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Structure of Integrated Device for Bicycle Safe Braking and Smart Directional Warning Lights

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(Received August 21, 2025; accepted November 27, 2025)

Keywords: integrated device, bicycles, safety brake, smart directional warning lights

In this study, we present the development of an integrated bicycle safe braking and smart directional warning light system, which is a combination of an advanced braking mechanism with intelligent directional signaling, to significantly enhance rider safety. The system addresses a common safety issue faced by cyclists and motorcyclists: loss of balance and potential flipping due to improper braking techniques, particularly when braking is applied first to the front wheel instead of the rear. Such improper operation often leads to dangerous falls and accidents. To mitigate this risk, the proposed system incorporates a safe braking mechanism that prioritizes rear-wheel braking before applying force to the front wheel. This braking sequence improves overall stability and control during deceleration. Furthermore, the system is integrated with a smart directional warning light function, enabling the brake controller to manage both braking and turn signaling simultaneously. The brake controller is designed to connect seamlessly with the bicycle frame, rider's helmet, and directional warning devices. When the rider initiates a turn—either left or right—while braking, the system automatically activates the corresponding directional warning signals. These visual alerts serve to notify nearby road users of the rider's intended movement, thereby enhancing situational awareness and reducing the likelihood of traffic accidents. Overall, the integration of safety braking with intelligent turn signaling provides a practical and effective solution for improving road safety, especially in urban commuting environments.

1. Introduction

The safety of cyclists has become an increasingly pressing concern, particularly in urban environments where frequent interactions with motor vehicles pose significant hazards. While professional cyclists are generally equipped with protective gear such as helmets and body padding, the vast majority of everyday bicycle users, including commuters, students, and recreational riders, typically ride without substantial safety equipment or signaling devices. As a

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https://doi.org/10.18494/SAM5895

result, numerous accidents have been reported involving cyclists who brake abruptly, make sharp turns, or change direction without prior warning, often leading to collisions with vehicles approaching from either the front or rear. Traditional bicycle braking mechanisms largely rely on mechanical springs. However, in regions with high temperatures, heavy rainfall, and elevated humidity, these components are especially vulnerable to corrosion and mechanical fatigue. Extended or high-intensity use can cause the springs to deteriorate or even fracture, ultimately resulting in brake failure. In such cases, rather than enhancing safety, the braking system itself may become a significant hazard by failing to operate in critical moments, potentially causing serious accidents.[1,2]

Ensuring that each braking action follows the correct procedure is critically important for bicycle safety. The proper braking technique for two-wheeled vehicles involves applying the rear brake first, followed by the front brake. When riding downhill, it is essential to maintain a continuous braking state by using a technique known as “pulsed braking” or “feathering”, which avoids locking the wheels and helps gradually reduce speed through controlled deceleration. Because of the importance of safe braking, numerous studies have focused on the development of reliable and effective braking systems for bicycles.[3,4] For instance, Lie and Sung conducted a comprehensive investigation into the braking performance and safety of bicycles operating on both flat and inclined surfaces. They developed equations of motion for a wheel model in conjunction with an ideal synchronous braking model, aiming to minimize braking distance and improve stability during riding. Their simulations, which considered various bicycle geometries, brake force distribution ratios, and road surface conditions, led to the proposal of an optimal braking design for enhanced safety and performance.[5]

In parallel, the automobile industry has made substantial advancements in improving vehicle safety, particularly through the development of automated and electronic braking systems.[6] Technologies such as automatic emergency braking, traction control, brake assist, antilock braking systems, and electronic stability control have been widely implemented to help drivers maintain better control and reduce accident risks. These systems not only enhance the safety of vehicle occupants but also contribute to the protection of pedestrians and cyclists. Recent innovations have also extended into bicycle safety. For example, Corno *et al.* proposed an antilock braking system for bicycles equipped with hydraulic brakes. Their design utilizes an electrostatic hydraulic actuator that modulates braking pressure when a loss of traction is detected, while remaining passive under normal riding conditions. The authors detailed the system’s control architecture and introduce three deceleration controllers—bang-bang, second-order sliding mode, and proportional integral—to improve braking performance under various scenarios.[7]

Soni *et al.* investigated the component selection process for bicycle braking systems, including detailed calculations of braking force, torque, and brake bias. The safety and reliability of using a bicycle rotor were validated through analytical calculations and thermal analysis.[8] In a related study, Chen *et al.* introduced a novel high-power switching valve specifically developed for hydraulic disc brake systems in bicycles, incorporating a hydraulic antilock braking function. Finite element analysis was employed to model and optimize the internal geometry of a solenoid valve, using both 2D and 3D simulations to evaluate the magnetic flux. The optimized valve design achieved a maximum output force of 280 N and a linear stroke of approximately 3.5 mm.[9] Further advancing the field, Salman *et al.* developed a physics-based model to analyze bicycle braking dynamics under critical safety scenarios, including fault conditions in the braking system.[10]

