

Structural and Electrical Integration of Dynamic Inductive Charging Pads into Asphalt Pavements

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Abstract—Dynamic inductive charging can transfer traction energy to electric vehicles while they move, but a roadway installation succeeds only when the electromagnetic system and the pavement are designed as one asset. This paper develops an integrated design and assessment framework for segmented transmitter pads embedded in asphalt pavement. Published results from full-scale accelerated pavement testing, a 230 kW Purdue and Indiana Department of Transportation pilot program, Utah State University embedment studies, Rutgers electromagnetic pavement simulations, Oak Ridge National Laboratory high-power experiments, and the Detroit public wireless roadway are synthesized. A transparent analytical case then evaluates a 200 kW, 85 kHz lane using energy, efficiency, thermal, interface-strain, drainage, maintainability, and safety criteria. At the 91.31% efficiency reported for an ORNL 120 kW experiment, a 1 km active lane transfers about 3.65, 2.19, and 1.56 kWh to a vehicle traveling at 50, 83, and 117 km/h, respectively. The analysis identifies the asphalt-to-module interface, water management, lateral alignment, and heat rejection as the controlling integration details. The proposed design uses a sealed replaceable carrier, a minimum practical asphalt cover selected by mechanistic analysis, staged coil activation, distributed sensing, and acceptance tests that combine pavement response with electrical performance. The result is a reproducible method for moving from a laboratory coupler to a maintainable road segment without overstating the available field evidence.

Index Terms—asphalt pavement, dynamic wireless power transfer, electric road system, inductive charging, pavement instrumentation, structural integration, thermal management, wireless electric vehicle charging.

I INTRODUCTION

Road transport electrification is increasingly constrained by charging time, vehicle mass, and the concentration of high-power demand at fixed stations. Dynamic wireless power transfer (DWPT) addresses a different use case: selected road segments energize a receiver beneath a moving vehicle. The concept can support predictable freight corridors and transit routes, where utilization is high enough to justify infrastructure that is more complex than a conventional pavement. The engineering difficulty is not simply transferring power across an air gap. The transmitter must survive compaction, wheel loads, moisture, thermal cycles, deicing chemicals, utility work, and maintenance interventions while preserving the flatness and skid resistance expected of an asphalt surface.

Electrical and pavement designs are strongly coupled. A deeper transmitter is structurally protected but has weaker magnetic coupling. A stiff carrier protects ferrite and windings but creates a modulus discontinuity that concentrates strain at its perimeter. A thicker asphalt overlay distributes tire stress yet increases the magnetic gap and dielectric losses. Higher power reduces the active roadway length required for a given energy target, but it raises inverter current, coil loss, and pavement temperature. Treating these decisions separately

produces a design that is efficient on an electrical bench or durable in a pavement model, but rarely both.

This paper therefore asks a practical question: how should a segmented dynamic inductive charging system be integrated into an asphalt pavement so that its electrical function, structural life, drainage, safety, and maintainability can be verified together? The answer is developed from published full-scale work rather than an invented experiment. Purdue University and the Indiana Department of Transportation designed a three-phase 230 kW pilot and constructed flexible and rigid accelerated pavement test sections [1]. Halling and Gardner evaluated direct embedment and cyclic structural loading at Utah State University [2]. Wang and co-workers quantified the electromagnetic effect of embedment depth and partially magnetized pavement [3]. ORNL validated a 200 kW design at 120 kW and 91.31% DC-input-to-battery efficiency [4]. Detroit placed a quarter-mile public segment into operation in November 2023 [5]. These sources provide complementary structural, electrical, and deployment evidence.

The contribution is an integrated framework with five outputs: a constructible cross-section; a coupled set of performance equations; a published-data case analysis; a verification matrix

that connects each failure mechanism to a measurable acceptance test; and a staged implementation plan. All values generated in the case analysis are identified as calculations or sensitivity assumptions. Published values retain their original scope and are not presented as measurements made by the author.

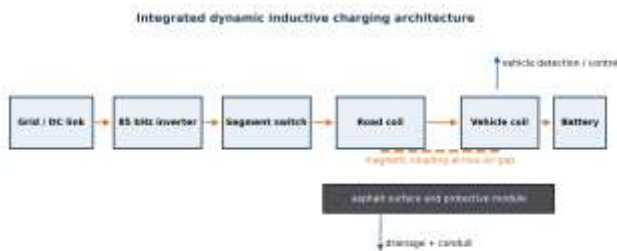


Fig. 1. Energy, control, pavement, and vehicle subsystems in a segmented dynamic inductive charging lane. Original schematic.

II PUBLISHED EVIDENCE AND RESEARCH GAP

A Electrical demonstrations and standards

Resonant inductive systems use compensated primary and secondary coils to exchange power at a controlled frequency. High-power demonstrations show that the conversion chain can be efficient when the coils are aligned and the compensation network is tuned. ORNL reported 120 kW delivered to a battery at 91.31% efficiency while validating an architecture intended for 200 kW operation [4]. Earlier ORNL demonstrations reported 120 kW at 97% across a six-inch air gap, although that percentage described a different laboratory boundary and should not be combined directly with the DC-to-battery value [6]. The difference illustrates why every efficiency claim must state its measurement boundary.

SAE J2954 establishes interoperability, electromagnetic compatibility, field exposure, safety, and test requirements for stationary light-duty wireless charging, while SAE J2954/2 addresses higher power levels for heavy-duty vehicles [7], [8]. A dynamic lane adds segmentation, vehicle detection, rapid energization, handover, billing, and traffic-speed variation. The standard frequency neighborhood around 85 kHz is useful for component design, but a roadway agency still needs project-specific requirements for civil interfaces, isolation monitoring, drainage, repair, and traffic control.

B Pavement integration studies

Utah State University tested direct embedment methods and monitored electrical properties through construction. The study also simulated tensile stress and applied cyclic loads to embedded samples, establishing that electrical performance must be tracked during structural testing rather than checked only before and after installation [2]. The work identified the encapsulation and pavement interface as design objects, not incidental packaging.

Purdue and INDOT advanced the evidence to full-scale flexible and rigid pavement sections. Their program used falling weight deflectometer testing, static loading, thermal activation, accelerated traffic, and finite-element calibration. The reported 2024 project formed the basis for a quarter-mile, 230 kW testbed on US-231 [1]. Subsequent peer-reviewed work reported 75,000 accelerated pavement passes without visible surface distress, although the embedded unit changed

strain, deflection, and rutting patterns [9]. The absence of visible distress after a finite test is encouraging; it is not equivalent to a full service-life guarantee.

Calibrated finite-element analysis by Cruz et al. showed acceptable agreement when loads were applied over full-depth hot-mix asphalt, but discrepancies near the charging-unit-to-HMA interface were sensitive to the assumed bond condition [10]. That finding is central to design: the interface cannot be modeled as perfectly bonded by default. Construction tolerances, tack coat quality, thermal mismatch, moisture, and repeated shear determine its actual behavior.

C Field demonstrations

Michigan opened a quarter-mile segment of 14th Street in Detroit for public-road testing in November 2023 [5]. The road energizes compatible vehicles through embedded coils and provides a valuable operational example involving real traffic, utilities, weather, and agency coordination. Its primary value for this paper is implementation scale; public information does not provide a complete long-term pavement distress dataset. Other demonstrations and feasibility studies show that heavy-duty fixed-route applications are plausible early markets because high utilization distributes infrastructure cost and reduces the uncertainty of receiver compatibility [11].

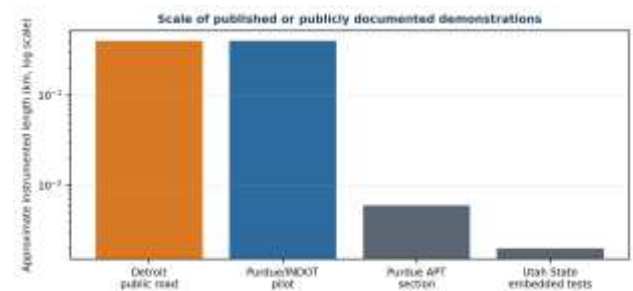


Fig. 2. Approximate scale of representative documented activities. Short test sections are plotted on a logarithmic axis and should not be read as equivalent service environments.

TABLE I
EVIDENCE USED AND ITS LIMITS

Source	Evidence used	Limit
Purdue INDOT [1]	230 kW pilot design; flexible and rigid APT sections; quarter-mile testbed	Project report; long-term highway service data remain limited
Utah State [2]	Direct embedment, electrical monitoring, cyclic structural loading	Material and specimen configuration is project specific
Rutgers [3]	Efficiency versus embedment depth and magnetic pathway	Finite-element electromagnetic study, not field energy metering
ORNL [4]	120 kW validation at 91.31% DC-to-battery efficiency	Laboratory system and alignment conditions
Detroit MDOT [5]	Quarter-mile public-road deployment	Public page does not report a complete performance time series
Moncada et al. [9]	75,000 APT passes and pavement response observations	Accelerated controlled loading differs from full climate and traffic exposure

The research gap is therefore an integration method that connects these different evidence types. Electrical papers often

optimize coupling and converters with a simplified mechanical enclosure. Pavement papers often represent the charging unit as a stiff inclusion with limited detail about switching, loss, and fault modes. Field announcements establish feasibility but rarely publish enough structural and electrical time-series data for independent life prediction. The present framework makes those interfaces explicit and proposes a monitoring dataset that can reduce this gap during future pilots.

