Science, Engineering and Technology Vol. 4, No. 2, pp. 1-13
www.setjournal.com *https://doi.org/10.54327/set2024/v4.i2.143*

Boundary Layer Modelling of Flow Acceleration and Energy Transfer Effects in Smart Pavement Design

Festus Fameso, Julius Ndambuki, Williams Kupolati, Jacques Snyman

Centre for Climate Change, Water Security and Disaster Management, Department of Civil Engineering, Tshwane University of Technology, Pretoria, South Africa.

Abstract

The integration of remote technology into the construction industry has advanced the emergence of smart, self-learning infrastructure across all levels of land transportation design and development. However, energy harvesting capabilities for smart road ventilation purposes have not yet been fully researched as the world gravitates towards energy sustainability. This study thus presents a mathematical investigation of the self-draining design potentials of road pavements, leveraging on energy absorption and conversion to accelerate conductive and convective ventilation of these pavements during wet conditions, as a means of ensuring the skid resistance and safety of such pavements are not compromised. Applying numerical methods with the aid of commercial software code MATLAB®, the classical physics of fluid-surface interaction was used to model accelerated drainage of microflood off paved surfaces through methodical modification of the thickness of the boundary layer associated with the flow regime over the flat road surface. Results indicate significant influences of energy exchange, thermal, and viscous diffusivity on flow acceleration. Alterations in parameters such as the slip factor, thermally induced Brownian motion or phoretic characteristics of the fluid particles at the boundary induce accelerated flow at the surface of the pavement. The findings contribute to the advancement of smart infrastructure by offering practical insights into the potential benefits of integrating energy-harvesting technologies into road pavement systems. By optimizing flow acceleration mechanisms, smart pavements can play a crucial role in improving road safety and sustainability in urban environments.

Keywords: *Energy conservation, Heat transfer, Numerical Modelling, Smart pavements, Pavement drainage.*

1. Introduction

In contemporary times, technology has become part of everyday living. The integration of technology into virtually everything around us has brought about advancements in almost every endeavour and even opened up vistas for innovation and development. The construction and infrastructure industry is not left out of this race to make everything around us "intelligent", self-diagnosing and self-learning. Currently, the idea of intelligent and sustainable systems and networks, driven by integrated and advanced remote technologies and cyber-infrastructure as demonstrated by [1] and [2] has transitioned from an object of mere academic curiosity to the next level of socioeconomic and environmental development revolution. In recent times, road construction technology has advanced towards accommodating intelligence as part of the evolution of transportation infrastructure. 'Smart' pavements are now designed in ways that incorporate remote sensing, data transmission and learning technologies to enhance road functionality and performance. Researchers such as [3], [4], [5], [6] have investigated and presented integrated smart sensing systems of road networks capable of monitoring pavement surface conditions and overall structural health employing integrated data-driven system

Corresponding author: *Festus Fameso (festus.fameso@gmail.com)*
Received: *16 April 2024*; Revised: *26 May 2024*; Accepted: *3 June 2024*; Published: *6 June 2024*

architecture. These are proposed to help roads have the capacity to manage and possibly repair themselves to save lives, improve their life cycle and ensure sustainability. What sets them apart from conventional road pavements, amongst others, include features that obtain and provide data in real-time about different attributes and parameters of the road condition. This can be in synchrony with components that help harvest energy from the road for storage or other applications as presented by [7] in their review of energy harvesting from pavements and roadways, or components that provide energy to the road to power applications such as lighting, road markings illumination, commuter visibility enhancers, wireless charging and many others.

The potential of these capabilities for converting or transferring energy is also being evaluated for the advancement of smart heating pavements which can help in mitigating the buildup of ice, snow, and microflooding on roads, which have historically led to issues such as pitting, erosion, and increased skidding. In this study, the self-draining potentials of road pavements of the future are investigated by mathematical methods of classical boundary layer fluid flow over surfaces, with the aim of proposing designs that accelerate conductive and convective ventilation of road pavements via energy absorption and conversion capabilities. This is in a bid to ensure that such roads are ‘smart’ enough to assess surface conditions that offer low traction during wet conditions and initiate mechanisms of integrated energy harvesting and conversion that will help stem the lubricating effects of low-depth, low-velocity precipitation run-off incursions on paved surfaces, and improve the overall safety of the road in such situations.

Following the section which has introduced and provided a background to this study, shedding a backdrop to the emergence of smart roads from the integration of cyber-electronic infrastructure into civil construction and facilities management such as in transportation systems and networks, and the potentials thereof as the world prepares for the emergence and application of these innovations in the near future, this paper is further divided into a literature review section where previous related studies have been carried out and where this study stand in relation, a methodology section where the mathematical methods applied in the study and presented, a results and discussion section where the outcomes of the computations are presented and elaborated upon for more clarity and understanding and a section which concludes and elucidates on the way forward with respect to the findings of this study. Thus the study will explore the physics of thermal fluid properties such as energy harvesting, conversion and thermal conductivity for heat transfer intensification in futuristic smart pavement towards improving them for performance and safety, thus providing the basis for an enormous innovation in next-generation road construction, which will be of major importance to transportation safety in a number of civil engineering sectors requiring optimal transport networks management.

2. Literature Review

Integrating smart systems in the design of road networks presents cutting-edge advancement in pavement infrastructure management, utilizing advanced technologies to monitor pavement surface conditions and overall structural health, especially during wet conditions. As illustrated in Figure 1, these embedded systems employ a variety of sensors, which are strategically entrenched within the road structure, to collect and transmit data on wetness conditions in real-time to central processing units through wireless communication networks. This integrated approach allows for continuous and comprehensive monitoring of road conditions, detecting issues such as cracks, potholes, and structural weaknesses long before they become severe problems.

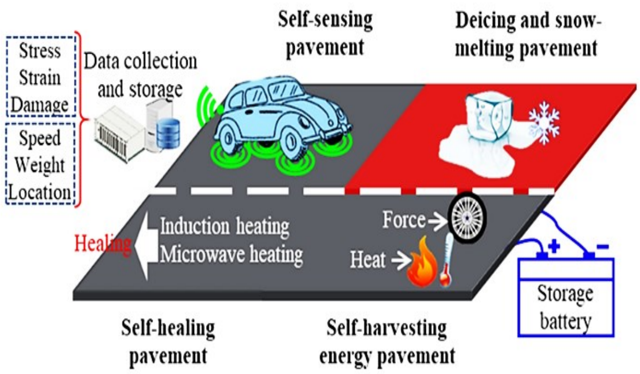


Figure 1. Schematic of a smart pavement [8].

Various studies have appraised the difficulties posed by flooding resulting from precipitation runoff and obstructed drainage with [9], [10] and [11] revealing concerns about how social economic practices and climate change continue to further exacerbate its consequences on civil, and specifically land transportation infrastructure. In their study, [12] and [13] opined that population growth, land use, and the need for housing have promoted continued watershed alterations via the development of more impermeable surfaces, construction on flood plains and land reclamation from swampy areas within the metropolis have become flood risk accelerators together with the challenge of rising sea levels, more incessant and aggressive rainfalls and the overall decadence and in some cases obsolescence in drainage infrastructure in many communities. Inquiries conducted by [14], [15], [16] and [17] revealed that floods can cause local accumulation and phase transition disruptions, resulting in widespread malfunctioning of road networks at crucial locations. Tackling this challenge effectively requires the development of integrated mathematical and network science-based frameworks to enhance the resilience of critical infrastructure networks against flooding. A modest flooding of 1.3% of road segments, according to [18] caused an 8% temporal expansion of the entire traffic network. This inferred that trips would experience a greater percentage increase in travel time, a variable which may not decay with distance from inundated areas, suggesting that the spatial reach of flood impacts extends beyond flooded areas.

