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Conceptual Design of a Combined Brake-Accelerator Pedal for Limbs Disabled Driver Using a Hybrid Approach

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ABSTRACT

This paper presents the conceptual design of a combined brake-accelerator pedal for limbs disabled drivers using a hybrid approach. A hybrid in which it consists of a combination of TRIZ for design generation, a Morphological Chart for design composition, and a Pugh Matrix for design selection. The aim is to generate and select the best concept design for a combined brake-accelerator pedal with special attention based on the needs of the disabled's ergonomics. In this paper, the function analysis, cause, and effects analysis, TRIZ contradiction matrix, and 40 Inventive principles were applied in the solution generation stage. The outcomes of solutions proposed in TRIZ were then refined using a Morphological chart to deliberate the design composition of the combined brake-accelerator pedal. As a result, three innovative design concepts of combined brake-accelerator pedals were produced. Pugh Matrix was finally utilized to perform multi-criteria scoring based on the baseline to select the best ergonomics concept for combined brake-accelerator pedals for disabled drivers.

Keywords: Combined brake-accelerator pedal, conceptual design, morphological chart, Pugh Matrix, TRIZ

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INTRODUCTION

Ordinary or standard cars in the market are equipped with ordinary control; steering, accelerator, and pedal are designed to provide feedback to drivers (Peters & Ostlund, 2005). For example, steering and pedal are designed for a rotational control distribution towards drivers' hands and feet. However, certain points or types of disabilities limit the driver from driving a

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conventional controlled car (Peters & Ostlund, 2005). Therefore, modifying or adaptive equipment is a proven step in maintaining on-the-road freedom for the disabled (NHTSA, 2015).

Being disabled gives a particular person the inner strength to stand on their own two feet, and achieving mobility is an important step towards this (Murata & Yoshida, 2013). Either disabled with or without a wheelchair, both need to drive their vehicle to attain greater self-sufficiency in their daily life (Monacelli et al., 2009). Likewise, driving is considered a complex task for the disabled, requiring physical attention, the ability to make decisions, quick responses, and accurate perception (MyHealth, 2017). It is the reason behind steps taken by the Ministry of Health, Malaysia, in introducing the Occupational Therapist role in Pre-Driving Screening and assessments on the car for disabled drivers. It includes a full check of both on and off-road functional ability and cognitive awareness (Frye, 2013).

Moreover, suggested modifications to Malaysian vehicles for the person with the disabled car are available online, in which the modifications can be made at a registered vehicle repair shop registered with the Road Transport Department (RTD, 2020). Car modification guidelines for a person with disabilities by RTD highlight the effects of driving for the disabled based on their disability and suggested aids for disabled driver assistance. Besides guidelines introduced by the Ministry of Health, a few other guidelines are available online, such as a self-evaluation outline for the driver to ensure the adaptation or modification is appropriate (MyHealth, 2017). An example is an outline from Driver Fitness Medical Guidelines produced by the Association of Motor Vehicle Administrators, National Highway Traffic Safety Administration (NHTSA) that shares tips on cost savings, licensing requirements, needs evaluations, qualified mobility dealers, vehicle selections, training, and vehicle maintenance (NHTSA, 2009).

Few countries worldwide, including Malaysia, Australia, America, and India, only allowed the disabled to drive an automatic transmission car modified with adaptable devices restricted to certain rules and guidelines. It is a good safety precaution to protect the disabled from road accidents. Other than safety, four other aspects of ergonomics are included: comfort, ease of use, productivity and performance, and aesthetics. These are important aspects in considering adaptation and modification for a disabled car to maintain its physical and physiological health.

Cars have been equipped with the same conventional foot pedals since a century ago. Automatic transmissions are equipped with separate brake and accelerator pedals that shall be pressed using the right foot. This design ensures that the throttle is released as soon as the driver applies the brakes. Hence, feet are mostly placed at the accelerator pedal instead of the brake pedal. Changing the accelerator pedal to the brake pedal will then add reaction time. It has been reported that braking in an emergency with separate brake and accelerator pedals takes a longer reaction time (Arora, 2016; Nilsson, 1989, 2002). The foot may be placed on the brake incorrectly, resulting in poor braking performance, or even miss the brake and wrongly press the accelerator. Various combinations of brake pedals have been designed to overcome the disadvantages of conventional pedals. It is proven by the availability of modifications introduced in several studies, as illustrated in Table 1.