III INTEGRATED SYSTEM ARCHITECTURE

A Segmented transmitter arrangement

A dynamic lane should energize only the short segment under an authenticated receiver. A roadside or median power cabinet converts grid power to a regulated DC link. Modular inverters excite successive primary coils through solid-state switches. Vehicle detection combines a low-power presence channel with receiver communication so that an empty segment remains de-energized. The sequence is detection, authorization, insulation check, soft start, closed-loop power regulation, handover to the next segment, and rapid shutdown when the receiver leaves or a fault is detected.

Segmentation limits stray field exposure and standby loss, but it introduces more joints, switches, and control dependencies. Electrical module length must therefore be coordinated with construction joints and repair boundaries. Long continuous coils reduce the number of cabinets but are hard to replace and may produce larger power ripple as a receiver enters and leaves the energized region. Short modules improve serviceability but increase terminations and roadside equipment. For the analytical case, a 2 m coil pitch grouped into 20 m independently isolated zones provides a useful balance; this is a design assumption, not a universal optimum.

B Pavement carrier and surface system

The recommended civil concept is a sealed, replaceable charging carrier installed within a milled recess, supported by a high-stiffness bedding layer, surrounded by compatible asphalt, and covered by a renewable wearing course. The carrier protects conductors and ferrite from aggregate impact and compaction. Its upper face should avoid abrupt corners because sharp stiffness transitions attract strain. Tapered shoulders, a roughened or keyed perimeter, and a verified bonding system reduce shear concentration. Longitudinal placement should keep the most critical edges away from the dominant wheel path where practical.

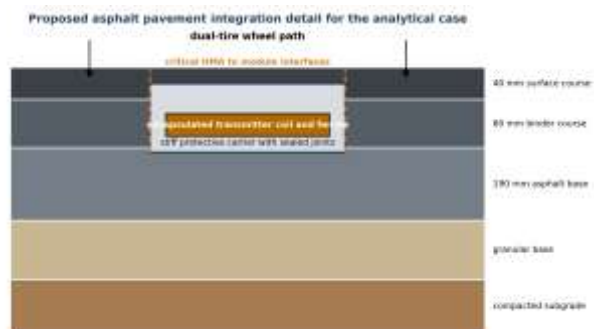


Fig. 3. Proposed integration detail used for the analytical case. Dimensions are design inputs and require project-specific mechanistic verification.

Drainage is treated as a primary subsystem. The recess must not become a bathtub beneath an impermeable carrier. Crossfall, sealed penetrations, lateral drainage paths, and accessible junction boxes are required. Conduits should enter from the side or bottom through strain-relieved glands. A leak-detection conductor or humidity sensor in each zone provides early warning. The wearing course must remain replaceable without damaging the coil carrier; survey control and as-built depth records are therefore essential before milling.

C Sensing and data architecture

Each zone should record inverter input power, receiver-reported output power, coil current, compensation voltage, frequency, phase angle, insulation resistance, enclosure temperature, surface temperature, activation count, active duration, fault code, and estimated lateral offset. Civil monitoring should add surface profile, rut depth, crack mapping, moisture, interface strain at selected research sections, and periodic deflection testing. A synchronized clock allows an engineer to relate thermal and electrical events to traffic and pavement response.

The minimum retained operational record is one aggregate row per vehicle passage plus high-rate fault snapshots. Storing all waveforms continuously is unnecessary and expensive, while retaining only monthly energy totals hides the onset of detuning or moisture problems. A practical hierarchy retains one-second operational summaries, event-triggered waveforms, daily health indicators, and seasonal pavement surveys. The asset identifier must link the electrical zone to the road chainage, lane, pavement layer, construction lot, and repair history.

IV COUPLED DESIGN METHOD

A Energy transfer

For a vehicle moving at constant speed, the useful energy obtained from an active lane is the product of battery-side power and exposure time. If the controlled power is specified at the transmitter input, efficiency must be included. With active length L in kilometres, speed v in kilometres per hour, input power P_{in} in kilowatts, and end-to-end efficiency η , the energy delivered to the battery is

$$E_b = \eta P_{in} L / v \text{ [kWh]} \quad (1)$$

Equation (1) is deliberately simple and is suitable for screening. A detailed dynamic model replaces constant efficiency with a function of lateral offset, air gap, coil overlap, temperature, battery state of charge, and switching transitions. The average power demanded by a road zone also depends on traffic arrival and compatible-vehicle penetration. If n vehicles occupy independent energized segments, the instantaneous feeder demand is approximately the sum of their input powers plus cabinet auxiliaries.

$$P_{zone}(t) = \sum P_{in,i}(t) + P_{aux} \quad (2)$$

B Resonant coupling and loss

A two-coil resonant model uses primary and secondary inductances L_1 and L_2 , mutual inductance M , coupling coefficient k , compensation capacitors, and the reflected load. Mutual inductance decreases with vertical and lateral separation. At angular frequency ω , resonance is maintained when the selected compensation network cancels

the dominant reactive term. For a first design check, coupling is written as

$$k = M / \sqrt{(L_1 L_2)} \quad (3)$$

Copper, semiconductor, ferrite, shielding, and pavement-related losses become heat. The loss assigned to the road module is not simply one minus system efficiency because some loss occurs on the vehicle. The thermal model must allocate each component loss. A conservative pavement calculation can apply measured road-side loss as a volumetric or surface heat source in the carrier and surrounding asphalt. Temperature changes resistance and detunes the resonant network, so thermal and electrical calculations should iterate.

$$\dot{Q}_{\text{road}} = P_{\text{in}} - P_{\text{gap}} - P_{\text{cabinet}} \quad (4)$$

C Structural response

The pavement is a layered viscoelastic system containing a comparatively stiff inclusion. Screening begins with tire contact pressure, axle configuration, seasonal asphalt modulus, layer thickness, carrier modulus, interface shear transfer, and subgrade support. The principal indicators are tensile strain at the bottom of asphalt, vertical compressive strain at the subgrade, shear and opening at the carrier interface, and surface deflection. A finite-element model should use contact and cohesive alternatives at the HMA-carrier boundary because published calibration work shows that the assumed bond condition can dominate the local response [10].

The paper uses a normalized interface strain index rather than inventing absolute microstrain values. The index compares each case with a fully bonded reference at the largest considered cover. It is a screening metric for ranking cover and bond condition, not a fatigue-life prediction. Final design requires locally calibrated asphalt modulus master curves, thermal properties, traffic spectra, and transfer functions between strain and damage.

D Thermal response

Road-side electrical loss, solar radiation, air temperature, vehicle shading, and asphalt conductivity determine temperature. A lumped model is useful for control design, while a two- or three-dimensional transient model is needed near the module edge. The lumped temperature response is

$$T(t) = T_a + R_{th} P_{loss} [1 - \exp(-t/(R_{th} C_{th}))] \quad (5)$$

Temperature limits should protect the asphalt binder, potting compound, ferrite adhesive, cable insulation, and power electronics. A single absolute trip temperature is insufficient because a rapid rise can signal a local fault before the absolute threshold is reached. The controller should therefore use both temperature and rate-of-rise limits, reduce power before shutdown, and lock out a wet or insulation-failed zone.

E Reliability and maintainability

A roadway charging system is a series of independently bypassable assets. A failed module should reduce available charging length rather than close the lane or disable the corridor. Cabinets require safe isolation, visible lockout, arc-flash labeling, and accessible test points outside live traffic where possible. The civil detail should permit surface-course renewal and targeted module replacement. Spare conduit, standardized connectors, and interchangeable modules are

more valuable over a road life than small gains in initial electromagnetic optimization.

V ANALYTICAL CASE DEFINITION

The case represents a one-kilometre active segment in an urban freight corridor. It is not a claim about the proprietary Detroit or Purdue hardware. The nominal transmitter input is 200 kW per occupied vehicle, chosen to match the design class reported by Xue et al. [4]. Frequency is 85 kHz. Nominal efficiency is 91.31%, anchored to their 120 kW validation. The pavement comprises a 40 mm surface course, 60 mm binder, 190 mm asphalt base, granular base, and subgrade. A sealed carrier lies below the renewable surface course. Twenty-metre zones are independently protected. The analysis varies speed, active length, lateral offset, cover, bond condition, and road-side loss.

TABLE II
BASE CASE INPUTS

Parameter	Base value	Status
Frequency	85 kHz	Design input consistent with common WPT practice
Input power per vehicle	200 kW	Analytical design level
Nominal efficiency	91.31%	Published ORNL validation anchor [4]
Active length	1.0 km	Analytical case
Zone length	20 m	Design assumption
Coil pitch	2 m	Design assumption
Surface course	40 mm	Proposed renewable layer
Total asphalt thickness	290 mm	Analytical pavement
Ambient temperature	35 °C	Hot-weather scenario
Lateral offset range	0 to 0.50 m	Sensitivity range

A Published performance anchors

Figure 4 deliberately places unlike evidence side by side to show the range of boundaries. The ORNL bar is an experimental end-to-end result from primary DC input to vehicle battery. The Rutgers bars are modeled WPT efficiencies for conventional and partially magnetized pavement at two embedment depths. They answer different questions. At 0.10 m depth, the magnetized pathway improved the reported value from 70.1% to 71.5%; at 0.40 m, it improved the value from 27.6% to 39.9% [3]. These values do not imply that ordinary asphalt causes ORNL performance to fall to 70%; coil geometry, air gap, model boundary, and other assumptions differ.

