based transportation [5]. To reach a mass-market and thereby being beneficial and reasonable, a standard is required to be agreed upon. Candidate solutions also need to be sufficiently safe and efficient for all vehicles as people to justify the otherwise high investment cost.

1.1 Motivation for road electrification

Few solutions exist to greatly increase vehicle range with little environmental impact, cost and with comparable time consumed to fill a tank of diesel, especially for HDVs. One solution might however be to provide electricity along the roads to transfer energy to the vehicle and thereby reduce emissions and the dependency of non-environmentally friendly energy sources.

Different kinds of electric roads have been proposed which utilizes different technical solutions. An example is the overhead wires, common in train infrastructure, to electrify HDV for long distance road transport [6]. This solution has been used for centuries and has few technical problems. However, the overhead wires are located about 5 meters above the road which makes the current collectors unpractical and visually unattractive for smaller personal vehicles and inoperable for the few vehicles reaching higher than 5 meters. With batteries limiting all long distance EV travels and to justify the investment both HDV and smaller passenger vehicles should be able to charge.

Vehicles can utilize battery switching [7] along the road to increase the reaching distance. An empty battery could automatically be replaced by a fully charged in a matter of seconds without the need for the driver to exit the vehicle. This would obviously require a new infrastructure consisting of batteries and battery swap stations along the roads and, especially for long distance HDV, induce frequent stops for battery switching and carrying of a large expensive battery.

Excluding earlier alternatives mainly favouring either HDVs or passenger cars, a remaining possibility is to conduct the electricity continuously from the road underneath the vehicles. Similarities could be seen with the third rail used on many trains or metro lines where overhead wires are not preferred. These electric roads could connect cities and allow the bulk distance to be driven on external power and the short remaining distance on energy stored in potentially smaller on-board batteries optimized for city routes.

The power transfer from the road to the vehicle can be achieved either by induction [8] or conduction [9] among other solutions. Both possibilities have been used successfully for transportation purposes for several years generally within the tram and train market. Without any mechanical contact between the vehicle and the road, the inductive system has many benefits why it could be seen as the most suitable. These are among other, reduced maintenance due to wear, robustness against weather and dirt and no visual impact on the road. Unfortunately it is also combined with high costs [10] and comparable low efficiency [11], especially during high speed. Assuming an inductive solution is not feasible, this paper focuses on the possibilities of a conductive solution where the idea is similar to the Scalextric toy cars following an electrified path in the road. Technical and general requirements for such a road to become reality are furthermore discussed.

2 Conductive rail design possibilities

There are numerous ways to design the rails. In this section, three possibilities are given and discussed.

The first design includes conductive plates placed in parallel at the surface level, see a[1] Figure 1. This enables an easy accessible connection but simultaneously also an increased risk of current leakage when flooded with water. A groove between the rails a[2] could channel the water and thus reduce leakage but it would be risky to cross, especially for motorcyclists due to the height fluctuations and the reduced friction. The construction also adds increased installation cost and requires additional maintenance and

cleaning.

With the rails easy accessible and short intermediate distance in between, the conductive rails could also be dangerous for people walking on the road. To add safety, the rails are segmented in lengths that are only energized when underneath or partly underneath a vehicle. The segment length could be equal to the distance needed, by a vehicle at a certain speed, to avoid an accident with an object on the road. If the segments are not completely covered by the vehicle, a minimum speed is required to activate the electricity. The distance in front or behind a vehicle in motion is argued possible to electrify with equal safety to a normal highway, as it would be impossible to accidently reach the segments without being hit. When no vehicle is present the power will be switched off and thereby could the rail be guaranteed safe.