Table 1

Comparison of literature survey

Authors (Years)	Modification Type	Remarks Strength (S) / Recommendation (R)
Jones et al. (2010)	Flip Accelerator Pedal	**S:** Restore independence for disabled left limbs **R:** Dual advantage consideration. Those with right-sided pathology are disadvantaged in this respect
Nilsson (2002)	Brake-Accelerator Pedal (Improved)	**S:** Eliminate the operator's risk of pressing the wrong pedal as well as reduce the reaction time in braking **R:** Safety feature installation. It might cause the unintended or mixed function of the brake or accelerator
Nilsson (1989)	Combined Accelerator-Brake	**S:** Eliminate the operator's risk of pressing the wrong pedal as well as reduce the reaction time in braking **R:** Safety feature installation
Arora (2016)	Combined Accelerator-Brake	**S:** Improve confusion issues

MATERIALS AND METHODS

A hybrid approach that involving the Theory of Inventive Problem Solving (TRIZ) has been widely used by researchers across many industries, including Mansor et al. (2014), Sapuan et al. (2009), Mastura et al. (2017), and many more. The hybrid thoroughly defines problem, idea generation, concept design, and proper design selections and scorings. This section proposes the hybrid approach to fill gaps and improve the combined brake-accelerator pedal invented in previous studies. The proposed approach will combine three strong methods to systematically cater to conceptual design elements in producing improved products. Figure 1 shows that the conceptual design framework begins with problem definition in general. It then flows to three stages of conceptual design before it ends. Stage 1 consists of conceptual design generation made of TRIZ.

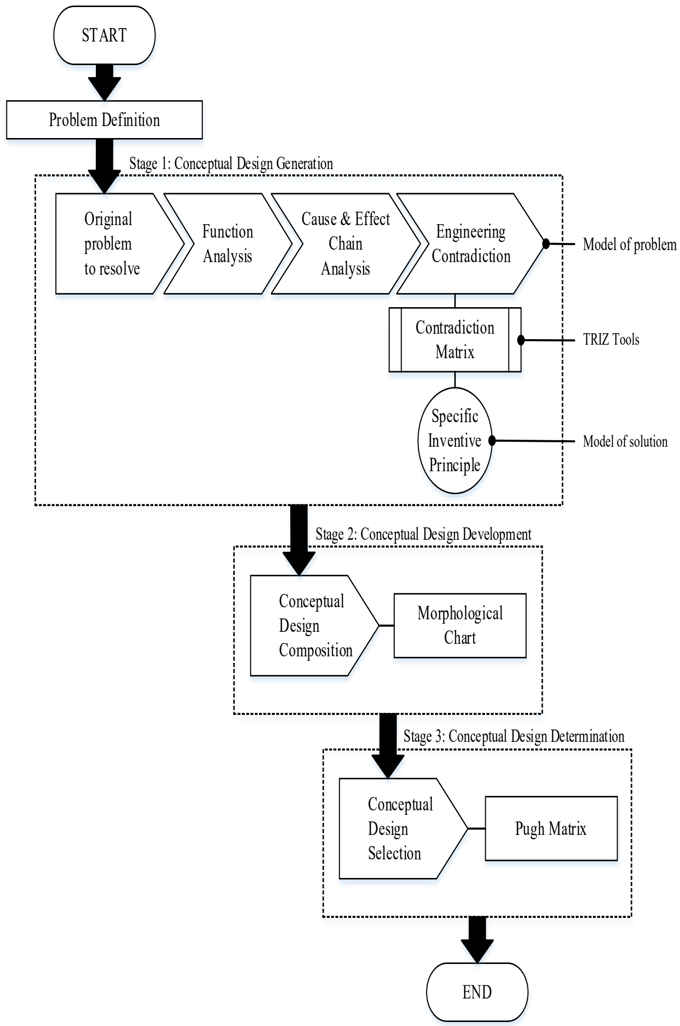


Figure 1. Framework of the hybrid approach

TRIZ theory emphasizes the existing differences in design needs and targets to promote efficiency in design work (Liu et al., 2016) as well as universal ways to solve problems and the ability of engineers to diverse the innovation to solve the problem (Yang & Chen, 2011). Besides, this is an inventive instrument necessary to invent the right thing and integrate it into products and processes with the right measure at the right time (Navas, 2013). With the ability to resolve contradictions related to engineering problems within different interests, TRIZ has been rapidly and widely adopted in an academic and industrial domain (Ferrer et al., 2012). Previous studies generally acclimatize TRIZ in industries as well as specific adaptations in the car design of automobile industries, including redesigning cars to solve parking issues (Manohar & Kalla, 2012) and modeling solar cars (Chang et al., 2016).