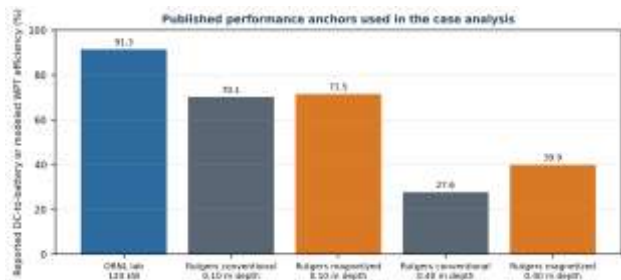


Fig. 4. Published electrical performance anchors. Bars have different system boundaries; direct ranking would be misleading. Data from [3] and [4].

The important integration result is directional: burying a transmitter deeper can impose a severe electrical penalty, and magnetic material can partially recover coupling under a specific geometry. However, magnetic aggregate or ferrite pathways must also meet asphalt workability, moisture, fatigue, temperature, and recyclability requirements. The most reliable near-term design is usually to minimize unnecessary nonmagnetic separation while protecting the coil with a replaceable structural carrier and wearing course.

B Energy delivered per pass

Equation (1) was evaluated for active lengths from 0.25 to 2.0 km and speeds from 30 to 90 km/h. At 200 kW input and 91.31% efficiency, a 1 km segment delivers 6.09 kWh at 30 km/h, 3.65 kWh at 50 km/h, 2.61 kWh at 70 km/h, and 2.03 kWh at 90 km/h. The result scales linearly with active length and power. At highway speed, meaningful energy requires either longer active length, higher power, or repeated segments.

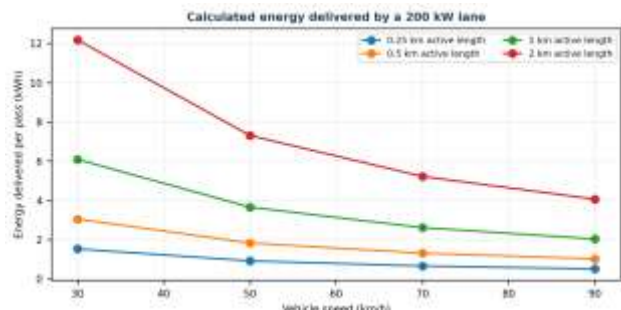


Fig. 5. Calculated energy per pass from (1), using 200 kW input and 91.31% efficiency. Values are analytical, not field measurements.

**TABLE III
CALCULATED ENERGY AND HEAT FOR A 1 KM ACTIVE LANE**

Speed	Exposure	Battery energy	Total loss
30 km/h	120 s	6.09 kWh	0.58 kWh
50 km/h	72 s	3.65 kWh	0.35 kWh
70 km/h	51.4 s	2.61 kWh	0.25 kWh
90 km/h	40 s	2.03 kWh	0.19 kWh
110 km/h	32.7 s	1.66 kWh	0.16 kWh

The total-loss column uses the difference between input and battery energy and therefore includes both road-side and vehicle-side losses. It must not be applied entirely as pavement heat. A component-calibrated thermal model should allocate cabinet, primary winding, ferrite, shield, air-gap, receiver, rectifier, and battery-conversion losses separately.

C Lateral offset sensitivity

Vehicle wandering changes mutual inductance rapidly. Rutgers reported that efficiency fell with lane deviation and that the advantage of a magnetized pathway could disappear by 0.5 m offset for the studied configuration [3]. The present sensitivity curve uses an exponential penalty anchored to the ORNL nominal efficiency. Its coefficient is an assumption chosen to illustrate control consequences; it is not fitted to proprietary hardware. At 0.15 m offset, the assumed model gives approximately 69.7% efficiency. Such a reduction increases grid energy and heat for the same battery-side power, or reduces received power if input current is limited.

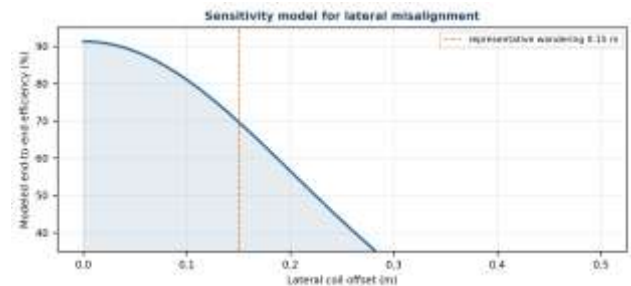


Fig. 6. Assumed misalignment sensitivity used to demonstrate the integrated control method. The functional form requires calibration for the selected coupler.

The result supports three requirements. First, lane markings and geometric design should keep the receiver near the electrical centerline. Second, the controller should estimate coupling before commanding full power and should reduce power during poor alignment instead of maintaining battery power at excessive current. Third, the civil designer should not compensate for weak lane keeping by making the magnetic assembly excessively wide without checking edge strain, cost, and inactive copper loss.

D Thermal sensitivity

Figure 7 applies (5) with a 35 °C ambient temperature, a 36 min time constant, and an illustrative thermal resistance of 0.55 K/kW for the combined local control volume. The three loss values represent operating states rather than measured module losses. The plot shows why duty cycle matters: a single vehicle creates a short pulse, while dense traffic can approach continuous equivalent activation. A thermal controller should use a moving duty-cycle estimate and should distribute power across available zones when traffic and feeder capacity permit.

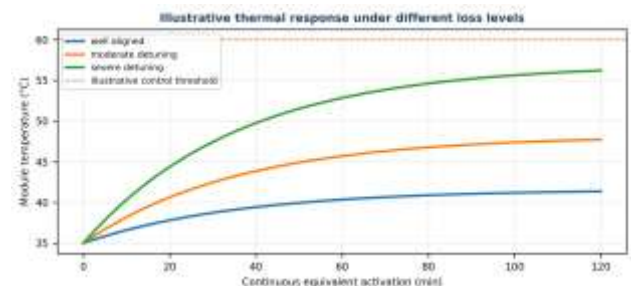


Fig. 7. Illustrative lumped thermal response. Loss allocation and thermal constants must be obtained from prototype calorimetry and field instrumentation.

At 40 kW local loss, the illustrative model crosses 60 °C after roughly 29 minutes of equivalent continuous operation. The correct response is progressive derating, not waiting for a hard

trip. Surface-temperature limits should also consider rutting susceptibility of the local mix. The module should use low-loss conductors, thermal paths that spread rather than concentrate heat, and potting materials whose conductivity and thermal expansion remain stable after water and freeze-thaw conditioning.

E Structural screening

Figure 8 ranks the combined influence of cover and interface condition. Increased cover distributes wheel load and lowers the normalized interface strain index, but it also increases magnetic separation. Partial bond raises the index by 25% in the screening model; a debonded edge raises it by 62%. These multipliers are assumptions intended to force evaluation of interface uncertainty. They are consistent with the published observation that numerical accuracy near the charging-unit interface depends strongly on bonding representation [10].

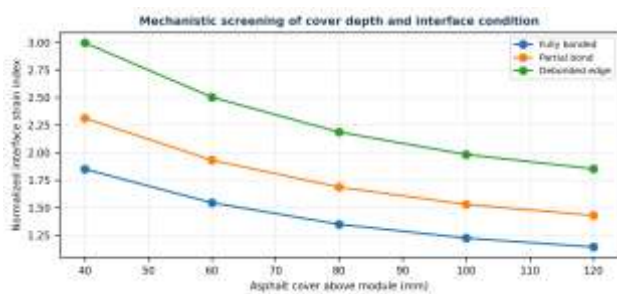


Fig. 8. Normalized structural screening result. The index is a comparative analytical metric and is not a measured strain or fatigue transfer function.

The integrated optimum is therefore not the deepest possible coil. A 40 to 60 mm renewable surface course above a structurally competent carrier may be preferable to burying the entire magnetic assembly within the full asphalt depth, provided rutting, shear, and surface-temperature checks pass. A local taper or compliant transition can reduce the stiffness step without adding uniform magnetic gap. Detailed finite-element analysis should compare intact bond, frictional contact, partial debond, and water-weakened interface cases under edge and wheel-path loading.

VI STRUCTURAL DESIGN REQUIREMENTS

A Materials and interfaces

The carrier should be electrically nonconductive where conductive loops would create eddy loss, mechanically stiff enough to protect ferrite, thermally conductive enough to spread loss, and resistant to water and chemicals. No single commodity material automatically satisfies all four conditions. Fiber-reinforced polymer, polymer concrete, high-performance cementitious composite, and hybrid enclosures are candidates. Conductive reinforcement requires electromagnetic analysis; conventional steel mesh placed above a transmitter can shield the field and heat by eddy current.

The surrounding HMA should be selected for rut resistance and adhesive compatibility. The tack or bonding system requires pull-off and shear qualification after water conditioning and thermal cycling. The carrier surface may use aggregate broadcast, grooves, or mechanical keys to improve interlock, but aggressive keys can create stress raisers or make removal destructive. A replaceable design uses controlled bond and defined extraction points rather than assuming permanent monolithic action.