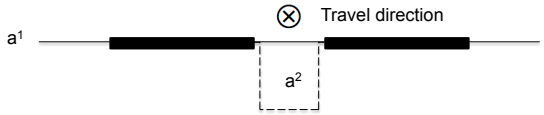

Figure 1: Flat rail (with groove)

The second method is to place the parallel rails underneath the surface, see b^1 Figure 2 [12]. The lowering could also be combined with a separating barrier b^2 and segmented lengths, as in the previously mentioned design, to reduce the risk of electrocution and losses. However it concurrently shapes a place where objects such as stones could jam and damage the current collector and where water, or in worst-case ice, funnels causing additional problems. It has been shown that snow or ice on the rail acts as an electrical insulator, preventing proper contact and current collection and thereby causing severe arcing damaging both the rail and the current collector [13]. A method to avoid or remove any object stuck is therefore needed, which could be hard to guarantee on low to moderately populated roads. This shape puts also high demand on the current collector being able to quickly elevate without getting stuck if the vehicle wobbles or overtakes another vehicle and it is also risky to cross for motorcyclists.

A monorail is utilized in the third design where the segments, instead of being parallel, alternate each other in a single line and are connected to ground in the normal state, see

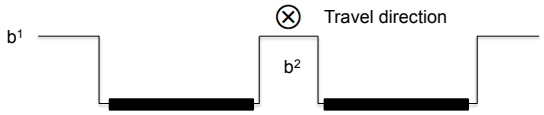

Figure 2: Lowered rail

Figure 3 [14]. When a vehicle is passing, the segment underneath is activated and supplies power similar to the previous designs. However the current is transmitted through a second connection to the ground through the previous or forthcoming segment. After the vehicle has passed, the current is switched off and the segment returns to its normal grounded state. With the short distance between the segments, safety could be argued to be similar to the previous parallel rails at surface level, see Figure 1 but it should be noted that the vehicle shields the short active segment. Furthermore, the current losses when covered with water are reduced due to the smaller area between the segments. The major drawback of this design is the complexity and cost of the system added since each segment individually is controlled through a switch that through precise communication with the vehicle is activated and deactivated in a matter of milliseconds. Test have been made where the switches has been replaced with a flexible conductor foil underneath the rail segments. The foil rises when magnetically activated by the current collector and mechanically activates the segment [15].

Figure 3: Monorail

3 Electric road requirements

The difficulties identified for the previously mentioned options were combined with an additional framework of requirements when the new rail design was to be developed. Overall was an average larger Nordic road, with approximately 5000-15000 vehicles daily in both directions and high demands on reliability, safety and driving experience, seen as the target. Both the personal vehicles as well as HDV should be able to utilize the technology and furthermore since, unlike train rails, roads are not a sealed-off area and

Table 2: Settings, Must haves and Beneficial requirements of an electric road

Settings	Must haves	Beneficial
5000-15000 vehicles daily	Safe for people and animal	Easy current collection
Nordic weather conditions	Low losses	No collection of water and gravel
Ensure safety in a non sealed off area	Less affect on friction	Enable queue driving
High social demands	Minor road impact	

the safety is set to highest priority. Furthermore, since the rail needs to be robust against normal weather and highway wear, any solution relying on mechanically moving parts, such as the flexible conductive foil, was ignored to avoid objects getting stuck or become a subject for sabotage. The important requirements are listed in the Table 2.

A rail at surface level without grooves was preferred since it could not be filled with ice or objects causing damage to vehicles. It would neither require any difficult cleaning methods than what is readily available for a normal road. A rail at surface level was also considered to have the least disturbance to the road that could cause accidents especially for motorcyclists, due to height fluctuations and reduced friction, and easiest to access and maintain. The placement at surface was also seen to reduce complexity to connect to or detach from the rail at high speed.

With the rail placed at surface level the focus of the design was to minimize the danger of electrocution for people and animals on the tack. It was furthermore seen as very beneficial if the safety could be maintained with the power left on by accident or when the vehicle was standing still in a queue. A minimum speed and a safety distance were otherwise required in order to activate the segments underneath the vehicle whereby a long-lasting queue could slowly discharge batteries without alternative power source.

Additionally a design that reduced the current leakage during flooding without groves was also targeted. This is especially crucial in countries where salt is used on the roads to minimize freezing since it also enhances the conductivity of water.