The impacts on roads due to microfloods are more evident in the chain of events that follow from the progressive micro and macro-physical damage to pavements to the affectance of the skid/antiskid characteristics of the road surface, the compromised safety of road users and disruption to travel in terms of increase travel times, but to name a few. These effects according to [19] in their review of the impacts of urban floods on roads and connectivity, were more significant on the middle and lower-middle income groups in the developing countries. Retaining pavement runoff water on road surfaces remained an indication of a lack of natural flood mitigation capability, and its impacts according to [20] could only be compensated for and addressed by implementing systematic stormwater management practices.

To estimate in real-time, the advancement, recession and extent of flood identify affected roads during a flood disaster, [21] employed data obtained via remote sensing, while [22] developed an improved methodology for processing raw light detection and ranging (LiDAR) data to support urban flood modelling, which often involved the application of 1D or 2D systems of flow velocity, water depth, discharge, stagnation, mass or momentum approaches. Real-time data transmission and numerical computations were employed by [23], with inverse distance weighting (IDW) of accumulated rainfall, the flooding history, rainfall range causing flooding from previous rainfall information and frequency probability of precipitation to determine the flood risk on roads during sudden local flooding of a small area (unit), which according to [24] occurred with higher frequency. In a similar vein, [25] leveraged physics-based approaches in the form of reliability and seismic damage probability functions to delineate the intricate operating scheme of interdependent stormwater drainage and road transport systems in the synthetical assessment of their resilience performance. The outcomes enable decision-makers to capture the varying component conditions in one infrastructure system (i.e. stormwater drainage system) and depict the aggravated adverse impacts on its interdependent infrastructure system (i.e. road transport system) after a hazard has occurred. The continuous advancement and development of high-performance computing technology according to [26] and [27] has opened up vistas of new possibilities and opportunities in applied scientific research, paving the way for deeper investigations than as witnessed in the past. This has also found application in flood modelling and management as demonstrated by [28] in their assessment of dual-drainage modelling to determine the effects of green stormwater infrastructure on roadway flooding and traffic performance using microscopic flow simulations to examine the specific hazard of roadway flooding and the effects of flooding on traffic performance. Likewise, [29] applied a hydro-inundation model to simulate surface water-related flooding arising from extreme precipitation at the city scale to predict broad patterns of inundated areas at the city scale. Machine learning techniques were also incorporated by [30] to develop a surrogate model trained to mimic relationships present within the physics flood inundation, for better modelling and prediction of combined tidal and pluvial flood inundation.

Despite all the positive news heralding the ongoing development of smart road pavements, it is still pertinent to note the realities of its lack of immunity from natural environmental elements such as precipitation, microflooding, pavement runoff water and foreign objects spillage onto the pavement surfaces and so on. Flooding could be of mega or micro magnitude in extent and duration as asserted by [31], with road flooding due to drainage overflow during rainfall being a classic example of micro flooding. According to [32]'s study on the definition and classification of flood inundation of coastal cities, floods classed as not large enough to cause significant property damage or threaten public safety, but capable of disrupting routine activities and putting added stress on infrastructure such as transportation systems and storm sewers can be referred to as minor flooding. They characterized them in terms of their depth (>3 cm) and velocity (>3 m/s), capable of affecting the values of real estate within the affected area and heightening risks to public health. Meanwhile, within the context of this study, the concept of microflooding will be focused on flood depths at < 3cm and velocities at ≤ 3 m/s, capable of causing disruptions to routine activities, compromising the integrity of road pavements and impacting the safety of vehicular traffic, particularly the skid resistance characteristics of the pavements. While attention is usually focused on the mega or macro magnitude flooding, the micro or temporary flood conditions also contribute significantly to negative impacts on social, economic and health conditions.

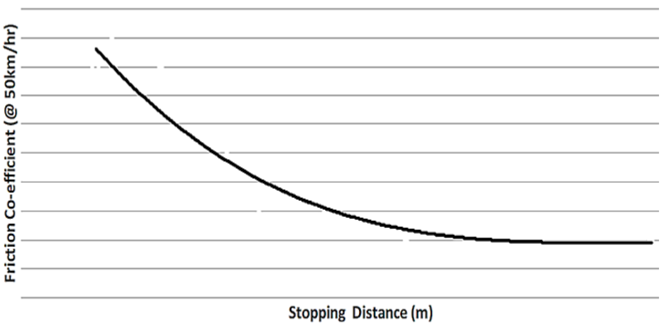


Figure 2. Relationship between stopping distance and friction.

The degree of friction offered by road surfaces has previously been associated with several road crashes by [33], linking uncontrolled skidding and subsequently accidents, to low traction offered by low frictional resistance characteristics between tyre and pavement. The situation is worsened by wet surface conditions where even large vehicles such as commercial aircraft skidding off runways in wet conditions have become a somewhat reoccurring incidence across the globe. Hence, [34] identified the frictional resistance of paved surfaces as being a fundamental feature of driving, ensuring the safe manoeuvring of dynamic bodies in both the longitudinal and transversal directions when moving on them. As clearly illustrated by [35] in Figure 2, the stopping distance a vehicle will traverse after braking is inversely proportional to skidding resistance which implies that a driver will travel a shorter distance on a road of good skid resistance to initiate the necessary evasive actions to prevent collision, as opposed to the longer distance required on a road of poor skid resistance. The lubricating effects of water on paved surfaces on the reduction in the fraction of the tyre/road contact area was demonstrated by [36], showing losses in friction forces generated ultimately leading to a reduced friction coefficient, and by extension the skid resistance. Similarly, [37] described the effect of weather changes on friction coefficient, revealing variations over dry-wet-dry periods. The relationship between road surface water depth and tyre/road friction has also been a subject of research interest with [38], [39] and [40] affirming that the coefficient of friction ($\mu = F/F_w$), which happens to be the ratio of the tangential force exerted by the rolling tyre and the force due to its weight as illustrated in Figure 3, varies as the logarithm of water depth, where it may be independent of water depth at low speeds (up to 50 km/h) but strongly influenced by water depth at high speeds (96 km/h or greater).

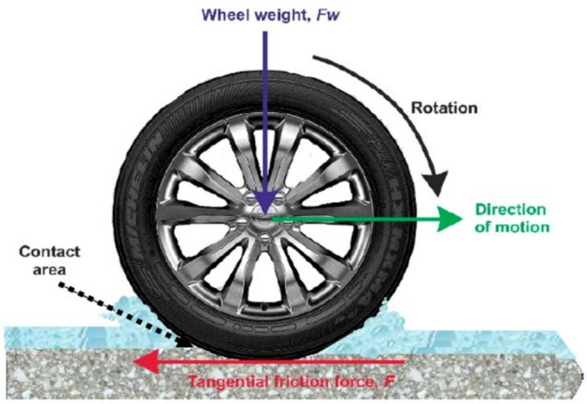


Figure 3. Various forces in action during a tyre-pavement interaction [33].