Lie and Sung conducted an investigation into the bicycle braking performance on both straight and inclined paths, highlighting the inherent safety risks associated with inadequate braking force distribution, delayed braking response, and the absence of early fault detection mechanisms.[5] Motivated by these safety challenges, in the present study, we aim to develop a fully integrated bicycle safety device that simultaneously enhances braking performance, reduces operating effort, and provides smart directional warning capabilities. Our research is focused on structural innovation and sensor integration to achieve a multifunctional and reliable safety solution. To address the mechanical limitations of traditional braking systems, we incorporate a dual-line brake architecture with a two-to-one piston linkage, forming a piston-assisted, energy-saving brake mechanism. This configuration allows the left compartment of the control box to house two force-transmitting rods connected to the left and right brake levers. Each rod independently drives the front and rear brake cables, with the rear cable attached at a position farther from the rotation axis and the front cable connected closer to it. This geometric arrangement ensures that braking is applied in the safer sequence—rear first, then front—through differential torque. The piston-assisted linkage reduces the rider's required hand force while maintaining consistent output force, thereby improving both comfort and braking stability during long-term use.

Embedded force, tension, and displacement sensors further transform the braking mechanism into an intelligent module capable of real-time monitoring the brake lever movement, cable tension, spring behavior, and mechanical response. These sensing functions enable the early detection of abnormal states such as wear, slippage, misalignment, and spring fatigue conditions that conventional bicycle systems cannot identify. This predictive diagnostic capability not only reduces the likelihood of sudden braking failure but also establishes the structural foundation for predictive maintenance. In parallel, the right compartment of the integrated control box supports a smart directional warning system, controlled via a touch- or smartphone-based interface. This system enables an intuitive activation of turn signals and hazard lights, providing clear visual cues of the rider's intended maneuvers. By combining sensor-based control with immediate lighting feedback, the system reduces the risks associated with unpredictable lateral movements and improves the visibility of cyclists in low-light or complex traffic environments. Overall, in this study, we will present a comprehensive integrated device that unifies a sensor-enhanced braking mechanism with smart directional warning lights into a single structural platform. The design advances bicycle safety by offering mechanical efficiency, intelligent sensing, predictive maintenance capability, and improved signaling performance. In this study, we demonstrate how sensor technology can be embedded into mobility systems to prevent accidents, strengthen operational safety, and enhance user protection.

2. Methodology

The proposed system consists of six major components.

(1) Dual-hand synchronous front and rear brake system: This mechanism includes a base, a driving pulley assembly, and a cover. The torque transmission unit is composed of a base, a return spring, and a fixed mount, while the linkage pulley assembly consists of a slider and pulley. The synchronous braking mechanism is mounted such that the brake cable head above the bi-directional threaded rod is connected to the rear brake cable, and the cable head below is connected to the front brake cable. Through the design of the bidirectional threaded rod, the displacement of the brake cable heads enables the fine-tuned adjustment of the braking force ratio between the front and rear wheels, thereby enhancing overall braking efficiency.

(2) Bicycle auxiliary lighting system: This lighting assembly consists primarily of a lamp holder, a base plate, and a lamp cover, as shown in Fig. 1(a). Figure 1(a) presents a schematic of the vehicle driving auxiliary light. In the figure, 2 indicates the central spacer positioned along the inner edges of the elongated slots on both sides of the lampshade. Components 4 and 5 denote the spacers aligned with the frame wall of the rotating frame and the annular wall of the lampshade. Components 23 and 33 indicate the supports that rest against the base plate. Component 6 marks the placement location of the direction plate. Component 211 designates the screw shaft hole, while component 214 identifies the adjustment mechanism that allows the upper part of the lamp holder to change its tilt angle. On both sides of the lamp cover are elongated slots with inner-edge spacers. These spacers are aligned in height with the frame