4 Poly segment monorail concept

The following technical concept is called the Poly Segment Monorail (PSM), developed to overcome the difficulties previously discussed. It is based on segments alternating each other in a single line, instead of the more common parallel rails. Similarities can be seen with the previously discussed monorail; however, instead of only being either energized or connected to earth, the PSM segments are also galvanically insulated compared to the next two segments on each side. An analogical comparison is three batteries with their conductive terminals alternated according to the pattern in the Figure 4. No current will be conducted to any adjacent segment due to the galvanic insulation.

A radio communication is established between the rail and the vehicle. The vehicle transmits a signal that the current collector is correctly positioned and the vehicle is ready to receive current. This communication allows only the segments underneath the vehicle to be energized. With the energized segments covered, people are shielded from the electric current even when the vehicle is moving at low speed.

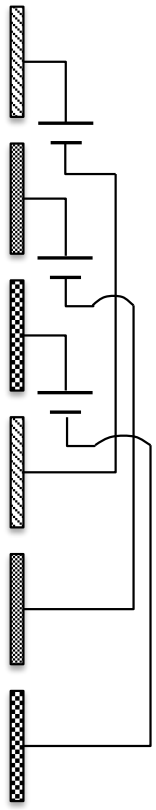

Figure 4: Analogical explanation of PSM

Since the segments are separated and placed in the longitudinal direction, dual current collectors are needed to continuously collect and return the current, one in the front of the vehicle and the second in the rear, see Figure 5. The distance between these needs to be fixed and standardized equal to the distance between two potentially different segments. Current collectors that are placed with an offset from this standard will result in improper connection and arcs.

Two insulated conductive plates are located at each current collector, one in each end. Both frontal conductive plates are activated once a connection to the segments below is established through radio communication. With the speed of the vehicle and the length of the current collector known, the coupled rear conductive plates can be activated as they enters the same segment as the frontal conductive plates. The current withdrawal through the front connected conductive plates is deactivated until a connection to the forthcoming segment is secured.

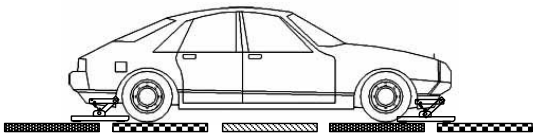

Figure 5: Car on Poly segment monorail

Because of the multiple connections for current withdrawal one can be switched off without generating arcs since the current will be conducted though the second connection. The expected cost added to an EV equipped to receive the high current from the road is $1000 [16] per current collector. This cost, and weight, could be compared to the $1000 per kWh battery [3], which could be reduced to a size suitable for city routes.

The segments are approximately 0.8 meter long and separated with 0.2 meter spacing in between. Consequently, three segments,

spanning 3 meters, are able to room underneath an average small car. The power supplied from one connection could be limited to between 75-150kW and additional peak energy needed should be transmitted from the on board battery. A longer vehicle with greater power need could use an additional one or two pairs of current collectors and thereby double or triple the maximum current withdrawal to a maximum of 450kW due to the separated power supplies. The components needed inside the road could therefore be made capable of handle only a third of the power compared to another system providing the total amount of 450kW through a single connection. Furthermore, since the length between two segments that has a potential difference is more than 2 meters the risk of being accidentally electrified if the current is unintentionally activated without any vehicle present is additionally reduced.

In the monorail design with the shorter lengths together, the conductive area between the segments will be effectively reduced, compared to other designs at surface level, and thereby the leakage that could be somewhat supposed to be linear to that area. This assumes that the distance between the segments as well as the water level is constant. For example a 0.1 meter wide monorail, with the previous assumptions, has 99% reduced intermediate area in comparison with two parallel 10 meter rails. Additionally, with three spaces between the conductive segments the PSM will have approximately three times the resistive length, compared to another comparable monorail, assuming that there is no resistance in the intermediate segments. Furthermore, the current collectors will frequently passage over the area between the conductive segments and will sweep and heat water and ice away, thereby reduce the leakage even further without the need for drainage between the rails.