As earlier stated, this study investigates induced energy transfer effects in smart heating pavements, employing mathematical modelling of the physics of heat and mass transfer between boundaries of different phases of matter. This aim is to decrease or prevent unintended and unrestricted road surface lubrication during wet conditions or instances of incursions from overflowing drainage systems resulting in microflooding of sections of the road. According to the principles of fluid dynamics, a viscous fluid flowing over a stationary impermeable solid or rigid interface, or vice versa, essentially does so at a zero velocity relative to the fixed surface's boundary as depicted in Figure 4. The modifying effects of this multi-phase interaction arising from adhesion or cohesion forces, and conductive or inductive heat transfer remain primarily concentrated and significant at the regions adjacent to, and close to the different phase boundaries known as the boundary layers.

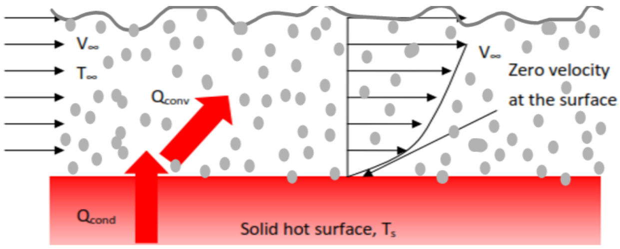


Figure 4. Energy and mass exchange by fluid flow over a flat solid homogenous surface.

As a result, for this case of a microflooded pavement of flood depth less than 3cm from the phase boundaries and flow velocity ranging between 0m/s (fully stagnated) and 3m/s (corresponding to the external frictionless flow), the boundary layer theory will be applied.

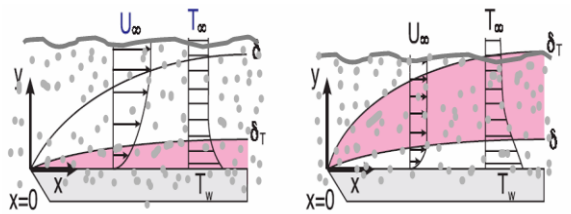


Figure 5. Development of boundary layers due to fluid flow over a flat solid homogenous surface [41].

As depicted in Figure 5, a numerical analysis will be carried out on an impermeable horizontal flat sectional model of a pavement with water moving continuously at a constant velocity and maintaining a constant temperature at the entry point. The boundary layer theorems of flow, heat and mass interaction will be carried out, and the energy exchange and transfer between both media from the surface of contact to the free stream of the fluid will be characterised and probed for drainage acceleration application either by inertial induction or thermal dispersion of the flowing pool of water.

3. Methodology

3.1. Modelling Assumptions

In the analysis of this problem, the following modelling assumptions were adopted:

- All flow is steady, viscous, incompressible and Newtonian.
- A perfectly flat and horizontal pavement surface geometry is assumed.
- All physical properties of the fluid are to remain constant.
- Dimensionless variables and similarity solutions where the stream function is uniform across the flow boundary layers are to be adopted in governing equations transformation.

Table 1. Definition of various terms in the equations 1 – 12.

T_w, C_w	Plate temperature, concentration	v	Kinematic viscosity
T_∞, C_∞	Ambient temperature, concentration	μ	Dynamic viscosity
Re_x	Reynolds number	δ	Boundary layer thickness
D_B	Brownian diffusion coefficient	δ_t	Thermal boundary layer thickness
D_T	Phoretic diffusion coefficient	α	Thermal diffusivity
L_1	Dimensionless slip factor	τ	Surface shear stress
Nb	Brownian Motion parameter	η	Similarity variable
Nt	Phoresis parameter	Ψ	Stream function
Pr	Prandtl number	θ	Dimensionless temperature
Sc	Dimensionless Schmidt parameter	Ø	Dimensionless concentration
S_n	Permeability parameter	$\theta'(0)$	Reduced Nusselt numbers
S_p	Surface roughness factor	$Ø'(0)$	Reduced Sherwood numbers
T, C	Temperature, Concentration	f_n	Dimensionless nth derivative of a stream function
f''	Surface friction coefficient	f'	Velocity ratio

3.2. Governing Equations

The basic governing equations are representative of the fundamental physical laws that govern the process, which in turn form the mathematical basis for the analysis. A two-dimensional boundary layer flow and heat transfer analysis of a steady, laminar, incompressible but viscous fluid moving horizontally past a heated surface is hence considered. The conservation equations of continuity, momentum, energy and concentration in Equations 1 – 4 respectively in their non-linear partial differential forms, were transformed to linear ordinary differential equations (ODEs) using similarity solutions of appropriate stream functions listed in Equations 5 – 8. The similarity functions, adopted from the study carried out by [42] were based on the fluid properties and shape of the velocity profiles of flow, shown in Figure 5, which suggests a geometrical similarity, differing only by a stretching factor in the vertical dimension as a function of the distance along the horizontal surface of the flow. The transformed linear ODEs were then solved using the Runge-Kutta numerical method, subject to the boundary conditions for the velocity, temperature and concentration field listed respectively in Equations 9 and 10. The terms in the equations are provided in Table 1.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} + \tau\left\{D_B\frac{\partial C}{\partial y}\left(\frac{\partial T}{\partial y}\right) + \frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right\} \tag{3}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_B\left(\frac{\partial^2 C}{\partial y^2}\right) + \frac{D_T}{T_\infty}\left(\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

$$\Psi(x,y) = \sqrt{u_\infty \nu x}\, f(\eta) \tag{5}$$

$$\eta = \left({}^{y}/_{x}\right)(Re_x)^{\frac{1}{2}} = y\left(\frac{u_\infty}{\nu x}\right)^{\frac{1}{2}} \tag{6}$$

$$\theta(\eta) = \left(\frac{T - T_\infty}{T_w - T_\infty}\right); \tag{7}$$

$$\text{Ø}(\eta) = \left(\frac{C - C_\infty}{C_w - C_\infty}\right) \tag{8}$$

At y = 0

$$u = L_1\left(\frac{\partial u}{\partial y}\right); \tag{9a}$$

$$v = -\frac{1}{2}\left(\frac{U_\infty \nu}{x}\right)^{\frac{1}{2}} S_n\,; \tag{9b}$$

$$T = T_w; \tag{9c}$$

$$C = C_w; \tag{9d}$$

At y → ∞

$$u \rightarrow U_\infty; \tag{10a}$$

$$v \rightarrow 0; \tag{10b}$$

$$T \rightarrow T_\infty; \tag{10c}$$

$$C \rightarrow C_\infty; \tag{10d}$$

By transforming the partial differential equations 1 – 4, *u* and *v* were obtained in terms of the stream function. By substituting them and other obtained derivatives, Equations 2 – 4 transform respectively to Equations 11 – 13;

$$\frac{\partial f_3}{\partial \eta} = -\frac{1}{2} f_1 f_3 \tag{11}$$

$$\frac{\partial \theta_2}{\partial \eta^2} = \Pr\left[-0.5 f_1 \theta_2 - Nb\,\theta_2 \text{Ø}_2 - Nt\,{\theta_2}^2\right] \tag{12}$$

$$\frac{\partial \text{Ø}_2}{\partial \eta^2} = -\frac{Nt}{Nb}\frac{\partial^2 \theta}{\partial \eta^2} - 0.5 Sc f_1 \text{Ø}_2 \tag{13}$$

With Equations 11 – 13, now first-order ordinary differential equations, solutions are subsequently obtainable and thus computationally evaluated by developing step-wise numerical solution algorithms. This was done using the Runge-Kutta differential equation solver and executed in commercial computational software MATLAB ® as illustrated in Figure 6.