In TRIZ, an inventive solution comes after inventive problems. Technically, an inventive situation results from an inability of a technical system to fulfill current functional requirements. For the formulation of inventive problems, it should be sufficient to combine the description of the situation, effects, and goal to be achieved (Guin et al., 2015). In this study, the researcher uses Engineering Contradiction to build an inventive problem to proceed.

As illustrated in Figure 1, the researcher has undergone basic flow guided by TRIZ, namely function analysis, cause and effects analysis, engineering contradiction, and inventive principles to complete conceptual design generation in stage 1. Function analysis is a key aspect for engineers to understand, especially in a complex system design (Aurisicchio et al., 2012), as it provides a systematic method for technical problem-solving (Pahl et al., 2006). It has the potential to improve product knowledge, highlight design key points, and identify useful, harmful, and useless functions (Aurisicchio et al., 2012). Next, cause and effect analysis takes place to reveal the trivial that may entail significant consequences perfectly. It plays an important role before generating solutions or concepts (GEN3, 2006). Wrong identification of the root cause probably will not generate a working solution (Zare et al., 2016). Thus, spending time in cause-and-effect analysis helps in reducing ineffective solutions. The process of generating cause and effect analysis is similar to the 5-why-brainstorming method in which they correlate. This reference situation provides methodologically important conclusions. Next, Engineering Contradiction was used to devise a proper inventive problem. A contradiction matrix was applied with engineering contradiction statements, and an inventive principle was extracted.

In stage 2, conceptual design development needs morphological charts to come out with conceptual design composition respecting the inventive principle's model of solutions. Generally, the morphological chart provides design features to generate ideas together with sub-solution identification of each sub-function visually (Mansor et al., 2014). Since this project had a TRIZ solution method for problem-solving, the morphological chart works as a refiner (decision-making) of each part listed. This combination of TRIZ solution and morphological chart is a quick translation of a general problem (which is found by TRIZ) to a specific problem (which is visualized by the morphological chart).

Stage 3 works as a final stage to determine and select the best design via the scoring of the Pugh Matrix. Pugh Matrix helps to narrow down the option based on the concepts best gratifying the stated criteria, not to find the better design (Haris et al., 2016). Moreover, the Pugh matrix commonly has a clear loser rather than a winner to help designers remove the losing option (Madke & D. Jayabhaye, 2016) before selecting the best option among all available alternatives (Joshi et al., 2019). Therefore, the Pugh matrix was chosen due to its wide acceptance, simplicity (Cun et al., 2020), ease to use (Madke & D. Jayabhaye, 2016), user-friendly (Lonmo & Muller, 2014), and better efficiency (Karnjanasomwong & Thawesaengskulthai, 2016; Muller, 2011; Thakker et al., 2009). For the same reason, the Pugh matrix has been applied to this project to analyze available choices of concept design composition.

RESULTS AND DISCUSSION

In this section, the conceptual design of ergonomics combined brake-accelerator pedal hybrid using TRIZ-morphological chart Pugh matrix approach is performed according to the initially proposed framework.

A combined brake-accelerator pedal has been through a few studies, as in Table 3. It starts with a flip accelerator pedal, and it is then combined to cater to a person with certain limb disabilities. These efforts are believed to help improve reaction time and reduce unwanted incidents, such as wrong pedals and late emergencies brake that might cause a crash. However, two problems are highlighted in this research: first is taking into consideration that a combined brake-accelerator pedal is used, and second is normal conventional pedal usage. Both carry pros and cons, so this case study shall resolve both issues with another improved design. Table 2 list the pro and cons of both applications.

Conceptual Design Generation (Stage 1)

As shown in Figure 1, Stage 1, concept generation begins with the original problem to resolve (problem listed in Table 2). The problem is clear, but it has no direction on where it starts and what is the root cause of the problem. Hence, the functional components and interactions are carefully identified to determine the real problem.