B Distress mechanisms

TABLE IV
STRUCTURAL FAILURE MODES AND DESIGN CONTROLS

Failure mode	Mechanism	Control and verification
Interface cracking	Stiffness mismatch, tire shear, thermal expansion	Tapered transition; cohesive/contact FE cases; crack survey
Debonding	Poor tack, water, cyclic shear	Surface preparation; shear/pull-off tests after conditioning
Rutting over module	Thin hot surface layer and elevated temperature	High-temperature PG binder; wheel tracking; thermal derating
Reflective cracking	Carrier edge or joint movement	Move edge from wheel path; transition strip; saw-cut control
Settlement	Weak bedding or disturbed base	Proof rolling; nonshrink bedding; density and level survey
Water pumping	Trapped water under repeated load	Positive drainage; sealed glands; moisture sensors
Ferrite fracture	Carrier flexure or installation impact	Stiff carrier; handling limits; post-install inductance scan
Surface polishing	Incompatible repair material	Specify texture and friction acceptance tests

C Construction tolerances

Survey tolerance affects both ride quality and magnetic gap. The carrier elevation should be controlled relative to final surface, not merely to the milled recess. Crossfall must continue through the charging zone. Longitudinal joints should be straight enough to avoid thin wedges of asphalt, and the carrier should not rock on isolated high points. Before paving, inspectors should record bedding continuity, enclosure level, conduit bend radius, connector torque, insulation resistance, inductance, resistance, and photographs tied to chainage.

Compaction is a coupled risk. Low compaction creates permeability and weak bond; excessive impact can damage ferrite or shift the carrier. A trial installation should determine roller type, amplitude, passes, mat temperature, and exclusion distance. Electrical resistance and inductance should be measured before embedment, after carrier placement, after each paving lift, and after opening to traffic. A step change localizes construction damage before the system is energized at high power.

D Pavement design analysis

The design traffic spectrum must reflect the fleet targeted by the charging lane. A freight corridor may experience high repetitions of tandem and tridem axles in a narrow wheel path. The module edge should be analyzed under the most damaging wheel positions, not only centered loading. Seasonal asphalt modulus, temperature gradient, braking shear, and weak support should be combined in a factorial matrix. Damage is accumulated separately for bottom-up fatigue, near-surface cracking, rutting, and interface failure because the stiff carrier changes each mechanism differently.

The reference pavement without a charging system should be analyzed with identical traffic, climate, and materials.

Performance acceptance is then expressed as a ratio or allowable life reduction. A road agency may accept a modest reduction if modules can be replaced during scheduled resurfacing and the charging service delivers sufficient benefit. It should not accept an unknown reduction hidden by a perfect-bond model.

VII ELECTRICAL AND CONTROL DESIGN REQUIREMENTS

A Power conversion and compensation

The inverter should achieve soft switching over the expected range of coupling and battery conditions. The compensation topology must limit reactive current during entry, exit, and receiver loss. A three-phase transmitter can reduce power pulsation and broaden interoperability across vehicle classes, which motivated the Purdue topology [1]. Modular converters allow a damaged zone to be bypassed and match maintenance boundaries.

Cable and bus design must include high-frequency skin and proximity effects, circulating current, connector temperature, and common-mode paths. The roadside cabinet requires surge protection, isolation monitoring, protective bonding, and coordinated overcurrent devices. The DC link may buffer fast vehicle-to-vehicle demand variation, but any stationary storage changes fire, ventilation, and emergency-response requirements. Feeder studies should evaluate coincidence, harmonic emission, voltage variation, and utility demand charges.

B Detection and handover

A segment should never energize solely because a metal mass is detected. The controller needs a valid compatible receiver, position confidence, electrical self-test, and clear foreign-object status. Power ramps after coupling is established and decays before the receiver leaves. Adjacent segments overlap only as required to control ripple. A failed communication channel causes a safe reduction or shutdown, while vehicle traction continues from its battery.

At 90 km/h, a vehicle traverses a 2 m coil pitch in 80 ms. Detection, authorization, switching, and control must therefore be deterministic. The communication design should not depend on a distant cloud service for the safety loop. Local controllers handle energization; higher-level services handle billing, updates, diagnostics, and traffic-energy optimization.

C Electromagnetic and functional safety

The safety case covers human exposure, implanted medical devices, vehicle electronics, metallic foreign objects, animals, maintenance personnel, and emergency responders. Field limits are evaluated at the pavement surface, lane edge, adjacent sidewalk, vehicle cabin, and accessible cabinet locations under normal and single-fault conditions. Shielding should be analyzed with the actual pavement and vehicle geometry because conductive civil components can redirect flux.

Foreign-object detection must identify objects capable of hazardous heating while avoiding excessive nuisance trips from benign road debris. Temperature and power-balance monitoring provide independent protection. A road-side energy mismatch between commanded input and receiver-

reported output can indicate a foreign object, detuning, damaged shielding, or communication error. The system should isolate the smallest possible zone and log the evidence needed for inspection.

D Cybersecurity and metering

Authentication protects billing and prevents unauthorized activation, but the safety system must remain fail-safe if authentication infrastructure is unavailable. Firmware should be signed, update paths controlled, and zone controllers isolated from public networks. Revenue metering requires a defined measurement boundary. Infrastructure operators should distinguish grid input, cabinet output, road-module input, and receiver output so that conversion loss, availability, and customer energy are auditable.

VIII VERIFICATION AND VALIDATION PLAN

Verification proceeds from materials to a full-scale lane because no single test reproduces all coupled effects. Coupon tests screen dielectric loss, thermal conductivity, water absorption, bond strength, and chemical resistance. A bench coupler establishes electrical maps over offset, gap, temperature, and load. A full-size module undergoes mechanical proof, water ingress, thermal cycling, insulation, and high-power tests. A pavement test section then evaluates construction, wheel loading, drainage, electromagnetic performance, and repair. Only after these gates should a public-road pilot begin.

TABLE V
INTEGRATED ACCEPTANCE MATRIX

Stage	Structural measure	Electrical or safety measure	Decision
Material coupons	Modulus, strength, bond after conditioning	Permittivity, permeability, dielectric loss	Reject incompatible material
Carrier prototype	Deflection and sealing under proof load	R, L, insulation, loss, thermal map	Revise enclosure or potting
Bench coupler	Mount stability and gap tolerance	Efficiency map, field map, FOD	Set control envelope
Paving trial	Density, level, interface cores	Pre/post paving R and L	Approve installation method
APT section	Strain, rut, cracks, FWD, moisture	Power, efficiency, temperature under traffic	Calibrate coupled models
Road pilot	Ride, friction, distress, drainage	Energy, uptime, exposure, faults	Approve staged expansion

A Electrical test matrix

The efficiency map should cover longitudinal overlap, lateral offset, vertical gap, receiver type, road temperature, battery voltage, and power command. Each result must report the measurement boundary and calibrated uncertainty. The field map covers nominal alignment, worst credible offset, empty-road energization fault, metallic object cases, and adjacent simultaneous vehicles. Thermal tests continue until temperatures stabilize or a protective limit is reached.

B Structural test matrix

The pavement section requires instrumentation at the module center, longitudinal edge, transverse edge, and reference asphalt. Wheel positions should include the module centerline, each interface, and adjacent full-depth asphalt. Accelerated loading is combined with planned thermal activation to separate traffic compaction from electrical heating. Measurements include surface profile, rut components by layer where possible, strain, temperature, moisture, deflection basin, bond condition, and visual distress. The 75,000-pass published study provides a useful benchmark for an early phase, but project acceptance should be tied to predicted field equivalency and observed damage rate [9].

C Data quality

Sensor timestamps, calibration records, missing-data flags, and software versions are part of the research record. Efficiency should not be calculated from unsynchronized input and output samples during vehicle entry. Structural measurements should include pavement temperature and wheel position. A pre-registered analysis plan should distinguish primary acceptance metrics from exploratory correlations. Raw or suitably anonymized pilot data should be published where commercial and privacy constraints allow.

IX RESULTS AND ENGINEERING DISCUSSION

A Governing tradeoffs

The case analysis shows that electrical performance is most sensitive to exposure time, coil separation, and alignment, while structural performance is most sensitive to the stiffness transition and bond condition. These sensitivities point in opposite directions: shallow placement improves coupling but puts the inclusion near high tire-induced shear and hot surface material. A renewable 40 to 60 mm surface course above a stiff carrier, combined with a tapered and well-drained interface, is a rational starting point for full-scale optimization. It is not a prescriptive dimension for every pavement.

At 50 km/h, the one-kilometre lane delivers 3.65 kWh per pass under the nominal assumptions. For an urban delivery truck consuming 1.2 kWh/km, that energy offsets about 3.0 km of traction energy; for a heavy truck consuming 1.8 kWh/km, it offsets about 2.0 km. The energy value alone does not justify a project. Utilization, battery downsizing, route reliability, peak demand, maintenance, and competing depot charging must be evaluated together.

B Structural interpretation of full-scale evidence

Purdue-related research demonstrates constructability and provides measured response under controlled accelerated loading [1], [9], [10]. The reported absence of visible distress after 75,000 passes supports continued development, but the local changes in strain, deflection, and rutting show that the charging unit cannot be treated as structurally invisible. Surface appearance also lags internal debonding. Periodic deflection and bond-sensitive nondestructive evaluation are needed before a pilot is declared durable.