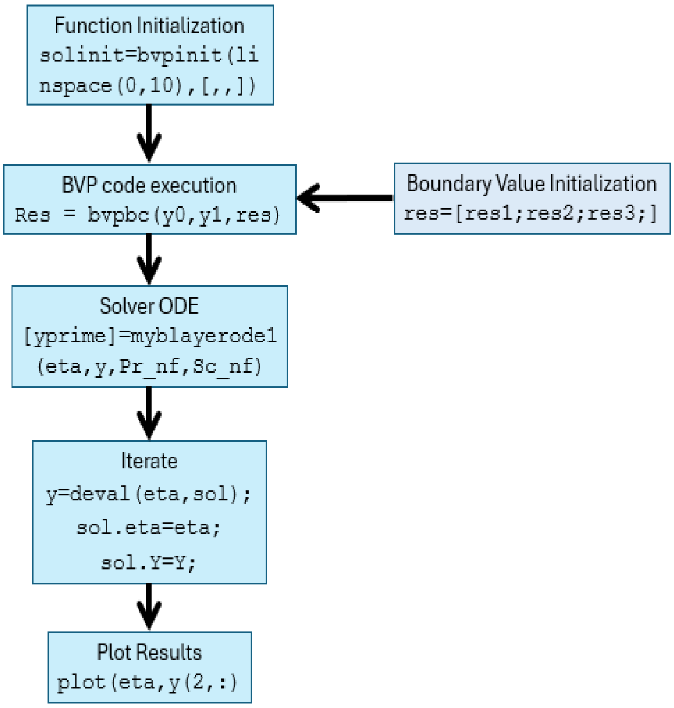


Figure 6. The numerical solution of the governing equations in the code solver environment.

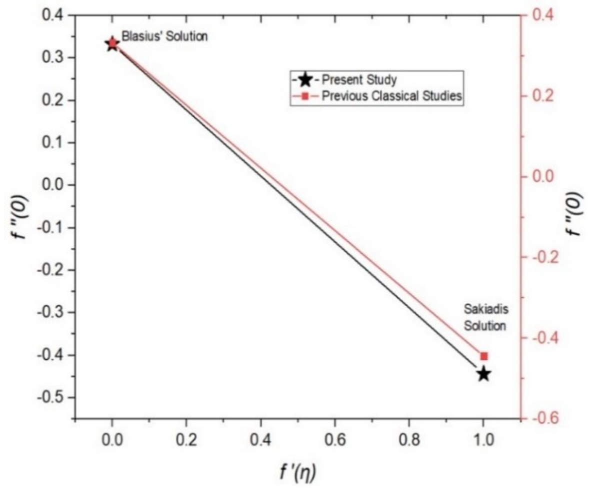
4. Results and Discussion

Equations 11 – 13 were solved as boundary value problems. In such instances as characterized by boundary value problems, the solution satisfies boundary surface characteristic conditions such as the surface roughness factor ($\mathcal{S}_{\mathrm{p}}(\mu)$), permeability ($\mathcal{S}_{\eta}$), conduction and diffusivity, ably represented in the form $y' = f(x,y)$, with 'x' being the independent variable, 'y', the dependent variable, and y' representing the derivative (dy/dx), of y with respect to x. Such that:

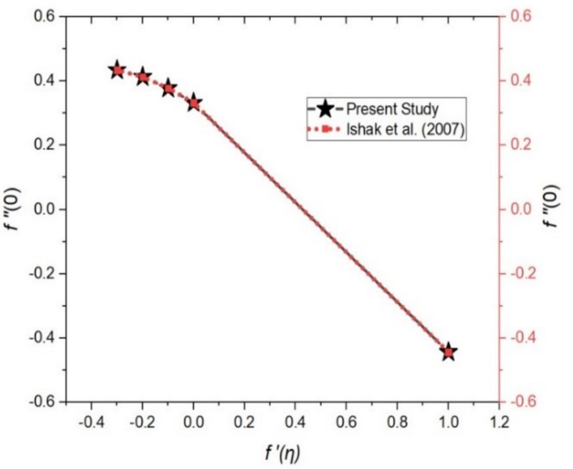
$$y' = f(x,y,p) \tag{14}$$

subject to boundary conditions:

$$g(y(a), y(b), \cdots, y(n), p) = 0) \tag{15}$$



(a)



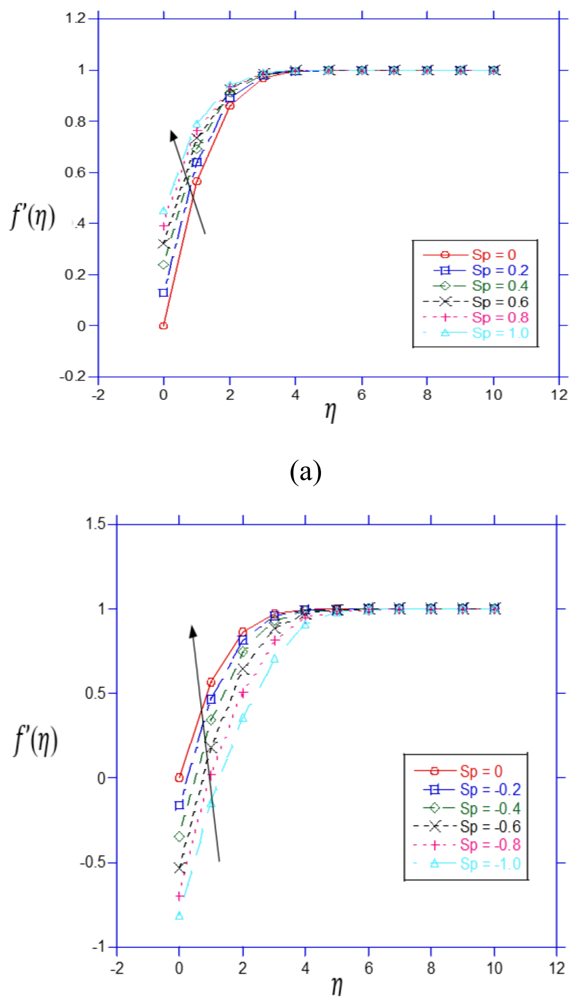
(b)

Figure 7. Validation of results of the current study with previous similar studies: (a) Classical Blasius and Sakiadis solutions (b) Ishak et al.'s solution

For the various values of the parameters of interest which include the velocity and temperature distributions, friction fact, velocity ratio, Nusselt and Sherwood Numbers, results were computed by resolving the corresponding ordinary differential equations for the evaluated parameters as they apply to drainage acceleration via energy absorption in futuristic smart municipal pavements. The results are forthwith presented and discussed. However, in order to validate the accuracy of the results obtained through the numerical method employed, the results for the surface friction coefficient ($f''(0)$), reduced Nusselt $\theta'(0)$ and Sherwood $\emptyset'(0)$ numbers were compared with previous analytical studies presented in Figures 7(a) and 7(b).