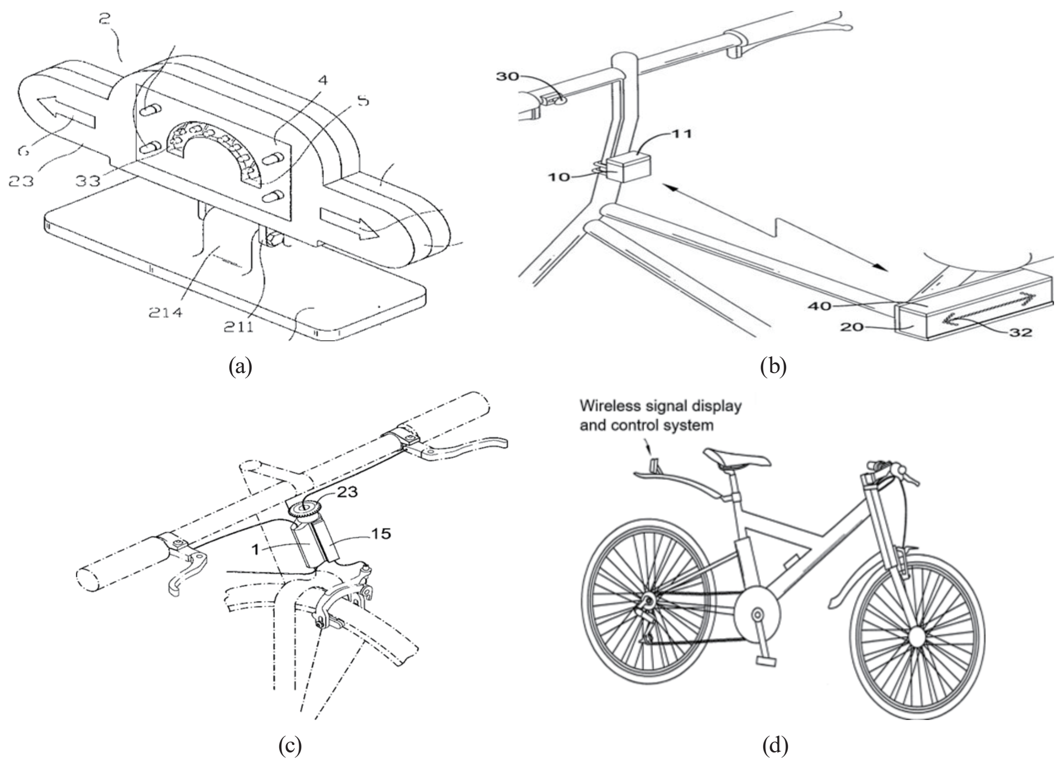

Fig. 1. (a) Bicycle auxiliary lighting system, (b) bicycle indicator unit, (c) switchable synchronous brake mechanism, and (d) wireless signal display and control system.

wall of the rotating bracket and the ring wall of the lamp cover, enabling them to rest against the base plate. This design isolates the light emitted from the directional signal section from that of the braking section. The bottom of the lamp holder is secured to the base via a shaft hole and bolt assembly, allowing the angle of the lamp holder to be adjusted vertically.

(3) Bicycle indicator unit: This unit comprises an operation module and a control module. The operation module includes a housing, a power source, a circuit board, lighting elements, and a wireless receiver, as displayed in Fig. 1(b). Figure 1(b) primarily illustrates the bicycle indicator device. Component 30 indicates the fixing mechanism, which provides convenient operational control. Components 10 and 11 denote the locations of the housing, power supply, and circuit board assembly. Components 20, 32, and 40 indicate the installation positions of the lighting and wireless-receiving elements, sensors, and directional signal displays, respectively. The control module consists of a control component and a mounting bracket. The mounting bracket is integrated with the control component and features a central handlebar interface section. This interface can be securely attached to the bicycle handlebar via a fastening mechanism.

(4) Switchable synchronous brake mechanism: This system includes a fixed component and a switching element, as shown in Fig. 1(c). Figure 1(c) shows the location of the switchable synchronized brake mechanism. Component 1 denotes the fixed and switching elements, while component 23 indicates the latch-type slider assembly, and component 15 represents the slider module. This mechanism is designed to activate the rear brake first, followed by the front brake, achieving a rear-first braking sequence that enhances both efficiency and safety. When the upper slider of the brake assembly is actuated by a pulled brake cable, the protruding key on the upper slider engages with the upper key of the slider set, causing displacement. Consequently, the lower key of the slider set engages the protruding key of the lower slider, thereby synchronously pulling the brake cable connected to the lower slider. The slider set operates independently under the tension from both ends of the brake cables. The switching element, inserted into a dedicated channel, moves within a slot, which limits its maximum rotation and ensures positional alignment through a locating groove.

(5) Wireless signal display and control system: This system is integrated with a bicycle helmet and equipped with a directional sensor, as displayed in Fig. 1(d). The sensor is fixed onto the helmet and detects head movement to generate directional signals. These signals are processed through a wireless transmission unit, which utilizes frequency-hopping and pairing technologies to generate wireless commands. The lighting indicator components are equipped with a wireless receiver unit to receive and execute the corresponding lighting responses.