Published findings are not entirely uniform about whether rut depth is higher directly over a stiff unit or in adjacent asphalt because surface-course thickness, measurement location, compaction, heating, and the definition of the comparison zone

differ. This is a useful warning. Future papers should publish the full transverse profile, layer contributions, construction density, temperature history, and exact coil-activation duty cycle rather than only a maximum rut number.

C Magnetic pavement materials

The Rutgers simulations show a potentially important route for deeper installations: a partially magnetized pathway increased modeled efficiency more strongly as depth increased [3]. At 0.40 m embedment, the absolute improvement was 12.3 percentage points. Yet a 39.9% result at that depth remains too low for practical high-power service unless the rest of the system boundary and geometry are improved. Magnetic pavement should therefore complement, not excuse, excessive burial depth.

Magnetic additives can affect density, binder demand, aggregate skeleton, moisture susceptibility, thermal conductivity, and recyclability. Their electromagnetic benefit may saturate with permeability, as the Rutgers report observed. A material program should optimize whole-life energy and pavement performance rather than maximize magnetic permeability in isolation.

D Risk prioritization

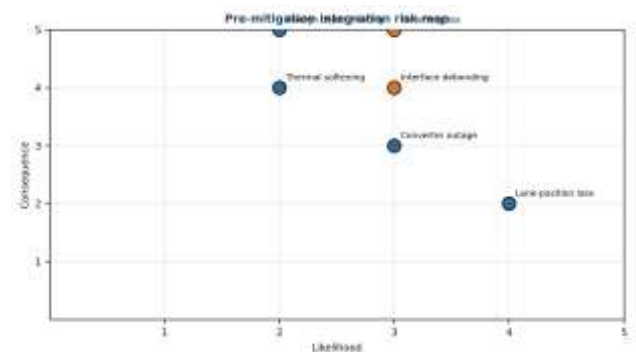


Fig. 9. Qualitative pre-mitigation risk map for the integrated design. Scores guide test priority and are not actuarial probabilities.

Water ingress and interface debonding receive the highest combined priority because each can trigger both civil and electrical failure and may remain hidden below the surface. Foreign-object heating has lower expected likelihood but high consequence and therefore needs independent detection. Lane-position loss is more frequent but normally manageable through derating. Converter outage is contained by zoning. The risk map should be updated after prototype data; leaving scores unchanged would defeat the purpose of evidence-based commissioning.

TABLE VI
KEY NUMERICAL FINDINGS

Finding	Value	Interpretation
ORNL experimental anchor [4]	120 kW at 91.31%	Use only within stated DC-input-to-battery boundary
Rutgers depth effect [3]	70.1% to 27.6%, conventional, 0.10 to 0.40 m	Avoid unnecessary embedment depth
Rutgers magnetic pathway [3]	39.9% versus 27.6% at 0.40 m	Potential recovery under studied geometry
Energy at 50 km/h	3.65 kWh per 1 km pass	Calculated for 200 kW input and nominal efficiency

Finding	Value	Interpretation
Energy at 90 km/h	2.03 kWh per 1 km pass	Longer lane or more power needed at speed
Purdue-related APT [9]	75,000 passes; no visible surface distress	Promising controlled test, not lifetime proof

X CONSTRUCTION AND COMMISSIONING STRATEGY

A practical pilot begins with utility survey and subsurface investigation, followed by trial trenching and drainage confirmation. The contractor then constructs a non-energized mock-up using production materials and equipment. The mock-up establishes milling accuracy, bedding, module placement, conduit handling, asphalt compaction, surface texture, and removal method. Electrical checks are repeated at each construction hold point. Only a passed mock-up authorizes the live section.

Installation proceeds in short zones so that an incomplete system can be protected and tested. Each carrier receives a permanent identifier and surveyed coordinates. Photographs and three-dimensional surface scans document its exact depth and orientation. The road is opened first as an unenergized pavement. Ride quality, friction, drainage, and baseline electrical properties are confirmed before low-power static charging, then low-speed dynamic charging, controlled fleet operation, and finally normal traffic.

TABLE VII
STAGED COMMISSIONING GATES

Gate	Required evidence	Release condition
1 Mock-up	Density, level, bond, drainage, R/L stability	Construction method accepted
2 Civil opening	Ride, friction, markings, sealed cabinets	Safe traffic operation without energization
3 Low power	Isolation, communication, field and temperature maps	All protection channels demonstrated
4 Controlled fleet	Energy accuracy, alignment, handover, fault recovery	Stable operation across weather window
5 Public traffic	Uptime, distress trend, maintenance response	Independent safety and asset review
6 Expansion	Life-cycle cost and verified performance	Benefits justify additional length

Maintenance plans should define electrical isolation before pavement work, maximum milling depth, approved patch materials, winter operations, debris inspection, cabinet access, firmware control, and emergency contacts. A road crew should be able to identify energized infrastructure from the asset system even when surface markings are worn. Utility locating methods must be compatible with the coil and power conduits.

XI ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS

The appropriate economic comparison is route service delivered, not charger cost per kilowatt alone. Dynamic charging can reduce vehicle battery size, charging dwell, and

depot peak demand, but it adds roadway construction, power distribution, lane closures, specialized maintenance, and interoperability risk. Fixed-route fleets provide the strongest initial case because daily passes, receiver types, speeds, and schedules are known. A lightly used general-purpose lane spreads capital cost across too little energy.

Life-cycle assessment must include copper, ferrite, carrier materials, cabinets, asphalt replacement, construction traffic, electrical loss, avoided battery capacity, and end-of-life recovery. Bi et al. showed that deployment pattern and temporal use materially affect life-cycle outcomes [12]. A highly efficient lane powered by carbon-intensive marginal electricity can still have limited climate benefit, while a lower-utilization project may be justified for resilience or zero-emission freight access. The analysis should state the grid scenario and functional unit.

The Rutgers report estimated wide potential electricity savings for magnetized pavement because the result depends on efficiency improvement and operating hours [3]. Such ranges are screening bounds, not bankable cash flows. A project financial model should use measured energy throughput, demand tariffs, downtime, resurfacing schedule, and residual value. Sensitivity analysis should expose the utilization threshold at which the project becomes preferable to depot, opportunity, or pantograph charging.

XII LIMITATIONS AND RESEARCH PRIORITIES

The analytical curves for lateral offset, thermal response, and normalized interface strain are transparent sensitivity models. They are not substitutes for finite-element electromagnetic, thermal, or pavement analysis and are not calibrated to a commercial system. The nominal efficiency comes from a laboratory experiment, while field conditions include dirt, water, vehicle variability, temperature, aging, and control transitions. Energy results are therefore best interpreted as an upper-level planning estimate.

The most urgent research need is a shared full-scale dataset with synchronized electrical input, receiver output, alignment, temperature, traffic, moisture, strain, deflection, rut profile, and distress. Test sections should include reference pavement and multiple interface designs. Reporting should include unsuccessful construction details and repairs because these determine agency risk. Long-term observation must cover freeze-thaw, hot-weather rutting, rainfall, deicing, snowplow interaction, resurfacing, and utility cuts.

Interoperability research should extend beyond nominal frequency and power. Vehicles with different receiver sizes and ground clearances must pass across the same segmented lane without unstable control or excessive field. Civil research should develop modular details that can be installed by ordinary paving contractors after a validated trial, rather than depending indefinitely on a specialist research team. Finally, agencies need asset-management rules for inspection intervals, remaining-life estimation, spares, and decommissioning.

XIII CONCLUSION

Dynamic inductive charging pads can be integrated into asphalt pavement, but the viable design is a coupled civil-electrical system. Published projects demonstrate high-power

transfer, direct embedment, full-scale accelerated testing, and public-road installation. They also show that embedment depth, bond condition, heat, alignment, and water control can determine performance as strongly as the nominal converter rating.

For the analytical 200 kW case, a one-kilometre active lane delivers 3.65 kWh per pass at 50 km/h and 2.03 kWh at 90 km/h when the 91.31% published efficiency anchor is applied. The result quantifies the need for sufficient active length at highway speed. Structural screening favors a shallow, sealed, replaceable carrier beneath a renewable wearing course, with tapered interfaces and positive drainage. Electrical design favors short independently protected zones, coupling-aware derating, distributed temperature and insulation sensing, and local fail-safe control.

The recommended implementation sequence is materials screening, bench mapping, full-size carrier testing, paving trial, accelerated pavement testing, unenergized road opening, low-power commissioning, controlled-fleet operation, and monitored public service. Expansion should follow only when the combined dataset demonstrates safe electromagnetic exposure, stable efficiency, acceptable pavement damage rate, maintainable construction, and a life-cycle advantage for the target route.

APPENDIX A REPRODUCIBLE CASE EQUATIONS AND DATA

The case calculations can be reproduced from four inputs: transmitter input power P_{in} , efficiency η , active length L , and speed v . Exposure time is $3600L/v$ seconds. Battery energy follows (1). Total conversion loss over the pass is $(1 - \eta)P_{in}L/v$. The numerical table below uses $\eta = 0.9131$ and $P_{in} = 200$ kW. The values contain no proprietary data.