Initially, the pedals system as a product as a subject (rectangle) and interaction body parts as an object (oval) with function interactions and other outside components that influence the performance of the system as supersystem components (hexagon) shall be identified. Each function is represented as an arrow: useful, insufficient, excessive, and harmful. Equitable to the naming, a normal useful function does not cause any damage or undesired effect on the object, whereas insufficient and excessive useful function may create some amount of damage or undesired effect on the object, and a harmful function certainly causes harm to the object (Yeoh et al., 2015)

Table 2

Conventional pedals versus combined pedals

Type of pedal	Conventional pedals	Combined brake-accelerator pedals
PROS	• The method of operation has been well-known since the early days.	• A new method of operation • Quick response • Effortless (minimize limbs movements as legs can stay on the pedals for both brake and accelerator functions)

Table 1 *(Continue)*

Type of pedal	Conventional pedals	Combined brake-accelerator pedals
PROS	• The method of operation has been well-known since the early days.	• A new method of operation • Quick response • Effortless (minimize limbs movements as legs can stay on the pedals for both brake and accelerator functions)
CONS	• Long reaction time to change pedals • Fatigue of long press on one pedal. • As it is fixed, certain disabled have a problem reaching.	• It can confuse a new user as it is newly introduced.

Figure 2 shows the Function analysis for this case study. The function analysis shows that one harmful effect in the foot and pedal pad interaction needs to be solved. Therefore, the next step will focus on this interaction to find the root cause of the problems.

Function analysis and cause and effects analysis are interrelated in that cause and effects analysis should highlight the most crucial interaction of function analysis and flow correspondingly with highlighted elements of functional analysis. In other words, within the same storyline, function analysis shows functions and interactions; meanwhile, cause and effects analysis answer why each cause questions until the potential root cause has been identified. For example, Figure 3 indicates the cause and effects analysis that starts with the cause (fatigue and discomforts while driving) as the utmost box and ends with two possible root causes; explicitly, one is a fixed bracket, and another one is the location of the pedals at the end of the analysis.

Subsequently, an inventive problem statement has to be determined to proceed with the concept design generations. The general problem statement then undergoes engineering contradiction to build up the statement, as shown in Table 3. Thus, the improving and worsening factors are extracted from the engineering contradiction equations. Finally, the inventive principle is reduced by referring to the contradiction matrix table, and the suggested inventive principle and realistic solution are listed in Table 4.