(6) Bicycle warning light system: This system consists of two major components. (1) Front-mounted controller: Installed on the front section of the bicycle, this unit contains a control module and a wireless transceiver module. (2) Brake signal generator: Designed to be mounted on the bicycle's brake lever, this generator features a strip-shaped insulating body housing two elongated electrodes that are electrically isolated from each other. One end of the insulating body forms a hollow elastic section, within which the two electrodes are normally open and positioned opposite each other. This elastic section is located at the pressure point

of the brake lever. When the rider applies the brake, the elastic section compresses, causing the electrodes to come into contact and generate a brake signal. The opposite ends of the two electrodes are electrically connected to the front controller, forming a signal path. At the rear of the bicycle, the warning light unit is installed, which comprises a processing unit, a wireless transceiver module, and multiple light modules. Each light module is connected to the output of the processing unit. The wireless transceiver module communicates with the front controller via a wireless link, enabling the real-time transmission of braking signals. Upon receiving the signal, the processing unit activates the corresponding rear light modules to provide a visual warning to following vehicles or riders.

The operational flow of this sensing system is illustrated in Fig. 2. To ensure efficient power management, both the sensor signal processing unit within the safety brake box and the front/rear LED warning lights share a common power source. Power can be supplied through multiple means, including hub dynamos, wheel rotation generators, wind turbines, solar cells, or standard lithium or lithium-iron batteries. However, note that while wind turbines are conceptually listed as a potential power source, the practical power output of a wind turbine mounted on a bicycle is generally insufficient to reliably drive the sensing and LED systems due to the low and variable wind speeds during typical cycling. Therefore, in practice, hub dynamos, wheel generators, solar cells, or rechargeable batteries are preferred as feasible and reliable power sources. Because of space constraints, the helmet's LED warning module is powered separately by a compact lithium battery to ensure consistent operation without adding significant weight.

3. Results and Discussion

By extensive data collection, in-depth research, and circuit design efforts, we have developed a functional and integrated signaling system. The circuit schematic, as illustrated in Fig. 3, serves as the foundation for the system's operation. The control unit is designed to respond to various brake lever actions in accordance with whether the left brake is engaged, both brakes are pressed simultaneously, or only the right brake is applied. Depending on the braking state, the

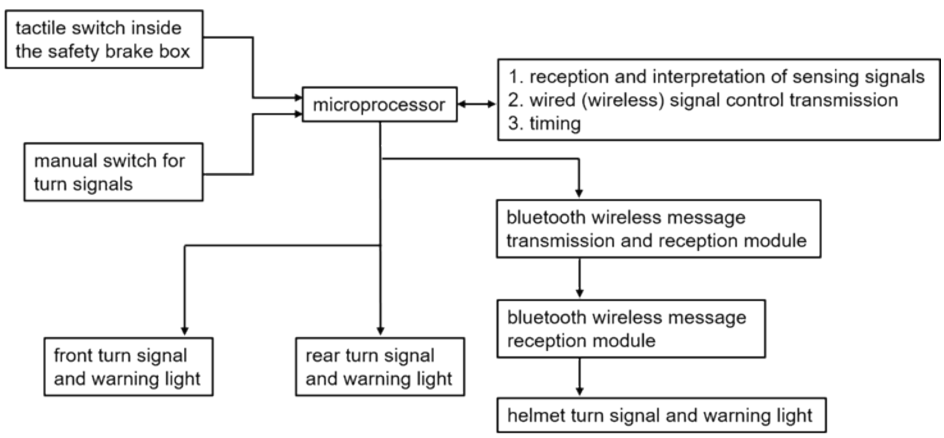

Fig. 2. Operational mechanism of the sensing system for smart directional warning lights.

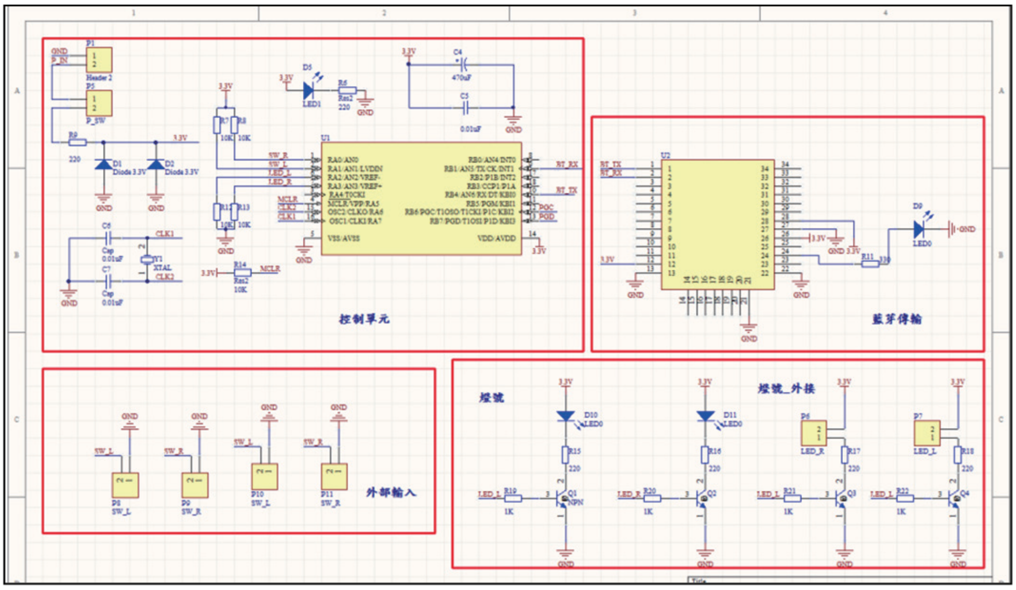

Fig. 3. (Color online) Circuit design schematic diagram.