TABLE VIII
REPRODUCIBLE ONE KILOMETRE CASE DATA

Speed km/h	Time s	Battery kWh	Loss kWh
30	120.0	6.087	0.579
40	90.0	4.566	0.434
50	72.0	3.652	0.348
60	60.0	3.044	0.290
70	51.4	2.609	0.248
80	45.0	2.283	0.217
90	40.0	2.029	0.193
100	36.0	1.826	0.174
110	32.7	1.660	0.158
120	30.0	1.522	0.145

For the illustrative offset plot, $\eta(y) = 0.9131 \exp[-0.75(y/0.25)^2]$, where y is lateral offset in metres. This function was selected only for sensitivity illustration and must be replaced by measured or electromagnetic-model results for a chosen coupler. The structural index is $I = b[1 + 0.85 \exp(-(c-40)/45)]$, where c is cover in millimetres and b equals 1.00,

1.25, or 1.62 for fully bonded, partially bonded, or debonded-edge cases. Those multipliers are analytical assumptions.

APPENDIX B DETAILED DESIGN CALCULATION WORKFLOW

A Corridor demand and vehicle energy balance

The first calculation is performed at route level rather than at coil level. For each target vehicle class, the designer assembles route distance, elevation, speed distribution, dwell, auxiliary load, payload, seasonal heating or cooling, and a conservative traction-energy intensity. The required energy supplied by the roadway is the difference between route demand and the energy that can be supplied by the selected onboard battery and fixed charging opportunities. Regenerative braking is included as a measured or simulated route credit, not as a fixed percentage copied from another fleet. The calculation is repeated for a cold day, a hot day, a high-payload trip, and degraded battery capacity.

If the lane is intended to maintain state of charge rather than fully recharge the vehicle, the battery-side power target can be linked to traction demand over the energized segment. A Class 8 truck at highway speed may need substantially more power than an urban van. The specified dynamic power should include a control margin but should not be inflated without checking feeder and thermal consequences. For every vehicle class, the design table should show receiver rating, ground clearance, coil envelope, permissible field, battery voltage range, and maximum acceptable charge current.

The route model should next locate candidate energized segments. Long straight sections with stable lane position, easy utility access, good drainage, and planned pavement rehabilitation are preferable. Intersections, sharp curves, bridge joints, frequent utility cuts, drainage sags, and areas with repeated braking or lane changes are poor first locations. Selecting an energized segment during a scheduled reconstruction project may reduce traffic-control and pavement-opening cost. The civil opportunity can be more decisive than a small difference in electrical energy demand.

B Traffic occupancy and feeder sizing

Peak feeder demand depends on the number of compatible vehicles simultaneously occupying independent energized zones. The engineer should use time-stamped traffic or fleet schedules rather than multiplying annual average daily traffic by penetration. For a dedicated fleet, vehicle headways can produce highly correlated charging demand. For general traffic, compatible-vehicle penetration and receiver authorization introduce uncertainty. A Monte Carlo or time-step model should represent arrival, speed, vehicle length, requested power, battery limits, and zone availability.

The feeder is not necessarily sized for every receiver to draw full rating simultaneously. A corridor controller may cap aggregate power, allocate power by state of charge or service priority, and reduce individual power during rare peaks. That strategy reduces grid connection cost but changes energy delivered per pass. The service-level agreement must therefore state whether the lane guarantees a minimum energy, a best-effort power, or priority for a designated fleet. Protection

devices and conductors must still be rated for the permitted operating envelope and fault current.

Transformer, rectifier, and cabinet efficiency should be represented separately from coupler efficiency. Auxiliary power includes cooling, communication, control, standby heating, lighting, sensors, and enclosure conditioning. Standby energy can become material when traffic utilization is low. The annual model should calculate grid energy, receiver energy, conversion loss by component, demand peaks, and hours of curtailed service. These values provide the electrical inputs for life-cycle cost and environmental assessment.

C Coil geometry and magnetic verification

Electromagnetic design begins with the complete geometry: primary and receiver winding dimensions, ferrite segmentation, shielding, conductor cross-section, carrier materials, vehicle floor, pavement layers, nearby steel, and the full range of air gaps and offsets. The model should solve inductance, mutual inductance, coupling, flux density, eddy-current loss, and force. Material properties must be specified at operating frequency and temperature. Low-frequency catalog permeability or room-temperature conductivity can misrepresent an 85 kHz system.

A design-of-experiments matrix should vary longitudinal overlap, lateral offset, roll, pitch, ground clearance, temperature, pavement moisture, receiver size, and adjacent vehicle position. The result is not a single efficiency number but a feasible operating envelope. The controller then uses coupling or impedance estimates to decide when full power is safe. A worst-case field study evaluates normal operation, an empty energized segment, a missing shield, a damaged ferrite tile, a metallic object, and a receiver that stops above a segment.

The magnetic model must be validated with progressively larger hardware. Coil inductance and resistance are compared first. Coupling is measured over a controlled positioning grid. Calibrated power analysers then measure input, inverter output, rectifier input, and battery or electronic-load output. The uncertainty budget should include current sensors, voltage probes, phase error, synchronization, and temperature drift. Reporting one rounded efficiency without uncertainty or boundary prevents meaningful comparison.

D Compensation and converter sizing

The compensation network is selected to provide the required power and soft-switching range without excessive component voltage or current. Component tolerances, aging, and temperature are included in the resonance analysis. The inverter, switches, capacitors, and busbars are sized for worst credible detuning, not only nominal aligned operation. A protection study covers overcurrent, overvoltage, loss of receiver, communication failure, ground fault, insulation degradation, and cooling loss.

Fast handover can create transient power ripple at the battery and current peaks in the road system. Simulation should use the real segment pitch and speed range. At low speed or a stopped vehicle, dwell over one segment increases, so the controller may reduce power or distribute excitation across adjacent coils. At high speed, authorization and switching latency consume a larger fraction of the overlap interval. These

cases establish minimum controller sampling, communication latency, and switch timing.

E Thermal network and material limits

A component loss map drives the thermal model. Copper loss depends on RMS current and AC resistance; ferrite and shield losses depend on flux and frequency; semiconductor loss depends on current, voltage, switching, and junction temperature. The road model includes carrier conduction, asphalt conductivity and heat capacity, soil boundary conditions, solar gain, convection, rainfall cooling, and vehicle shading. Thermal contact resistance at potting and carrier interfaces can dominate local temperature and must be measured.

The design is checked for an isolated pass, a vehicle queue, repeated platoons, a stopped receiver, and partial cooling failure. Asphalt performance is evaluated at the resulting local temperature, not at weather-station air temperature. The maximum temperature may occur below the surface and persist after power ends. Therefore, thermocouples or fibre-optic sensors should be placed near the winding, carrier top, interface, and surface during qualification. Infrared surface imaging alone cannot detect every internal hot spot.

F Mechanistic pavement analysis

The structural model imports the exact carrier geometry from the electrical design. Asphalt layers use temperature- and frequency-dependent modulus or a viscoelastic representation. The base and subgrade reflect seasonal moisture. The carrier may be linear elastic, while interfaces are represented with bonded, frictional, cohesive, and partially debonded alternatives. Mesh refinement is concentrated at corners, conduit penetrations, joints, and changes in bedding support. Symmetry should not remove a critical edge or asymmetric wheel path.

Wheel loading includes steering, single, tandem, and tridem configurations relevant to the lane. Contact stress may be nonuniform, especially for heavy truck tires. Load positions sweep across both longitudinal and transverse module edges. Braking and turning introduce horizontal shear. Thermal expansion is applied before or together with traffic loading because a hot carrier and asphalt can have different expansion and stiffness. The analysis records asphalt tensile strain, shear at the interface, vertical subgrade strain, carrier stress, and relative opening.

Damage models are calibrated for local materials where possible. Fatigue and rutting predictions are compared with the unmodified reference pavement under identical inputs. Sensitivity analysis varies cover, carrier stiffness, edge taper, bedding modulus, interface strength, and water-weakened bond. The selected cross-section should remain acceptable under a plausible degraded interface, not only a perfectly bonded construction state. A design that fails abruptly after small bond loss has insufficient robustness.

G Drainage and environmental durability

Hydraulic design maps surface flow, layer permeability, edge drains, conduit paths, junction boxes, and low points. Every penetration is classified by water path and repair accessibility. The module enclosure receives an ingress rating appropriate to

immersion and pressure cycling, but an enclosure rating does not replace roadway drainage. Water trapped at the HMA-carrier boundary can weaken bond and pump fines even when the electrical enclosure remains dry.

Durability conditioning combines water, salt solution, freeze-thaw, elevated temperature, fuel and oil exposure, ultraviolet exposure for surface materials, and cyclic mechanical load. The sequence matters because a crack formed mechanically can enable later moisture damage. Electrical resistance, insulation, inductance, bond, mass change, and visual condition are recorded through conditioning. Acceptance limits should be tied to safe operation and predicted life rather than a pass/fail visual inspection.

APPENDIX C FULL SCALE TEST AND FIELD MONITORING PROTOCOL

A Test section layout

A useful full-scale experiment contains at least one conventional reference lane and multiple charging details. Suggested variables are carrier edge geometry, surface-course thickness, bedding type, and interface treatment. Randomization is difficult in a linear pavement, so the analysis should account for position, support variation, and construction sequence. Before installation, falling weight deflectometer or equivalent measurements establish the uniformity of the existing foundation. Density and material samples document every lift.