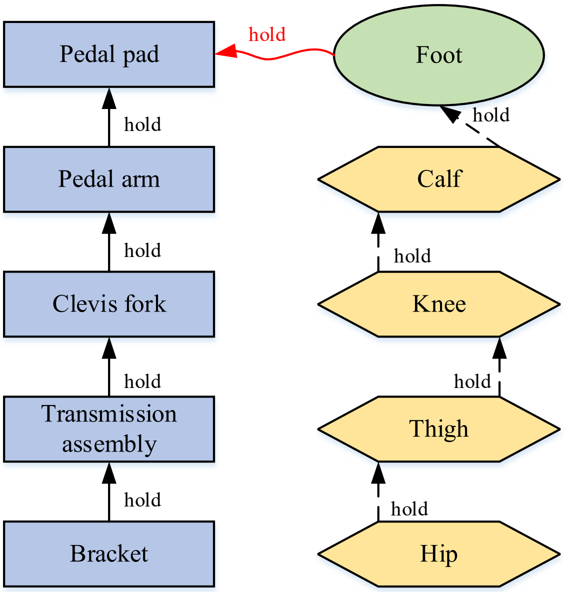


Figure 2. Function analysis for pedals

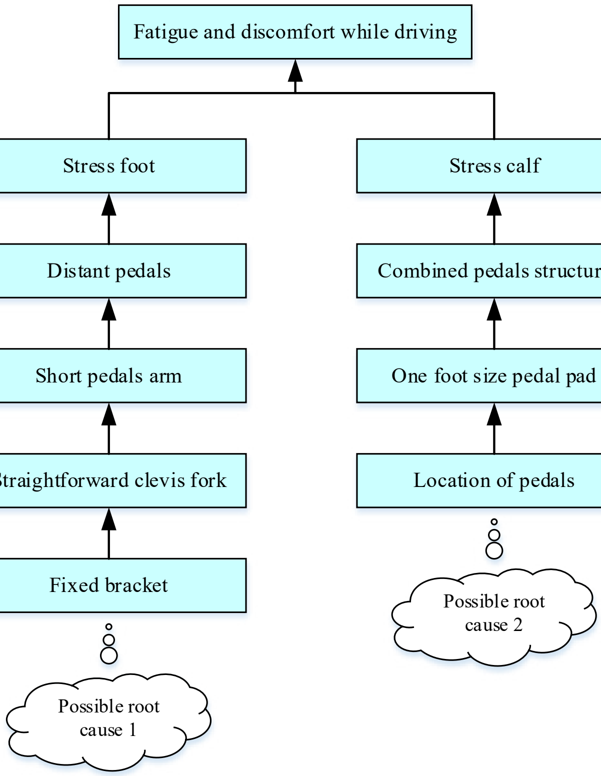


Figure 3. Cause and effect analysis for pedals

Table 3
General problem statements versus inventive problem statements

No.	General Problem Statements	Inventive Problem Statements (Engineering Contradiction)
1.	Operating pedals caused pain and discomfort towards limbs disabled drivers.	**IF the** accelerator and brake pedals are combined, **THEN** it improves pain and reduces rotation movements of the legs **BUT** it can cause confusion
2.	With various disabilities and sizes of disabled drivers, standard pedals cause a problem of reach.	**IF it** is in a fixed position **THEN** standardization in product production **BUT** the problem with disabled reaching and operating.

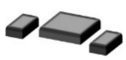
Table 4
Improving and worsening factors versus inventive principles

Improving factor	Worsening factor	Inventive Principle	Realistic solution
#35 Adaptability and versatility	**#30** Object-generated harmful factors	**#35** Parameter change **#11** Beforehand cushioning **#32** Color change **#31** Porous material	Combine the brake pedal and accelerator pedal to the same cross-section pedal plates.
#35 Adaptability and versatility	**#36** Device complexity	**#29** Pneumatic & hydraulic **#15** Dynamization **#28** Mechanics substitution **#37** Thermal expansion	To dynamize the plate of the pedal from static to movable to fit limbs' disabled needs.

Conceptual Design Development (Stage 2)

Based on the foregoing stage's evaluation of all design factors, it is time to merge all the concepts to generate new conceptual designs for the component. Numerous conceptual designs will result from combining all the ideas from all of the component's parts. There can be many concepts that possibly be generated from a combination of the morphological charts. However, only three are chosen in this case study. The three combinations come after the integration of the morphological chart and TRIZ. Since TRIZ is very abstract, a morphological chart helps visualize the ideas related to proposed solutions by TRIZ, as mapped in Table 5. The morphological chart used recommended inventive principles for two problems defined as the design strategy to inspire the design features. Three combinations named PD1, PD2, and PD3 as concept design composition developed, and the selection of the most recommended design happens in the next stage. Table 5 has three main columns: TRIZ solution principles and design strategy, design features, and solution. The design feature's column lists all attributes that are manipulative. Meanwhile, the solution's column comprises another three sub-columns (A, B, and C) filled with elements to choose from. Another row in the same table is an outcome of combinations of attributes in design features and solutions under concept design composition.

Table 5
Morphological chart for pedals

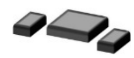
TRIZ Solution principles and design strategy	Design features	Solution		
		A	B	C
#35: Parameter change Change the parameter	1. Cross section of the pedal plate	Square	Squircle	Foot shaped
#5: Dynamization Moveable rest	2. Cross-section of a resting area	Square	Squircle	Foot shaped
#5: Dynamization Moveable plate	3. Transmission	Manual	Auto (Button)	-
	4. Button location	at door	at dash	nearby gear
	5. Manual operation	shaft	lifter	-
Concept design composition		**1. B1 - B2 - B3 - C4 = PD1**		
		2. C1 - C2 - A3 - B5 = PD2		
		3. A1 - A2 - B3 - A4 = PD3		

The similarity of the three selected combinations is the dynamization of the rest and pedal plate. Therefore, it is very important to cater to variable sizes of disabled drivers. Meanwhile, the significant difference between all proposed concepts is the transmission assembly to hold the pedal arm and pedal plates, the shapes of the pedal, the location of the button (if it exists), and the manual operation part (if it exists). Nevertheless, the automatic transmissions, button locations, and shapes give value added to the concept with a slight addition of cost in contras.