system activates the appropriate warning signals to alert nearby vehicles and enhance rider safety. The communication process between the control unit and the receiver unit is implemented through a hybrid transmission architecture. After the sensing circuit detects a braking or turning event, the microprocessor processes the signal and triggers the corresponding communication protocol. The system first transmits data through a wired connection within the safety brake box to ensure stable internal signal delivery. Subsequently, the processed command is sent to the external receiver module via a Bluetooth-based wireless communication interface, enabling reliable and low-latency signal transmission to the helmet-mounted or rear-mounted indicator units. The receiver unit then passively receives the Bluetooth signal and decodes the transmitted command. If the decoded signal corresponds to a right-turn action, the right-turn indicator is activated; if it corresponds to a left-turn or braking action, the respective left-turn light or brake light is illuminated. This combined wired–wireless communication design ensures robust signal integrity within the mechanical control box while maintaining flexible and interference-resistant wireless transmission to external display modules. The overall operational flow of the system is outlined in the flowchart shown in Fig. 4. This design demonstrates how a responsive, brake-integrated warning and signaling mechanism can improve communication between cyclists and other road users, potentially reducing the risk of accidents.

Conventional bicycle brake systems typically operate using a single brake cable to actuate both brake arms. In contrast, we introduce a dual-cable mechanism in which two brake cables are simultaneously connected to a single brake caliper, significantly enhancing safety. If one cable accidentally breaks, the other can still function effectively, thereby maintaining braking capability. To achieve this without altering the original structure of the brake caliper, a specially designed actuator capable of enabling either single-cable or dual-cable operation to drive the existing brake system is required. This actuator is referred to as the “dual-to-single piston-type joint”. When one or both brake cables are pulled, the joint activates the brake caliper to clamp

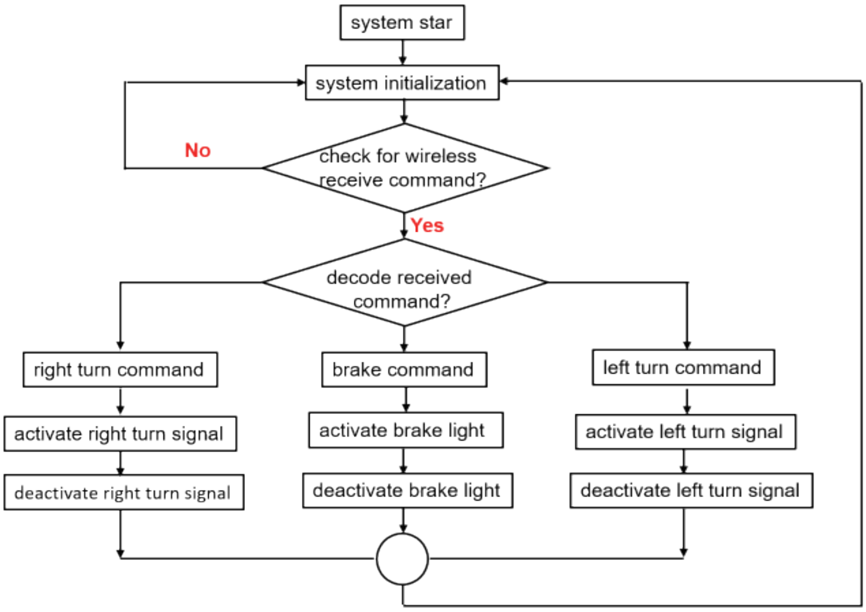

Fig. 4. (Color online) Receiver-side flowchart.

the wheel rim. Upon releasing the cables, the system returns to its original, nonbraking state through a restoring motion. This back-and-forth movement mimics the action of a piston, as illustrated in Fig. 5. In Fig. 5, the upper-left double arrow indicates the location where the two brake cables from the front brake lever are connected. A cover is installed at this point to secure both cables in place. The lower-right arrow points to the area where the brake cable connects to either the front or rear brake caliper. In this control box, two force levers are each connected to separate brake cables, simultaneously actuating both the front and rear brake calipers.