The above-mentioned results were analysed in comparison with previous analytical results published on similar studies such as Blasius' and Sakiadis' exact solutions utilizing Similarity methods [43]. Their studies remain to date notable analytical solutions of flow energy and mass conservation without inertia linearization from the solid surface into the flow domain. Additionally, comparisons were made with the study conducted by [44]. Through these comparisons, direct correlations were established, thereby instilling confidence in both the method used and the results derived from it.

Presented in Figures 8(a) and 8(b) is the velocity distribution of micro flood water flowing freely over the pavement, as modelled in this study, showing the streamlined contours of the flow field represented by η. As illustrated, the flow progresses for various values of flow slip governed by the surface roughness factor ($\mathcal{S}_{\mathrm{p}}(\mu)$), from the fluid-solid surface at zero to the ambient. The flow patterns exhibit similarity across all cases, with the profile originating from the wall at zero and curving upwards, akin to the classical Blasius problem, before asymptotically approaching free stream values at an inflexion point where $\eta \approx 4$. This point defines the edge of the boundary layer, where frictional effects due to forces of cohesion and adhesion can be felt by the flowing fluid.



(a)

(b)

Figure 8. Velocity distribution profile curves for
(a) $\mathcal{S}_{\mathrm{p}}(\mu)$ = (0: 0.2 : 1) @ $f'(\eta)$,
(b) $\mathcal{S}_{\mathrm{p}}(\mu)$ = $(-1$: 0.2: 0) @ $f'(\eta)$.

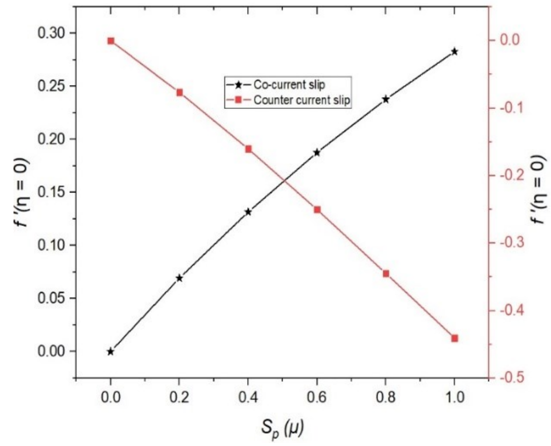


Figure 9. Velocity distribution profile curves @ $f'(0)$ for ($\mathcal{S}_{\mathrm{p}}(\mu)$ = $(-1$: 0.2: 1).

At the surface of interaction where $\eta = 0$, the velocity ratio for the co-current ($\mathcal{S}_{\mathrm{p}}(\mu)$ =+ve) and counter-current slip factors ($\mathcal{S}_{\mathrm{p}}(\mu)$ = -ve) increase and decrease respectively with the slip factor as shown in Figure 9. These scenarios of flow regimes revealed by these results are significant in their effects of boundary layer thickness on flow acceleration. While taking cognisance of the fact that the fluid velocity changes gradually from zero at the wall to that of the freestream, transitioning from a stationary state to the overall flow speed, with increasing slip factor however, the fluid near the boundary approaches the free streamflow speed due to a thinner boundary layer, leading to enhanced flow acceleration. Consequently, the fluid closer to the pavement surface moves at a higher velocity.

As a function of the surface roughness, it only infers that the flow acceleration gets influenced to proceed more rapidly by methodically controlling the roughness of the pavement's surface in contact with the flowing water pool. The knowledge of this can have significant implications on aspects of pavement design and construction, material selection, and overall engineering performance. It's worth noting that increased friction reduces slip, whereas reduced surface friction increases flow slip and, consequently, the velocity ratio. It will however require more in-depth investigations to identify the optimal balance points between frictional characteristics in the design and engineering of smart pavements that ensure enhanced flow acceleration for drainage purposes yet maintain appropriate levels of vehicular skid resistance to ensure traffic safety on these roads.

The contributions of heat transfer to the enhancement of low acceleration through convective action, variations in mass concentration, and buoyancy effects were similarly investigated, and the method was validated by the comparisons of the reduced Nusselt $\theta'(0)$ and Sherwood $\emptyset'(0)$ number results from the current study with those of a previous study by [45], as presented in Table 2.

Table 2. Validation of the current model results.

	$\theta'(0)$	$\emptyset'(0)$
Falana and Mensah	-0.53622	-0.39648
Present Work	-0.536219	-0.39648

Figures 10(a) and 10(b) present the temperature and mass concentration profiles due to the intensified activation of Brownian motion and phoretic tribological effects among interacting fluid particles respectively. These effects are initiated by the variation in the quantum of thermal and mass transport energy existing between the energy-absorbent smart pavement surface and the flood water encountering it at the solid-fluid interface. This Brownian motion and phoretic parameters Nb and Nt respectively are defined in Equations 16 and 17 by:

$$Nb = \frac{\tau}{\nu} D_b (C_w - C_\infty) \qquad (16)$$

$$Nt = \frac{\tau}{\nu} \frac{D_T}{T_\infty} (T_w - T_\infty) \qquad (17)$$

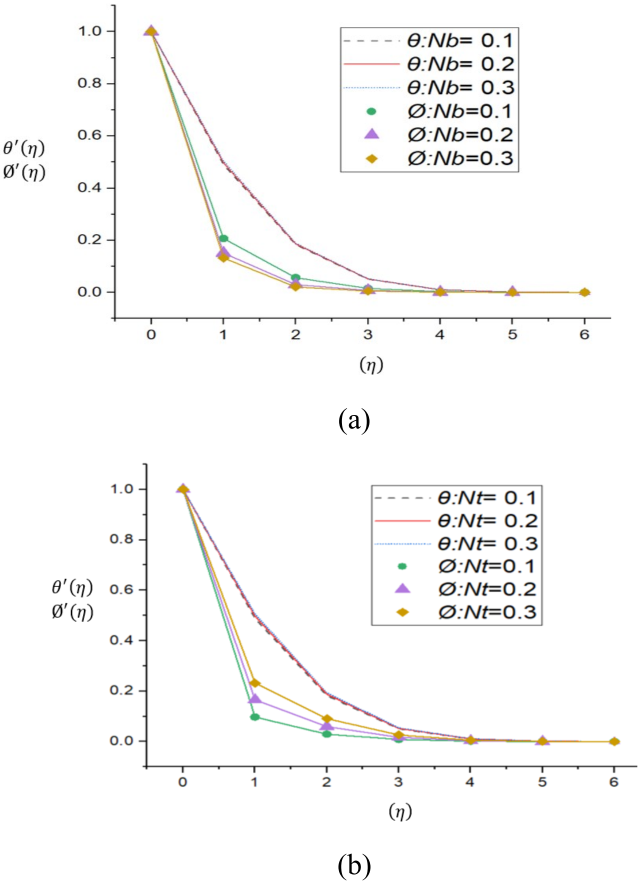


Figure 10. Temperature and concentration distribution profiles at full velocity slip and constant Prandtl parameter (A) at variable Nb parameters (B) at variable Nt parameters.