Instrumentation is placed at the charging-unit center, both transverse edges, a longitudinal joint, adjacent full-depth asphalt, and the reference section. Asphalt strain gauges are oriented longitudinally and transversely near the bottom of selected layers. Pressure or strain sensors in the base help identify load transfer. Thermocouples are installed at the winding, carrier top, interface, surface, base, and reference pavement. Moisture sensors or leak conductors are placed beneath the carrier and in junction boxes. Sensor redundancy is necessary because installation and compaction can damage gauges.

B Baseline characterization

Baseline testing occurs after construction but before electrical activation. It includes survey elevation, three-dimensional surface profile, roughness, texture, friction, density, permeability where appropriate, deflection basin, ground-penetrating radar, thermal image under natural heating, electrical resistance, inductance, insulation resistance, and communication checks. A static wheel test maps strain and deflection at predefined positions. Baseline repeatability is established before accelerated loading begins.

Electrical baseline tests use a controlled receiver rig whose position and gap are surveyed. Low power is applied first. Input and output power, field, temperature, and protection response are measured at the alignment grid. The resulting map is stored as the commissioning fingerprint. Later deviation from this fingerprint can indicate moisture, connection change, ferrite damage, settlement, or sensor drift.

C Accelerated loading sequence

Accelerated pavement testing should be divided into blocks separated by condition surveys. A representative plan might

inspect at 0, 5,000, 15,000, 25,000, 50,000, 75,000, and 100,000 passes, with additional inspections when a change-point algorithm detects abnormal strain, rutting, or temperature. Load level, tire pressure, wheel wander, speed, and pavement temperature are controlled and reported. The charging system is activated under a planned duty cycle during selected blocks so that mechanical and thermal effects can be separated.

The sequence includes four states: traffic without charging, charging without traffic, combined traffic and charging, and recovery with neither. Traffic-only blocks reveal compaction and mechanical damage. Charging-only blocks establish thermal response and expansion. Combined blocks show interaction, while recovery distinguishes reversible temperature effects from permanent deformation. A conventional reference section experiences the same traffic and environment.

At every condition survey, transverse profiles cover the complete lane rather than only the module center. Crack maps include width, length, orientation, and relation to module edges. Deflection tests repeat the original positions and temperature corrections. Electrical mapping repeats at selected offsets and power levels. If a module trips, the raw waveform and physical inspection are retained; automatically restarting until the fault disappears would erase valuable evidence.

D Field pilot monitoring

The field pilot begins with a defined observation period in which only trained vehicles use the system. Vehicles carry reference energy meters and precise positioning. Weather stations record air temperature, pavement temperature, rainfall, humidity, and freeze events. Traffic sensors record axle class, lane position, speed, and headway without retaining unnecessary personal information. The monitoring plan defines who reviews alarms and the maximum time to isolate a suspect zone.

Key electrical performance indicators are energy availability, successful session rate, battery energy per pass, efficiency by measurement boundary, forced derating, segment handover success, temperature margin, insulation margin, foreign-object alarms, false trips, and mean time to restore. Civil indicators are rut depth, roughness, friction, cracking at unit edges, deflection change, moisture alarms, settlement, patch condition, and maintenance hours. The two sets are reviewed together. For example, falling efficiency with rising moisture can precede both bond damage and insulation failure.

Seasonal reviews compare like-for-like operating bins. A winter efficiency value at a small gap cannot be compared directly with a summer value for a different receiver and offset. Data are stratified by vehicle, speed, alignment, power, temperature, and zone. Statistical process control can identify gradual changes, but engineering thresholds still govern safety trips. Every software update or hardware repair creates a new configuration version in the dataset.

E Acceptance criteria

TABLE IX
EXAMPLE PILOT PERFORMANCE CRITERIA TO BE FINALIZED
BY THE OWNER

Metric	Example form	Purpose
Electrical availability	$\geq$ target percentage by zone and month	Verify service reliability
Energy accuracy	Meter difference within stated uncertainty	Support billing and research
Efficiency	Lower percentile above project threshold	Control loss and heat
Insulation resistance	Above manufacturer and code limit	Prevent shock and leakage
Temperature margin	No operation above derating and trip envelope	Protect materials and users
Rut depth	No excessive differential versus reference	Protect ride and drainage
Cracking	No rapid edge-crack growth	Detect interface failure
Friction	Meets road authority requirement wet and dry	Traffic safety
Roughness	No unacceptable local bump or settlement	Ride and dynamic load
Water ingress	No enclosure leak; drainage functional	Protect electrical and bond systems

Numerical thresholds are intentionally not prescribed in Table IX because they depend on road class, jurisdiction, hardware, materials, and safety certification. They must be set before testing, with instrument uncertainty and action levels. An acceptance metric should state the averaging period, excluded conditions, minimum sample count, and response to failure. A monthly average can hide a small dangerous subset, so lower percentiles and worst credible cases are important.

F Stop rules and forensic inspection

Testing stops automatically for insulation failure, uncontrolled temperature rise, exposed conductor, hazardous field, smoke, significant settlement, loose surface material, or a rapid structural response change. The section is made safe before inspection. Investigators preserve controller logs, waveforms, weather, traffic, photographs, and samples. Nondestructive evaluation precedes destructive coring where possible. If a core is taken, its orientation and exact distance from the carrier edge are recorded.

A failure review separates initiating event, contributing conditions, detection, protection response, and consequence. Root-cause analysis should not stop at “water ingress” or “debonding”; it should identify the path, construction detail, material change, or control deficiency. Corrective action is validated on a mock-up or isolated zone before broader re-energization. The updated detail and software version are documented so that later performance is traceable.

APPENDIX D ASSET MANAGEMENT AND LIFE CYCLE IMPLEMENTATION

A Asset breakdown and ownership

The roadway system should be decomposed into grid connection, transformer, rectifier or DC supply, cabinets, zone controllers, primary coils, carriers, cables, communications, sensors, pavement interfaces, drainage components, and vehicle-side equipment. Each item has an owner, inspection interval, expected life, replaceability class, and safety isolation method. Ambiguous ownership between the road agency, utility, technology supplier, and fleet operator creates longer outages than many technical failures. Contracts should define who controls firmware, energy data, traffic data, spare parts, and emergency response.

The asset register links every module to chainage, lane, depth, orientation, installation date, material batch, electrical fingerprint, photos, test certificate, warranty, and repairs. Geographic information must be accurate enough to prevent accidental milling or excavation. The road authority should retain an offline export in a nonproprietary format so that asset safety does not depend on one vendor portal.

B Inspection and condition states

Condition states combine electrical and civil observations. A green zone operates without abnormal trend. An amber zone remains safe but shows declining efficiency, rising temperature, moisture, repeated nuisance trips, edge cracking, or differential rutting and receives planned investigation. A red zone is isolated because a safety limit, rapid deterioration, or exposed damage is present. A bypassed zone remains structurally monitored even when electrically off because water or settlement can continue.

Routine remote inspection reviews power balance, temperature, isolation, communication, and fault rate. Drive-by inspection records surface distress and ride. Detailed annual or seasonal inspection adds profile, friction, targeted deflection, cabinet thermal scan, drainage check, and torque or connector checks where safely accessible. After flooding, utility work, resurfacing, collision, lightning, or an abnormal fault, a special inspection is triggered.

C Maintenance intervention logic

A declining-efficiency alarm is first checked against vehicle mix, offset, temperature, and meter calibration. If the change is zone specific, the system compares inductance, resistance, insulation, temperature, and neighboring zones. Increased resistance suggests connection or conductor damage; changed inductance can indicate ferrite fracture or geometry change; moisture and falling insulation suggest ingress; normal electrical fingerprints with surface distress suggest a primarily civil issue. This diagnostic order avoids opening the pavement before simpler causes are excluded.

Module replacement should use a documented lane-closure, isolation, saw-cut, extraction, bedding restoration, reconnection, paving, and commissioning method. The repair boundary should not create a narrow strip of asphalt that cannot be compacted. Replacement restores surface texture and crossfall. The new module receives a new identifier linked to the retired unit so that failure history is preserved.

D Resurfacing and rehabilitation

Resurfacing is planned at initial design. The asset register records the permissible milling envelope and a reference datum independent of the wearing surface. Before milling, zones are isolated and surveyed. Trial milling confirms locator accuracy and depth control. If the wearing course is renewed without exposing the carrier, electrical mapping before and after resurfacing quantifies the effect of changed cover and materials. Any added overlay thickness must be checked electromagnetically before construction.

Major rehabilitation may choose removal, deeper reconstruction, or a new charging module generation. A modular system should allow the electrical technology to change without discarding the full pavement foundation. Decommissioning removes hazardous conductors or leaves them isolated and documented, recycles copper and electronics, and restores a conventional maintainable pavement. Abandoned unrecorded infrastructure is unacceptable.

E Life cycle cost structure

Life-cycle cost includes investigation, design, utility interconnection, hardware, road construction, traffic control, commissioning, energy loss, demand charges, communication, software, inspections, planned surface renewal, fault repair, module replacement, downtime, decommissioning, and residual value. Vehicle-side receiver and battery effects are included when the investment decision spans fleet and infrastructure. Costs are discounted over a study period aligned with pavement rehabilitation and vehicle replacement cycles.