Specifically, two cables are connected to the front brake caliper and one to the rear, resulting in a total of three brake cables. This configuration significantly enhances safety compared with the previously mentioned system. The principle of torque is applied to connect the brake cable from the handlebar to the outermost hole on each force lever (the hole farthest from the pivot), while the two cables connected to the brake calipers are attached to two inner holes (closer to the pivot). This longer moment arm at the outermost position provides a mechanical advantage, resulting in reduced braking effort. Figure 6 illustrates the relationship between the right lever (controlled by the rider's right hand) and the sliding switch, showing their corresponding actuation sequence. The operational process is described as follows.

(1) The right lever first makes contact with the sliding switch, triggering the warning light.
(2) When the lever is pulled to approximately one-quarter of its full stroke, the rear brake begins to engage.
(3) At about one-third of the lever stroke, the front brake is activated.
(4) As the lever returns to roughly two-thirds and three-quarters of its release path, both the front and rear brakes begin to disengage.
(5) During the final return, the lever once again contacts the sliding switch.

This sequence demonstrates the coordinated interaction between the mechanical brake

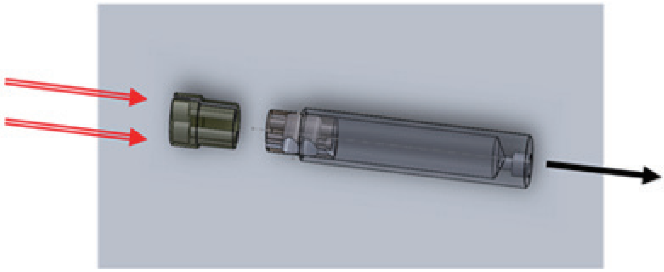

Fig. 5. (Color online) Schematic diagram of the dual-to-single piston-type joint.

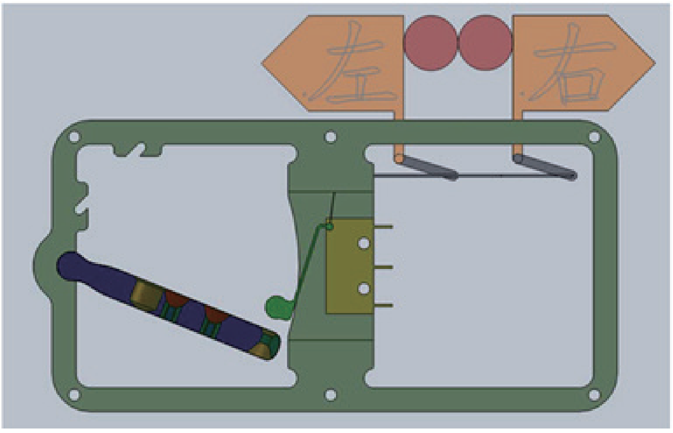

Fig. 6. (Color online) Correlation diagram of the right lever (right-hand control) and the sliding switch.

mechanism and the electrical signaling system, ensuring both safety and intuitive operation. The introduction of the dual-to-single piston-type joint represents a notable advancement in bicycle braking safety. Unlike conventional single-cable systems, which pose a risk of total brake failure if the cable snaps, this dual-cable configuration provides a crucial redundancy that enhances reliability.

This is especially important in high-risk or emergency situations, such as sudden descents or urban commuting, where brake failure could result in serious accidents. Moreover, the use of a specialized actuator that allows seamless integration with existing brake calipers ensures that this system can be adopted without requiring an extensive modification of current bicycle structures, thus offering a practical pathway for retrofitting. The physical prototype of the energy-saving dual-lever safety brake box has been successfully installed on a bicycle. To simulate real riding conditions, a motor was used to pull a steel cable, replicating the actual motion involved in braking. This setup was used to conduct a durability test on the brake system. According to the testing standards, the mechanism must withstand at least 100000 actuation cycles without exhibiting any significant wear or functional failure. In this study, the system was subjected to more than 1000000 actuation cycles, during which no damage or malfunction was observed, demonstrating the excellent durability and reliability of the proposed brake system.

Mechanically, the design cleverly leverages torque principles to minimize rider effort. By connecting the handlebar brake cable to the hole with the longest moment arm on the force lever and the caliper cables to the shorter arms, the system creates a mechanical advantage that amplifies braking force while reducing hand fatigue. This is particularly beneficial for children, the elderly, or users with limited grip strength. Additionally, the integration of both front and rear braking into a single control box enables more balanced braking distribution, reducing the likelihood of skidding or loss of control due to unbalanced forces. Compared with other systems such as the single-lever safety brake (designed for riders with only one functional hand), the proposed design not only accommodates special needs but also addresses general safety concerns for the broader cycling population. While the single-lever system focuses on accessibility, the dual-to-single piston-type joint goes a step further by improving system redundancy, mechanical efficiency, and ease of implementation. This holistic approach reflects a deep consideration of both user safety and mechanical practicality, making the system a valuable contribution to the development of more secure and user-friendly bicycle braking technologies.