The profiles of both thermal energy and mass transfer descending from the wall at $\eta = 0$ into the freestream are indicative of the occurrence of the highest transfer of heat and mass at the interface of interaction at the boundary between the pavement surface and the water. However, as illustrated in Figure 10 (a), variations in the Brownian motion of the fluid particles seem not to have any significant or discernible effects on heat transfer rates $\theta'(\eta)$, suggesting that its contribution to heat dissipation is relatively minor.

Conversely, the mass concentration $\emptyset'(\eta)$ is perturbed by increasing Brownian motion. As the Brownian motion increases, the boundary layer thins, leading to faster acceleration of flow and bringing the rate of mass transfer closer to that of the free stream at the wall. This contributes to increased momentum transport and overall drainage acceleration over the surface. The induced increase in Brownian interaction promotes more random movement of fluid particles, influencing the dispersion and distribution of mass within the system. This accelerates the removal of water or other contaminants from the pavement structure, contributing to effective drainage.

As depicted in Figure 10 (b), phoretic action due to induced gradients in the temperature of interacting particles of the fluid showed an influence on mass transfer while insignificantly affecting heat transfer rates. This is also suggestive of a more dominant effect of particle motion on the dispersion and distribution of mass within the system as a consequence of the thinning of the region affected by frictional forces between the streamlines as the phoretic parameter decreases. While heat transfer rates remain largely unaffected by the phoretic action in this instance, phoretic action enhances the mixing and diffusion of particles, leading to a more uniform distribution of the mass concentration. This perturbation of mass concentration helps in the transport and spreading of mass, accelerating flow and potentially aiding in the effective drainage from the pavement structure.

The effective contribution of thermal or mass diffusion in promoting flow acceleration, as influenced by variations in the Prandtl parameter is presented in Figures 11a and b. The depictions show the variation in the Prandtl parameter and its attendant effect on the thermal energy and mass transfer rates in the boundary layer profile. While changes in boundary layer thickness typically do not directly impact the Prandtl number as it is an inherent fluid property, there are indications that some methodical alteration of this property has an inverse impact on the boundary layer thickness. Prandtl parameter effects were observed to have minimal impacts on mass transfer rates but exert a pronounced effect on thermal energy transfer.

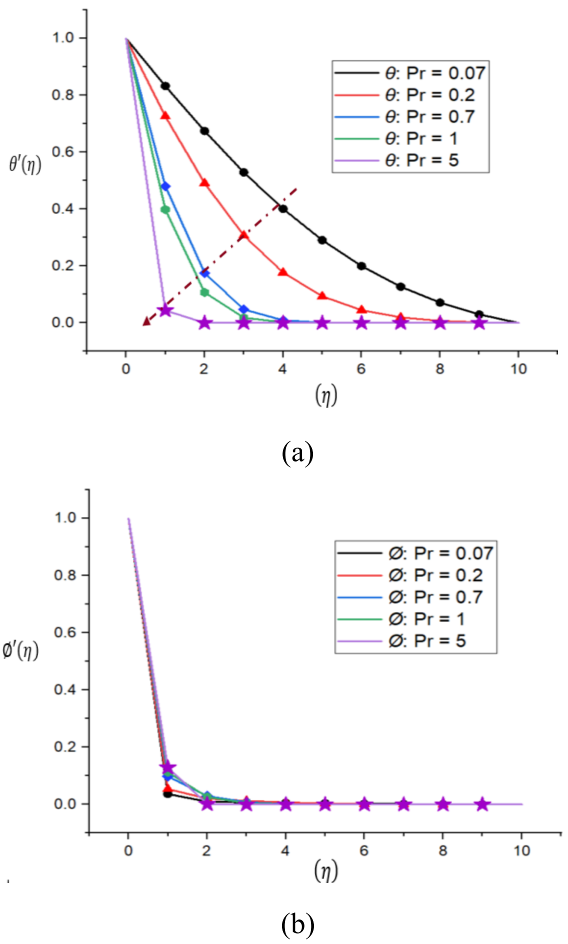


Figure 11. Variation of Prandtl parameter at constant physical flow parameters: (a) Against the rate of heat transfer; (b) Against the rate of mass transfer.

Here so, an increase in the parameter alters the thickness of the boundary layer, decreasing it, and hence, indicating the extent to which flow acceleration is influenced by induced viscous effects compared to thermal gradient-induced diffusion effects. The Prandtl number affects the balance between momentum and thermal diffusivities in the fluid and thus impacts the rate at which energy is transported. At low Prandtl numbers, diffusion is essentially driven by the existing thermal gradients as opposed to kinematic or momentum effects, while the opposite is the case as the parameter increases. With increasing momentum diffusivity and the progressive thinning of the boundary layer, there tends to be more pronounced flow variations and, consequently, stimulation of accelerated flows. Where the application is geared towards heating the pool to induce accelerated evaporation and drying, thinning of the boundary layer hastens the heat transfer process due to the reduced thermal resistance offered by the steep relative velocity gradient between the flow streamlines. Conductive heat transfer is enhanced from the solid boundary to the fluid, as well as across the layers of the fluid.

Flow acceleration influenced by the methodical control of pavement surfaces suggests that engineers can succeed in preventing common issues such as hydroplaning and water-induced structural damage through the optimization of surface texture parameters during the design and construction phases of road projects. Automation and sensory technology can also be integrated into these phases to ensure dynamic monitoring and adjustments of performance under varying weather conditions. Furthermore, advanced materials and coatings that enhance the Brownian interaction of fluid particles can contribute to the pavement's structural integrity and also support environmental sustainability by reducing the need for chemical cleaners and minimizing runoff pollution. Adaptation of real-time data acquisition and management systems, with thermal or surface slip control features can help to optimize flow conditions in-situ and prevent damage caused by prolonged water exposure. This level of adaptability ensures that the pavement can respond to changing conditions, enhancing its durability and performance. Additionally, smart pavements could communicate with vehicles and infrastructure, providing data on surface conditions and potential hazards, further enhancing road safety and efficiency. This approach not only extends the lifespan of the pavement but also enhances safety for vehicular traffic by maintaining better traction and reducing the risk of accidents. These innovations have the potential to transform the infrastructure landscape, aligning with the goals of sustainable development and smart city initiatives. Furthermore, they are expected to inform the design and engineering of future road pavements that prioritize safety and environmental sustainability within smart cities, in line with road infrastructure safety management systems such as the ones highlighted by [46]. According to [47], attention is shifting towards novel data flow and management approaches. With advancements in design and innovation, the installation of road pavements with embedded digital infrastructure to obtain and transmit traffic information to base stations from proper monitoring, control and management response is becoming increasingly feasible.