4.1 Switching mechanism and choice of current

A major requirement difference for solutions intended for highway usage, compared to any used on trams, is the capability to handle the increased frequency of vehicles. The high vehicle density requires switches to be able to react to and withstand several vehicles per minute for many years, which excludes mechanical switches. Furthermore, the losses acceptable for the few trams or trains will be much larger in a similar solution intended for road bound vehicles, which means that it once again is important to reduce the losses.

The switches need to be able to turn off the current more than 5000-15000 times per day for several years without maintenance. To reduce the strain, the switching should occur when there is no power load. That means the power should be turned on slightly before a vehicle enters a segment and the power from the previous segment should be turned off when the forthcoming segment is supplying the power. Due to the very fast and frequent switching are semiconductors without mechanical components a feasible technique to use. A semiconductor has generally a lower cost, is much faster and has a greater durability compared to mechanical switches. A dangerous situation could occur with a faulty switch that fails to deactivate an active segment after the vehicle has passed. Additional overhead control with possibility to both detect faults and immediately deactivate switches or sections of segments remotely in order to maintain safety and allow maintenance is therefore proposed.

With the design implying a short distance between the switches, one for each segment, they are probably more economically placed inside the rail to reduce cabling and roadwork. In another scenario, especially for lower dense roads, could segments within approximately 20-100 meters be connected into sections and controlled with only three switches, one for each phase, to reduce the cost, see Figure 6. Since the vehicle will not cover the energized sections, the safety of the system can be questioned. To compensate for the reduced safety, a minimum speed of the vehicle should be declared to activate the sections, similar to the designs previously explained, that will make the electric road equally safe as a comparable normal road. Switches, to control the electricity, could in this case beneficially be placed in the roadside to ease installation and maintenance. With minimum complexity in the road the installation in the road could also be made cheaper and more robust. With longer electrified sections, additional switches are also needed inside the vehicles since the current is constantly on.

One-phase alternating current (AC) could be beneficial, since it allows the current to be switched off during the zero voltage passage causing less strain on the switching mechanism.

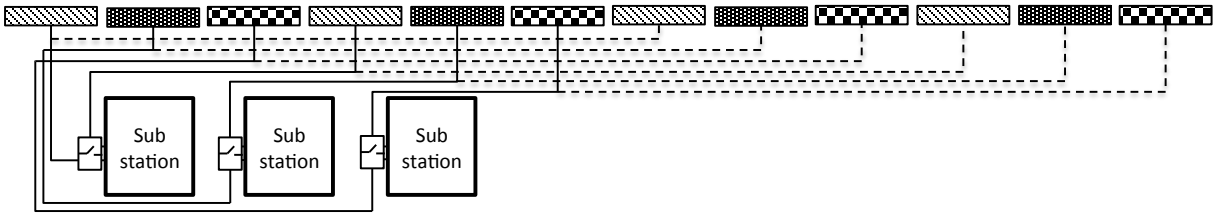

Figure 6: Three phased AC used to providing longer sections of segments though substations

The normal frequency of 50Hz is however to low with the short segments and high speed vehicles. The common three-phase AC system could also, after being galvanically insulated, be used to provide current to the road through sub stations and without additional rectifiers otherwise needed. A skew load could theoretically occur if too many vehicles would simultaneously connect to the same phase but this is highly unlikely with the short segments and the many vehicles with their independent speed. The major drawback with a single phase AC system is the rectifier needed in the vehicle, which most likely will be impractically large and expensive.

A system using direct current (DC) is more simple and robust and is also the most commonly used in similar systems. Apart from being harder to switch off during load, a DC system at road level could also, when combined with water and salt, be exposed to electrolysis that could erode the rails or any metallic structure along the road. Due to the relatively infrequent passage of trams, connected for a short period of time to any exposed segment, no significant electrolysis is dealt to the road. However low voltage DC communication used in train rails has proven causing electrolyse problems where cars are frequently crossing the rails. AC significantly reduces the electrolyse that otherwise will occur during rainy days, especially with salt as electrolyte in combination with frequent passage of vehicles.