Conceptual Design Selection (Stage 3)

In Stage 3, the final conceptual design for the combined brake pedal will be selected after the development of the composition in the previous stage. At this time, the Pugh matrix took place. There are four main columns in the Pugh matrix analysis table, Table 6: Criteria, Baseline, Alternatives, and Totals (Burge, 2009). The criteria column was further devised into two sub-columns. The left column comprises five main ergonomics elements, as shared in the previous section, while the right column is a sub-criterion of each element. These criteria came from each element's definition, literature, and elaboration.

Table 6
Pugh matrix for pedals

			Alternatives			
Criteria	**Weightage**	**Baseline**	 **PD1**	 **PD2**	 **PD3**	**Totals**
Safety	3	0	+	+	+	9
Comfort	6	0	+	-	0	18
Ease of use	4	0	+	+	+	8
Productivity and performance	4	0	+	+	+	-8
Aesthetic	6	0	+	+	+	18
Others	6	0	+	-	0	18
		Totals	33	5	17	
		Rank	**1** ✓	3	2	

The baseline indicates a number corresponding to the current design, which is '0', '+' indicating an improvement of design compared to the current design, and '–' indicates the deterioration of design compared to the current design or a negative impact on the design. The alternatives column is split into three sub-columns specifying design selections from the concept design composition of the morphological chart in the previous subsection.

The total column is the sum of marks according to the row. Another total at the end of the table indicates the total row that will be the final numbers for the column of each alternative, and the final row shows the ranking of the alternatives.

Table 6 shows that concept PD1 is leading in the first rank with 33 scores over the other two concepts, PD3 (17 scores) and PD2 (5 scores). It is because concept PD1 carries a few important criteria such as squircle pedal shape, squircle rest plate shape, automatic movable, and an automatic control located nearby gear drivers that can easily reach it. Henceforth, movable pedals and pedals rest with the control button to refine the reach of users.

The chosen concept design mechanism was prepared on the CATIA V5 R20, as shown in Figure 1. The middle pedal works as a combined brake-accelerator while the right and left pedals rest. All three pedals are movable, but the resting paddle is non-pressable, and it serves the disabled driver with a left or right limb for resting. The working paddle accelerates upon pressing upwards, similar to a normal accelerator; meanwhile, pressing downwards is a braking mechanism. The initial position of the pedal is neither accelerating nor braking to avoid any confusion of action. This natural pedal function also can improve the driver from fatigue. Furthermore, since disabled driver varies in size of their legs and the capabilities of legs, right or left, movable pedals and resting improve the foot's reach.

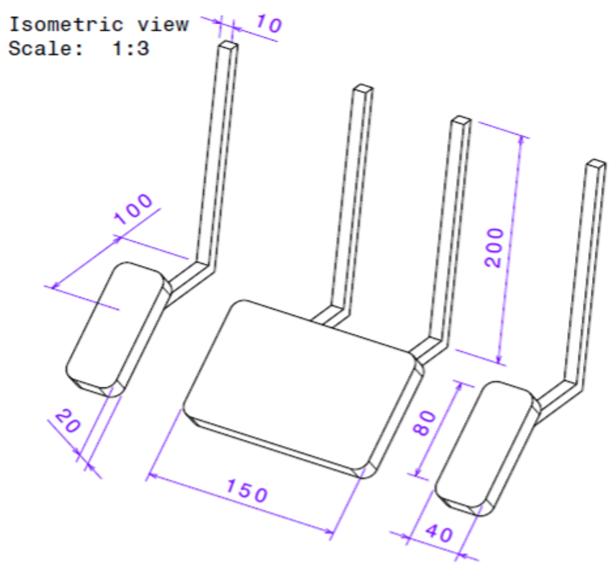


Figure 4. An ergonomics combined brake-accelerator pedal

CONCLUSION

In conclusion, the development of these improved ergonomics combined brake-accelerator pedals avoids braking and accelerating interference. It is advantageous over conventional pedals and previously combined pedals. A TRIZ, morphological chart, and Pugh matrix hybrid introduce systematic generation, development, and selection of the concept design. Also, making the pedal movable brings together better reach dimensions for the disabled to venture, as shown in Table 8. It is an ongoing project. There will be a verification step in the future to test further the redesign made to the combined-brake pedal development.

Table 8
Movable reach comparison

Part	Dimension/ Direction	Current Design (mm)	Redesigned (mm)	Improved	Same	Worsen
Pedals	X	n/a	160.00 (right/left)			
	Y	n/a	160.00 (front/back)			
	Z	n/a	350.00 (up/down)			

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