5. Conclusion

In conclusion, this study demonstrates the feasibility of leveraging futuristic smart pavement systems to enhance road surface drainage and mitigate the impacts of microfloods caused by precipitation runoff, providing valuable insights into the design and engineering of next-generation smart road pavements. Mathematical modelling methods were employed in investigating the potential of harvesting energy from road pavements as a means to accelerate the drainage of surfaces affected by stagnant or freely flowing microfloods. The classic boundary layer theory of flow, heat and mass transfer over flat surfaces was used to analyse the energy and momentum transfer effects on flow acceleration, with the modelling of the flow process into differential equations which were solved numerically, imposing appropriate similarity functions and boundary conditions on streamlines of layers of fluid flowing over the flat surfaces. The interaction between the solid and fluid interfaces was accounted for in the exchange of momentum, energy and mass at the boundary between the two phases and flow parameters' influence on the alteration of the boundary layer profile, in turn, flow acceleration on flat-surfaced energy dissipating smart pavements were evaluated. The study highlighted the impact of energy exchange, thermal diffusivity, and viscous diffusivity on flow acceleration, specifically how they affect the thickness profiles of the boundary layer in both the momentum flow regime and the thermal flow regime.

Moving forward, further research is necessary to explore the practical implementation of smart pavement systems and evaluate their effectiveness in real-world conditions. Continued advancements in technology and materials science will drive innovation in smart infrastructure, offering new opportunities to improve road safety and sustainability in smart cities. Furthermore, the integration of smart pavements allows for the implementation of energy harvesting, absorption, conversion, and induction transfer for various applications. One such application is the acceleration of drainage for microflooding and other instances of roadway surface incursions. Consequently, by considering these factors in pavement design, engineers can optimize drainage performance and enhance the resilience of road networks in urban environments.

Acknowledgements

The authors would like to acknowledge the Centre for Climate Change, Water Management and Disaster Management, Department of Civil Engineering, Tshwane University of Technology, Pretoria and the National Research Foundation (NRF), South Africa for their technical and financial support towards the success of this project.

Competing Interest Statement

The authors declare that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data and Materials Accessibility

Supplementary materials and data used in this research are accessible upon request. For access, please contact the corresponding author.

Author Contributions Statement

The authors generally contributed in equal measure to this study but specifically in the following ways – Festus Fameso: Conceptualization and Writing (original draft). Julius Ndambuki: Conceptualization and review. Williams Kupolati: Programming and Synthesis. Jacques Snyman: Data Analysis.

References

[1] K. S. Khattak, and Z. H. Khan, "Evaluation and Challenges of IoT Simulators for Intelligent Transportation System Applications," *Science, Engineering and Technology*, vol. 4, no. 1, pp. 94-111, 2024.

[2] B. Memic, A. H. Dzukbur, E. Avdagic-Golub, "Green IOT: Sustainability Environment and Technologies," *Science, Engineering and Technology*, vol. 2, no. 1, pp. 24-29, 2022.

[3] N. Lajnef, M. Rhimi, K. Chatti, L. Mhamdi, F. Faridazar, "Toward an Integrated Smart Sensing System and Data Interpretation Techniques for Pavement Fatigue Monitoring," *Computer-Aided Civil and Infrastructure Engineering*, vol. 26, no. 7, pp. 513-523, 2011.

[4] P.G. Hubbard, R. Ou, T. Xu, L. Luo, H. Nonaka, M. Karrenbach, K. Soga, "Road deformation monitoring and

event detection using asphalt-embedded distributed acoustic sensing (DAS)," *Structural Control and Health Monitoring*. vol. 29, no. 11, pp. e3067, 2022.

[5] J.H. Jeong, H. Jo, G. Ditzler, "Convolutional neural networks for pavement roughness assessment using calibration-free vehicle dynamics," *Computer-Aided Civil and Infrastructure Engineering*, vol. 35, no. 11, pp.1209-1229, 2020.

[6] I. Khan, K. S. Khattak, Z. H. Khan, T. A. Gulliver, "Impact of Road Pavement Condition on Vehicle Free Flow Speed Vibration and In-vehicle Noise, *Science, Engineering and Technology*, vol 3, no. 1, pp. 1-8, 2023.

[7] S. Ahmad, M. Mujeebu, M. A. Farooqi, "Energy harvesting from pavements and roadways: A comprehensive review of technologies, materials, and challenges," *International Journal of Energy Research*, vol. 43, no. 6, pp.1974-2015, 2020.

[8] S. Dong, W. Zhang, A. D'Alessandro, B. Han, "Developing highly conductive asphalt concrete by incorporating stainless steel fibres/wires for smart pavement," *Journal of Materials Science*, vol. 58. Pp. 1-23, 2023. doi:10.1007/s10853-023-08736-5.

[9] M. Pregnolato, A. Ford, V. Glenis, S. Wilkinson, R. Dawson, "Impact of Climate Change on Disruption to Urban Transport Networks from Pluvial Flooding," *Journal of Infrastructure Systems*. vol. 23, no. 4, pp. 04017015, 2023.

[10] S. Praharaj, T. D. Chen, F. T. Zahura, M. Behl, J. L. Goodall. "Estimating impacts of recurring flooding on roadway networks: a Norfolk, Virginia case study," *Natural Hazards*. vol. 107, no. 3, pp.2363-2387, 2021.

[11] Z. Y. Jasour, A. C. Reilly, G. L. Tonn, C. M. Ferreira. "Roadway flooding as a bellwether for household retreat in rural, coastal regions vulnerable to sea-level rise," *Climate Risk Management*. vol. 36, 2022.

[12] B. R Rosenzweig, L. Mcphillips, H. Chang, C. Cheng, C. Welty, M. Matsler, D. Iwaniec, C. I. Davidson, "Pluvial flood risk and opportunities for resilience," *WIREs Water*. vol. 5, no. 6, pp. e1302, 2018.

[13] J. E. Schubert and B. F Sanders. "Building treatments for urban flood inundation models and implications for predictive skill and modelling efficiency," *Advances in Water Resources*. vol. 41, pp. 49-64, 2012.

[14] W. Wang, S. Yang, H. E. Stanley, J. Gao. "Local floods induce large-scale abrupt failures of road networks," *Nat. Commun.* Vol. 10, no. 1, pp. 2114, 2019.

[15] K. C. Van Ginkel, E. E. Koks, F. De Groen, V. D. Nguyen, L. Alfieri, "Will River floods 'tip' European road networks? A robustness assessment," Transportation *Research Part D: Transport and Environment*, vol. 108, pp. 103332, 2022.

[16] S. Loreti, E. Ser-Giacomi, A. Zischg, M. Keiler, M. Barthelemy, "Local impacts on road networks and access to critical locations during extreme floods,"*Sci Rep.,* vol. 12. No. 1, Jan 28:1552, 2022.

[17] K. Shaaban, "Challenges and Lessons Learned from Building a New Road Drainage System in a Developing Country," *Intermountain Engineering, Technology and Computing (IETC)* [Online]. Accessed: September 2023.

[18] A. A. Rajput, S. Nayak, S. Dong, A. Mostafavi, "Anatomy of perturbed traffic networks during urban flooding," *Sustainable Cities and Society*, vol. 97, 2023.