4.2 Communication between rail and vehicle

In the harsh environment underneath the vehicle, radio communication could be used between the vehicle and the rail. For example the upcoming 802.11p standard for vehicle to vehicle and vehicle to road communication [17]. The standard has short connection establishment delays and high-speed communication that is crucial during the short intervals the vehicle communicates with the rail to indicate presence and speed to activate the proper segment. The signal is weak not to activate a distant segment and it is coded to avoid the road to be turned on by accident [9]. Not before the vehicle has appropriate speed and with the current collector firmly placed on the rail a signal will be transmitted.

There are many examples of automatically guided vehicles but fewer with enough safety to be used on highways. A fixed metallic rail in the road, serving as guidance, would increase the possibility of the vehicle to be automatically controlled laterally with sufficient safety. This could also simplify the current collector that does not have to compensate for the driver's poor ability of precise positioning above the rail. Other techniques, such as lasers in combination with the continuous communication with the rails, could enable automatic braking if the vehicles in front, or several vehicles ahead, for any reason suddenly reduce the speed. The rail could also be used to share other information between vehicles such as traffic information or electricity price and billing with the electricity supplier.

The lifespan for an electric road, not the surrounding asphalt, could be estimated to be much longer than the lifecycle of an average car. It could therefore be argued that any costly technology such as sensors and communication equipment, not affecting the safety, should be placed inside the car where technology can evolve and scale effects be achieved. Technology installed in the road has a great chance to become outdated within its lifetime and therefore suggested limited to the radio antenna and possibly switches. What further adds to the reasoning is that with less technology in the road the construction costs will be reduced and a greater implementation of electrified road could be made faster. It is important that there is a minimum safety built into the road such as capability to disable the current where there is no vehicle present and also monitoring the switching function sine the safety should not be dependent solely on the vehicle.

4.3 Poly segment monorail difficulties

There are, in the light of the many benefits, also difficulties to overcome with the PSM technique. Many are more or less shared between all conductive solutions and described earlier such as to gain safety, robustness and low cost while some may most likely not yet have been discovered. There are however some issues that, as a direct cause of monorail design with the many segments and galvanic insulation, need additional thought. First, there are three times as many switches and cabling required due to the galvanically insulated current, that although not a technical problem could be a significant cost. Secondly, due to same cause, the distribution chain of energy to the rail needs to be galvanically insulated and separated in to three phases. Despite being a cost, galvanically insulated distribution of energy could also become a danger if potential difference to ground occurs. The effects and additional safety in this matter needs further attention. Third is the dual or more current collectors combined with switches needed inside the vehicle. Additional packaging and technical complexity inside the vehicle are inevitable but other factors such as customer acceptance of the increased maintenance or increased cost are additionally important.

The additional cost for the more complex construction of the PSM needs to be compared to the reduced total cost for current losses and the value of the ability to allow queue driving and increased safety compared to other rail designs.

5 The greater vision

Regardless of the technology considered the best, whether it is inductive or conductive or

based on cost, safety or reliability, the advantages and opportunities of such a system is likely to be very large. This is especially true since it allows the low cost long distance electric mode operation similar to a battery EV without the cost, wear, efficiency losses, and weight of a large battery [16]. A solution that is both cheaper to use, more environmentally friendly, more efficient and have longer distance capacity compared to traditional combustion vehicles will have the ingredients to be commercially widespread.

The problem is not solely linked to PSM or any other conductive or inductive solution but it is shared between all fixed and potentially widespread technologies dependent on additional technological changes. It could be seen from the hen and the egg perspective where a large-scale deployment of rail not will be approved before there is a standardized vehicle able to use the rail. Vehicles will neither be broadly demanded before the infrastructure exists. Furthermore, with the potentially few early EVs capable of reaching the current from the road and the great upfront cost to install and maintain the rail, the payback time and risk are likely to be extensive.