To align with the braking and signaling habits of bicycle users, an additional manual switch is integrated into the system to allow riders to explicitly confirm their intended turning direction. This switch enhances the predictability of rider behavior, especially in situations where automatic signaling may be insufficient. In scenarios where the manual switch and the brake lever signals are not synchronized—for instance, when the rider sets the manual switch to indicate a right turn but simultaneously engages the left brake—the system is designed to prioritize the signal from the manual switch. This ensures consistent directional indication and minimizes confusion for surrounding road users. The directional (amber) and warning (red) lights are composed of hexagonal LED circuit modules strategically mounted on the front and rear of the bicycle, as well as on the rider's helmet. The LED lighting system operates under the following signal modes:

(1) While the bicycle is in motion, red lights flash to indicate active movement.
(2) When the bicycle is stationary or braking, the red warning lights remain steadily illuminated.
(3) When turning left or right, the amber lights flash in the corresponding direction at a frequency of 100 Hz, and the red warning lights remain fully lit to enhance visibility.

The system also includes a variety of preprogrammed flashing modes, offering riders the flexibility to select different signaling patterns in accordance with their preferences or specific riding environments. These can be activated either through push buttons mounted on the handlebars or via smartphone control, adding an element of intelligent interactivity and convenience. This integrated signaling approach not only improves communication between cyclists and nearby vehicles but also reflects an effort to emulate the safety protocols used in motorized vehicles, such as motorcycles. By combining manual control, brake-triggered signaling, and intelligent LED lighting, the system is aimed at enhancing both safety and user experience in urban and high-traffic cycling scenarios.

The control circuit testing results are illustrated in Figs. 7(a)–7(d), which present four distinct operational states: (a) the controller is in an idle state (no operation), (b) the indicator lights are activated during a right turn, (c) the indicator lights are activated during a left turn, and (d) the brake light is activated during braking. Each of these lighting signals is triggered by corresponding hand brake inputs; specifically, the left-hand brake activates the left-turn indicator, while the right-hand brake activates the right-turn indicator or the brake light,

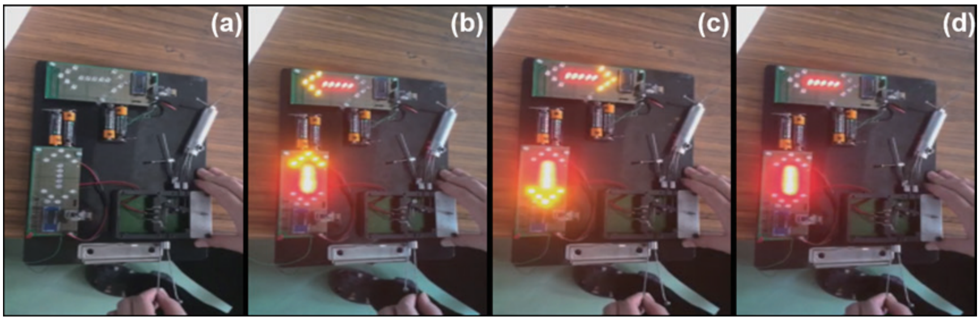

Fig. 7. (Color online) (a) Controller in idle state, (b) right-turn activated, (c) left-turn activated, and (d) brake activated.

depending on the context. This testing setup demonstrates the successful integration of the control circuit with the mechanical brake system, ensuring that directional signaling and braking indicators respond accurately and promptly to user input. Such real-time feedback enhances riding safety, especially in urban environments where clear signaling to surrounding vehicles and pedestrians is crucial. Moreover, the circuit's ability to differentiate between left- and right-hand brake inputs further supports intuitive operation for the rider, minimizing the chance of confusion or incorrect signaling during real-world cycling scenarios.

The proposed system has been successfully installed on an actual bicycle and subjected to real-world riding tests conducted during both daytime and nighttime. These tests were designed to comprehensively evaluate the system's functional stability and visibility under varying lighting conditions. As shown in Fig. 8, the daytime test demonstrates the activation of the indicator lights for right turn, left turn, and braking. The signals were clearly visible and responded promptly to the rider's input. Figure 9 illustrates the results of the nighttime test, showing the same three states: right turn, left turn, and braking. Owing to the integration of high-brightness LED modules, all signals remained highly visible even in low-light environments. The results confirm that the system operates reliably and consistently in both daytime and nighttime scenarios. Its ability to maintain clear and immediate signaling under different environmental conditions highlights its robustness and all-weather functionality. This significantly enhances rider safety by ensuring that surrounding vehicles and pedestrians are accurately informed of the cyclist's intentions at all times.