[19] A. Kadaverugu, K. V. Gorthi, N. R. Chintala, "Impacts of Urban Floods on Road Connectivity - A Review and Systematic Bibliometric Analysis," *Current World Environment*, vol. 16, no. 2, pp. 575-593, 2021.

[20] J. G. Lee, A. Selvakumar, K. Alvi, J. Riverson, J. X. Zhen, L. Shoemaker, F. A. Lai. "Watershed-Scale Design Optimization Model for Stormwater Best Management Practices," *Environ. Model. Softw*, vol. 37, pp. 6–18, 2012.

[21] E. Schnebele, G. Cervone, S. Kumar, N. Waters, "Real-Time Estimation of the Calgary Floods Using Limited Remote Sensing Data," *Water*, vol. 6, no. 2, pp. 381-398, 2014.

[22] N. A. Aziz, R. K. Price, Z. Vojinovic, A. F. Abdullah, "Improved methodology for processing raw LiDAR data to support urban flood modelling – accounting for elevated roads and bridges," *Journal of Hydroinformatics*, vol. 14, no. 2, pp 253-269, 2012.

[23] E. Kim, I. Ra, K. Rhee, C. Kim, "Estimation of Real-Time Flood Risk on Roads Based on Rainfall Calculated by the Revised Method of Missing Rainfall," *Sustainability,* vol. 6, no. 9, pp. 6418-6431, 2014.

[24] D. J. Jo, I. O. Son, H. I. Choi. "Development of a New Flood Index for Local Flood Severity Predictions," *Korea Water Resour. Assoc.*, vol. 46, pp. 47–58, 2013.

[25] Y. Yang, S. T. Ng, S. Zhou, F. J. Xu, H. Li, "Physics-based resilience assessment of interdependent civil infrastructure systems with condition-varying components: A case with stormwater drainage system and road transport system," *Sustainable Cities and Society*, vol. 54, 2020.

[26] F. Fameso, D. Desai, S. Kok, D. Armfield, M. Newby. "Residual Stress Enhancement by Laser Shock Treatment in Chromium-Alloyed Steam Turbine Blades," *Materials*, vol. 15, no. 16, pp.5682, 2922.

[27] F. Fameso, D. Desai, S. Kok, M. Newby, D. Glaser, "Simulation of laser shock peening on X12Cr steel using an alternate computational mechanical threshold stress plasticity model," *The International Journal of Advanced Manufacturing Technology*, vol. 111, no. 1, pp.1-11, 2020.

[28] K. L. Knight, G. Hou, A. S. Bhaskar, S. Chen, "Assessing the Use of Dual-Drainage Modeling to Determine the Effects of Green Stormwater Infrastructure on Roadway

Flooding and Traffic Performance," Water, vol. 13, no. 11, 2021.

[29] D. Yu, J. Yin, M. Liu, "Validating city-scale surface water flood modelling using crowd-sourced data", *Environmental Research Letters*, vol. 11, no. 12, pp.1-22, 2016.

[30] F. T. Zahura and J. L. Goodall. "Predicting combined tidal and pluvial flood inundation using a machine learning surrogate model," *Journal of Hydrology: Regional Studies,* vol. 41, 2022.

[31] B. E. Bassey, J. Effiong, "Causes of Localized Road Flooding in Calabar South Local Government Area During Rainfall," *In: 11th Annual National Association of Hydrological Science Conference*, 2021.

[32] H. R. Moftakhari, A. Aghakouchak, B. F. Sanders, M. Allaire, R. A. Matthew, "What Is Nuisance Flooding? Defining and Monitoring an Emerging Challenge," *Water Resources Research*, vol. 54, no. 7, pp.4218-4227, 2018.

[33] H. Astrom, and C. G. Wallman, "Friction Measurement Methods and the Correlation between Road Friction and Traffic Safety. A Literature Review," *Swedish National Rode and Transport Research Institute, Linköping, Sweden*, p. 47, 2001.

[34] H. Pérez-Acebo, H. Gonzalo-Orden, D. J. Findley DJ, E. Rojí, "A skid resistance prediction model for an entire road network," *Constr. Build. Mater.* Vol. 262, p. 120041, 2020.

[35] K. Naidoo, N. Zungu, T. Lewis, "Investigations and Proposals for Investigatory Level Requirements for Skid Resistance Of South Africa's Roads", *In: Virtual Southern African Transport Conference*, 5 - 7 July, 2021.D.

[36] D. F. Moore, "The Friction of Pneumatic tyres," *Elsevier Scientific Publishing Company*. 1975.

[37] D. J. Wilson, "An analysis of the seasonal and short-term variation of road pavement skid resistance," PhD Thesis, University of Auckland, Auckland, Australia, 2006.

[38] A. G. Veith, "Tyres – Roads – Rainfall – Vehicles: The Traction Connection. Frictional Interaction of Tire and Pavement," *ASTM STP 793 (W.E. Meyer and J.Reichter, Eds.), American Society for Testing and Materials*, vol.3, no. 40, 1983.

[39] M. Kane, V. Edmondson, M. Do, V. Cerezo, "Effect of road texture characteristics on skid resistance parametric study via the DFM". 2018.

[40] M. Rasol, F. Schmidt, S. Ientile, L. Adelaide, B. Nedjar, M. Kane, C. Chevalier, "Progress and Monitoring Opportunities of Skid Resistance in Road Transport: A Critical Review and Road Sensors,' *Remote Sens.* Vol. 13, pp. 3729, 2021.

[41] Y. A. Cengel, J. M. Cimbala. "Fluid mechanics: Fundamentals and applications (4th ed.)," *McGraw-Hill Education*, 2017.

[42] A Falana and O. F. Fameso, "Effect of Slip Velocity on Forced Convection Flow, Heat and Mass Transfer Over a Continuous Moving Sheet in a Nanofluid with Suction and Injection," *Journal of Applied Science, Engineering and Technology*, vol. 17, no. 1, pp. 24-30, 2017.

[43] N. D. Katopodes, "Boundary-Layer Flow. In Free-Surface Flow," *Butterworth-Heinemann*, pp. 652-708, 2019, https://doi.org/10.1016/b978-0-12-815489-2.00009-5

[44] A. Ishak, R. Nazar, I. Pop, "Boundary Layer flow of a micro-polar fluid on a continuously moving or fixed permeable surface," *Intl. Journal of Heat and Mass Transfer*, vol. 50, pp. 4743 – 4748, 2007.

[45] A. Falana, and D. Mensah, "Heat Transfer in a Nanofluid flow past a permeable continuous moving Non-isothermal Surface," Masters Dissertation, University of Ibadan, Ibadan, Nigeria. 2014.

[46] F. Kiso, A. Dzananovic, S. Sabanovic-Karicic, "Development of Road Infrastructure Safety Management System According to Updates of EU Directive 96/2008/EC," *Science, Engineering and Technology*, vol. 1, no. 1, pp. 35-41, 2021.

[47] G. Bosurgi, D. Bruneo, F. De Vita, O. Pellegrino, G. Sollazzo, "A web platform for the management of road survey and maintenance information: A preliminary step towards smart road management systems," *Structural Control and Health Monitoring*. vol. 29, no. 3, 2021.