5.1 A common agreement

A joint agreement at national or continental level that spans the vehicle manufacturers, road agencies and electricity suppliers is required to gain wide market acceptance and achieve a meaningful benefit. Crucial to avoid adaptive current collectors or adapters and enable a greater expansion is the standardization of interface, both physical and wireless, between the vehicle and the road as well as the voltage level. Supportive technologies both on the vehicle and in the road should on the other hand be possible to enhance and upgrade with backward compatibility.

There is for the time being no joint vision how the EU requirements could affect an electrification of the roads [6]. New concepts of mobility facilitated by efficient and green freight corridors and development of appropriate infrastructure to be developed are however in line with the European directives [4]. A major presented goal is the reduction of green house gases of 80-95% below 1990 levels by 2050 to limit the climate change below 2°C. These kinds of targets are probably beneficial but it might be more effective to forcing a change into the market, like the regulations made by the CARB [18] where zero emission vehicles are forced into the market. A grand scale implementation of an electric road capable of supplying energy equal to what today is made possible by the oil could be a real alternative (maybe the only one) to fossil based transportation [5] and thereby eliminating the green house gasses from highway transports.

6 Suggested future research

Additional research is needed to estimate an overall lifecycle cost comparison between a PSM monorail and an equal design of parallel rails and therefore suggested as future research. This benchmark should further be complemented with comparable data for an inductive system capable of transmitting current in acceptable highway speed. Crucial in such a study is not only the component cost throughout the electrical distribution and communication, but also losses, maintenance, safety and reliability.

The greater vision for electrification of roads has previously been discussed but the critical ingredients for any concept to be realized should further be investigated. This research should extend beyond the benefits and drawback between the systems but also include customer acceptance and user friendliness. What is further worth noting is the regulations that does not yet exists for any such system that could be beneficial or prevent further expansion. How the regulations and a possible introduction of electric roads are affected by a diminishing supply of oil should also be taken into consideration.

7 Conclusion

Electric roads allow virtually unlimited pure electric reach without the need to stop and recharge. Many different techniques, both conductive and inductive, are possible. A monorail conductive solution, called Poly Segment Monorail or PSM, is suggested in the paper, which is efficient in terms of losses, road impact and possibility to withstand weather and dirt. This solution is capable of supplying both HDV as well as passenger vehicles, which is argued necessary justifies the infrastructure investment.

The paper discusses the benefits of the PSM technique, with galvanic insulated segments where electricity can only be conducted between every third segments. Due to the long distance between the conductive segments, losses as low as a third compared to other monorails could be achieved without the need for drainage. The current is activated underneath the vehicle through a coded radio signal and with the vehicle as a shield could queue driving be enabled without risk for humans on the road. A reaching distance greater than 2.2 meters between the conductive segments also reduces the accidental risk for electrocution if the voltage is unintentionally faulty left on. The three insulated power sources allows the maximum current supplied between two segments to be reduced to a third compared to any solution with two parallel rails. With less current transferred, both losses and rail costs are likely reduced. With a multiple of two current collectors additional per vehicle, the same power output requirement from the rail could be maintained with a third of the component capacity compared to a similar design with the

same power output.

The many segments with a high density of passing cars will demand very tough switches and precise communication which both needs additional research. The up to three times as many switches and galvanically insulated power supply system could be seen as the most technically complex obstacles for the PSM to be safe and reliable thus realized.

Perhaps the biggest overall difficulty is however to agree upon a standard that gains market acceptance and thereby achieve a meaningful benefit. Cooperation between countries together with vehicle manufacturers, road agencies and energy suppliers could be seen as a long term prerequisite. The complication also includes the absence of regulations and future requirements for this area of application. Targets such as the 80-95% reduction of 1990 levels of greenhouse gas emissions within the EU before the 2050 could be the driving force. Electric roads could be a real environmentally friendly alternative to fossil based transportation and thereby achieve this target.

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