Note that the system employs high-brightness LEDs to ensure clear recognition even from a considerable distance. As shown in Fig. 9, the turn-signal and brake indicators remain highly visible even when the rider's clothing is dark or provides minimal contrast. This demonstrates that the signal lights are sufficiently bright and distinguishable for practical use in real riding environments. Regarding power supply considerations, the proposed system is designed with low-power LED components and an efficient communication mechanism between the control unit and the display modules. These design choices significantly reduce overall energy consumption, making the system compatible with compact rechargeable battery units commonly used in bicycle accessories. Therefore, the system not only achieves adequate visual performance but also meets the practical requirements for power management in real-world applications.

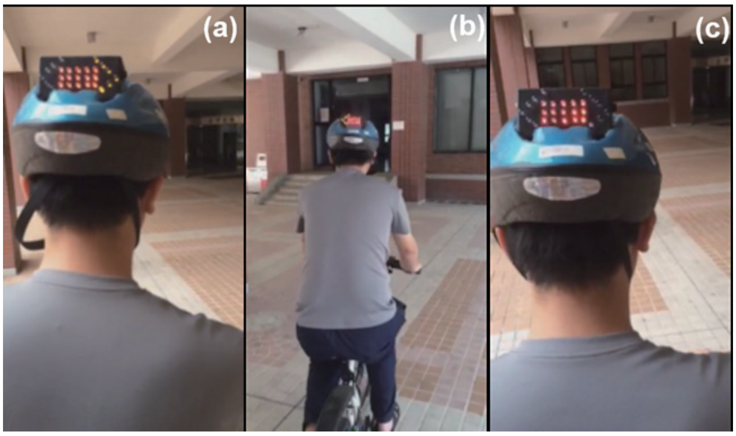

Fig. 8. (Color online) Daytime physical test images of the control circuit: (a) right-turn activated, (b) left-turn activated, and (c) brake activated.

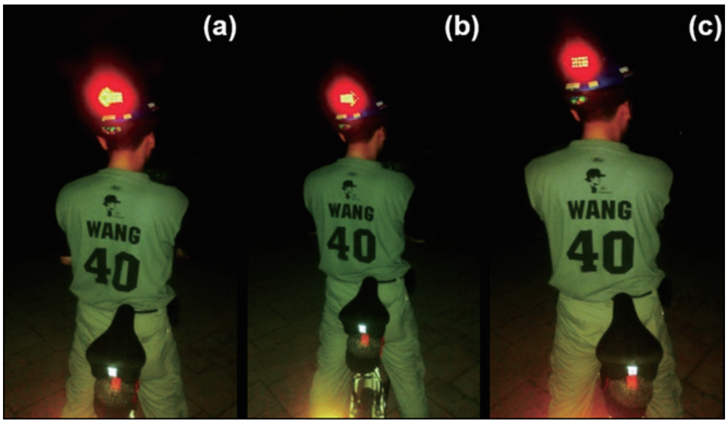

Fig. 9. (Color online) Nighttime physical test images of the control circuit: (a) right-turn activated, (b) left-turn activated, and (c) brake activated.

4. Conclusions

In response to global efforts toward energy conservation and carbon reduction, the number of people choosing bicycles as a mode of transportation continues to grow. To enhance rider safety, we presented a newly developed integrated product designed not only for the bicycle industry but also for potential application in the motorcycle sector. With mass production and cost reduction in the future, this innovative product is expected to gain widespread acceptance among riders. The proposed design offers six key advantages.

(1) High safety: The system uses brake cables to simultaneously activate both front and rear brakes, and features a safety mechanism that prioritizes rear-wheel braking before front-wheel braking, reducing the risk of flipping over.

(2) Simplicity: The dual-lever mechanism is designed for ease of manufacturing and maintenance, making it both practical and cost-effective.

(3) High integration: The system seamlessly combines a "safety brake mechanism" with "smart directional warning lights". Riders can operate both functions simply by using the brake lever, enhancing usability.
(4) Broad applicability: If the smart directional indicators and brake mechanism are separated, they can be individually integrated into the bicycle's left/right turn switches and the braking system. This setup allows the safety helmet to display turn signals and braking status, expanding safety features across the riding system.
(5) Effort-saving design: The system employs torque-based mechanics, allowing users to engage the brake with less physical effort, making it particularly suitable for children and the elderly.
(6) One-handed operation: The mechanism enables synchronized braking with a single hand while still ensuring the rear brake engages before the front, maintaining optimal safety.

In conclusion, we introduced a structurally innovative and novel product that demonstrates clear advancements in both design and functionality. With its strong potential for industrial application and contribution to rider safety, it holds significant promise for future commercialization and market success.

Acknowledgments

This work is supported by Summit-Tech Resource Corp., and by projects under Nos. NSTC-114-2314-B-038-083, MOST-111-2221-E-038 -007 -MY2, MOST-111-2221-E-038 -004 -MY3, 109-TMU-NTUST-109-10, NSTC 113-2221-E-390-011, and NSTC 114-2622-E-390-001.

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