Benefits include avoided depot chargers, lower depot demand, reduced battery capacity where operationally feasible, greater payload, reduced dwell, improved route completion, and potentially deferred grid work at depots. Each benefit needs an observable mechanism and responsible party. A road agency should not count a fleet battery saving that contracts do not return to the infrastructure owner unless the analysis is explicitly societal. Uncertain variables receive ranges and scenario probabilities rather than a single precise net present value.

TABLE X
LIFE CYCLE MODEL VARIABLES

Category	Primary variables	Recommended sensitivity
Utilization	Compatible passes, power request, active days	Low, expected, contracted minimum
Electrical	Efficiency, standby load, demand charge	Temperature and alignment distributions
Civil works	Lane closure, excavation, paving, drainage	Install during planned rehabilitation
Maintenance	Fault rate, spare modules, response time	Vendor and owner responsibility
Vehicle benefit	Battery reduction, payload, dwell	Fleet-specific operational proof
Residual risk	Interoperability and obsolescence	Open interfaces and modular replacement

APPENDIX E FIELD DATA DICTIONARY AND REPORTING TEMPLATE

The following minimum data structure is intended to make a pilot auditable. Every record includes the zone identifier, configuration version, synchronized timestamp, data-quality flag, and measurement uncertainty or sensor class. Personal identifiers are not required for engineering analysis; a rotating vehicle-class identifier is sufficient unless the fleet operator has a separate legitimate need.

TABLE XI
MINIMUM OPERATIONAL DATA FIELDS

Field	Unit or type	Engineering use
Timestamp	UTC with millisecond precision	Synchronize input, output, traffic, and faults
Zone identifier	Permanent text key	Link electrical and pavement assets
Configuration	Firmware and hardware version	Separate behavior after changes
Vehicle class	Coded category	Stratify receiver and load demand
Speed	km/h	Exposure time and handover analysis
Lateral offset	m with confidence	Coupling and lane-position analysis
Vertical gap	mm or class	Coupling normalization
Input energy	Wh at defined boundary	Grid or cabinet performance
Receiver energy	Wh at defined boundary	Efficiency and billing check
Primary current	A rms	Loss and component stress
Frequency	Hz	Resonance and control state
Phase indicator	degree or power factor	Detuning diagnosis
Module temperature	°C at named location	Thermal protection and aging
Surface temperature	°C	Pavement performance context
Insulation resistance	MΩ	Ingress and electrical safety
Moisture state	sensor value or alarm	Drainage and ingress diagnosis
Activation duration	ms	Duty cycle and thermal load
Fault code	Controlled vocabulary	Reliability and forensic analysis
Weather	air temperature and precipitation	Seasonal normalization
Data quality	valid, suspect, missing	Prevent silent use of bad measurements

A monthly technical report should state compatible vehicle passages, energy input and delivered, efficiency distribution by operating bin, availability by zone, derating time, fault counts, false foreign-object alarms, thermal margin, insulation trend, civil distress change, repairs, software updates, and missing-data rate. It should also list any change in measurement

boundary. Summary charts must retain sample counts and percentiles so that low-use or unstable zones are visible.

The civil condition file stores transverse profiles at fixed chainages, georeferenced crack vectors, friction, roughness, deflection basins, layer temperature, moisture, photographs, and repair polygons. Survey points should be recoverable after resurfacing. Electrical and civil datasets join through zone and chainage identifiers. This structure allows an analyst to test whether efficiency change precedes moisture alarms, whether heating changes rut rate, and whether faults cluster at a construction lot or interface detail.

Published research datasets should include a data dictionary, calibration certificates or summaries, sensor locations, construction records, analysis scripts where possible, and a list of exclusions. Commercially sensitive control parameters may be removed without deleting the measured engineering outcomes. Providing negative results and repair histories improves future designs more than publishing only the highest efficiency achieved during a demonstration.

NOMENCLATURE

TABLE XII
SYMBOLS AND ABBREVIATIONS

Symbol	Meaning	Unit
APT	Accelerated pavement testing	—
DWPT	Dynamic wireless power transfer	—
EV	Electric vehicle	—
FOD	Foreign-object detection	—
HMA	Hot-mix asphalt	—
L	Active charging length	km
M	Mutual inductance	H
P _{in}	Input power at stated boundary	kW
E _b	Energy delivered to battery	kWh
k	Magnetic coupling coefficient	—
η	End-to-end efficiency	—
R _{th}	Equivalent thermal resistance	K/kW
C _{th}	Equivalent thermal capacitance	kWh/K
v	Vehicle speed	km/h

REFERENCES

- [1] O. A. Moncada, Z. Imran, C. Vickers, K. Gkritza, S. Pekarek, D. Aliprantis, A. Brovont, B. Jahangiri, and J. E. Haddock, "Full-scale dynamic wireless power transfer and pilot project implementation," Purdue Univ., West Lafayette, IN, USA, Rep. FHWA/IN/JTRP-2024/11, 2024, doi: 10.5703/1288284317744.
- [2] M. W. Halling and T. Gardner, "Infrastructure issues related to in-motion wireless power transfer," Utah State Univ., Logan, UT, USA, Rep. CAIT-UTC-NC30, 2017.

- [3] H. Wang et al., "Durable and electrified pavement for dynamic wireless charging of electric vehicles," Center for Advanced Infrastructure and Transportation, Rutgers Univ., Rep. CAIT-UTC-REG 30, Aug. 2022.
- [4] L. Xue et al., "Design and analysis of a 200 kW dynamic wireless charging system for electric vehicles," in Proc. IEEE Applied Power Electronics Conf. Expo., 2022, pp. 1096–1103, doi: 10.1109/APEC43599.2022.9773670.
- [5] Michigan Department of Transportation, "Wireless charging roadway," 2023. [Online]. Available: <https://www.michigan.gov/mdot/travel/mobility/initiatives/wireless-charging-roadway>. Accessed: Sep. 22, 2026.
- [6] Oak Ridge National Laboratory, "ORNL demonstrates 120-kilowatt wireless charging for vehicles," Oct. 19, 2018. [Online]. Available: <https://www.ornl.gov/news/ornl-demonstrates-120-kilowatt-wireless-charging-vehicles>.
- [7] Wireless Power Transfer for Light-Duty Plug-in/Electric Vehicles and Alignment Methodology, SAE Standard J2954, 2024.
- [8] Wireless Power Transfer for Heavy-Duty Electric Vehicles, SAE Information Report J2954/2, Dec. 2022.
- [9] O. A. Moncada, P. Orosa, J. Li, and J. E. Haddock, "Full-scale testing of flexible pavement with embedded dynamic wireless power transfer components," Int. J. Pavement Eng., vol. 27, no. 1, Art. no. 2604702, 2026, doi: 10.1080/10298436.2025.2604702.
- [10] H. Cruz, O. A. Moncada, B. Jahangiri, C. Tirado, S. Nazarian, and J. E. Haddock, "Analyzing the mechanical response of a calibrated finite element model for flexible pavement with embedded dynamic wireless power transfer technology," Transp. Res. Rec., vol. 2678, no. 11, pp. 405–415, 2024, doi: 10.1177/03611981241242077.
- [11] T. Konstantinou et al., "Feasibility study and design of in-road electric vehicle charging technologies," Univ. of Texas at Austin, Center for Transportation Research, 2021.
- [12] Z. Bi, L. Song, R. De Kleine, C. C. Mi, and G. A. Keoleian, "Plug-in vs. wireless charging: Life cycle energy and greenhouse gas emissions for an electric bus system," Appl. Energy, vol. 146, pp. 11–19, 2015.
- [13] B. J. Limb, Z. D. Asher, T. H. Bradley, E. Sproul, D. A. Trinko, B. Crabb, R. Zane, and J. C. Quinn, "Economic viability and environmental impact of in-motion wireless power transfer," IEEE Trans. Transp. Electrification, vol. 5, no. 1, pp. 135–146, Mar. 2019.
- [14] F. Chen, N. Taylor, and N. Kringos, "Electrification of roads: Opportunities and challenges," Appl. Energy, vol. 150, pp. 109–119, Jul. 2015.
- [15] F. Chen, C. F. Coronado, R. Balieu, and N. Kringos, "Structural performance of electrified roads: A computational analysis," J. Cleaner Prod., vol. 195, pp. 1338–1349, Sep. 2018.
- [16] F. Chen, R. Balieu, E. Córdoba, and N. Kringos, "Towards an understanding of the structural performance of future electrified roads: A finite element simulation study," Int. J. Pavement Eng., vol. 20, no. 2, pp. 204–215, 2019.
- [17] A. Foote and O. C. Onar, "A review of high-power wireless power transfer," in Proc. IEEE Transportation



Electrification Conf. Expo., 2017, pp. 234–240, doi: 10.1109/ITEC.2017.7993277.

[18] M. R. Khalid, I. A. Khan, S. Hameed, M. S. J. Asghar, and J. S. Ro, “A comprehensive review on structural topologies, power levels, energy storage systems, and standards for electric vehicle charging stations and their impacts on grid,” IEEE Access, vol. 9, pp. 128069–128094, 2021.