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Recent Publication Trends on Throttle Body Design

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ABSTRACT

Throttle body (TB) role in regulating air for internal combustion engine (ICE) is crucial and proven beneficiary for ICE performance. Researchers have shown interest in the study of TB which is reflected by the numbers of publication on TB. Between 2011 and 2021, seven review articles with keyword "throttle body" were published in Science Direct investigating on alternative fuel, enhancement on fuel injection technology and control system. Despite the reviews highlighted above, there remains a paucity of review on TB design. Therefore, this study gathered literatures from year 2011 to 2021, focusing on Scopus and Science Direct databases to investigate and analyse numbers of publications relating to TB design. Out of 186 publications found, only 49 articles were chosen after the inclusion and exclusion process. The findings highlighted six themes or patterns in research of TB design which are categorize as airflow study, control system design, design process study, manufacturing / production, new approach TB, and performance study. The results will benefit TB designers and provide guidelines towards a better contribution to the body of knowledge for future studies.

Keywords: Throttle body design, throttle control, thematic review, throttle body research trends, future study of throttle body

1. INTRODUCTION

The effect of emission from vehicles on global warming is one of the major issues discussed across the globe. Numerous strategies have been proposed and applied to make sure a better air quality to the society [1]. The effort globally involved governments and also supported by the initiative by vehicle manufacturers to adapt technological approach aiming to reduce emission. One of the aggressive governmental effort declared by the European Country was to prohibited the use of Internal Combustion Engine (ICE) in vehicles starting year 2030 [2]. However, a different school of taught emphasized that in order to achieve carbon neutrality, ICE is not to be blame but the focus should be on carbon dioxide reduction strategy [3].

Various technological approaches have been implemented to ICE that have successfully contributed to a better emission control. The introduction of fuel injection system for example has given great impact to the ICE performance and emission control. Muslim *et al*. [4] reviewed the studies done on retrofitting fuel injection technology for small motorcycle engine meanwhile

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Huang *et al*. [5] reviews the potential of dual injection technology to adapt with renewable fuels. These reviews showed significant knowledge exploration by researchers towards decreasing the impact of vehicles emission to the environment.

Besides that, the study on alternatives fuels had also been reviewed by Mehra *et al*. [6]that focussed on the hydrogen enriched compressed natural gas (HCNG) engines towards better power output and emission parameter check. Furthermore, Carbot-Rojas *et al*. [7] explored in their study on the usage of various biofuels and the effect on the control strategy of ICE model. This showed the efforts done by researchers on investigating the possibilities of a better fuels to power the ICE without sacrificing the environmental aspect.

Moreover, the implementation of engine management system (EMS) in modern vehicles is the ultimate improvement in ICE which had been the focussed of review done by Ashok *et al*. [8]. EMS ensures the air fuel mixture for ICE is at optimum condition and emission is controlled.

Besides that, throttle body (TB) usage to replace the carburettor is also one of the improvements that had a significant result on emission control. This had been discussed by the review done by Ashok *et al*. [9] that highlighted numerous efforts from researchers to achieve better electronic control system for electronic TB. Mainly the efforts undertaken by researchers were to develop a better control strategy to overcome nonlinearities in currently used butterfly TB.

However, despite the contribution of TB to the ICE emission control is significant, there is no review paper discussing on the trends of research done relating to the area of TB design. Therefore, this paper will attempt to review the issues that been discussed in the TB design publications from year 2011 to 2021 based on the following research question: What are the trends on throttle body design discussed in the literature from 2011 to 2021? Implementing this research question in the research will ensure that this review was focused and aligned on a clear aim.

The structure of the research paper is as follows: Section 2 describes the methodology used. Section 3 discusses the Findings. Section 4 provide discussion and suggestion for future studies. Section 5 concludes the research conducted.

2. METHODOLOGY

The term thematic review using ATLAS.ti as the tool as introduced by Zairul, [10], [11] and I. S. Che Ilias *et al*. [12] is implemented because the method of this study applies thematic analysis procedure to a literature review. Clarke & Braun, [13] defined thematic analysis as a process of discovering the pattern and constructing themes through extensive reading on the subject. The following step is to identify the pattern and construct categories to understand the trend of throttle body (TB) design publications. The goals of the research are to analyse and interpret the findings from reviewed literatures and suggest recommendations for future research in TB design. The selection of literatures was performed according to two selection criteria: 1) publication from year 2011- 2021, and 2) Have at least keyword(s) throttle body and design. Review papers were excluded from this review due to contradiction with the objective of this paper.

The literature search was performed using Scopus and Science Direct search engines. The initial search came out with 57 results from Scopus and 129 results from Science Direct. However, 137 articles were removed due to their results were not discussing on TB design element. Some of the articles were also found incomplete, or the full articles are not accessible, have a broken link and overlapped and metadata incomplete. Therefore, the final paper to be reviewed down to 49 articles (see Figure 1). Full papers, conference papers, and book chapters were selected for this

review. The articles were uploaded in the ATLAS.ti 9 as primary documents, and then each paper was grouped into 1) author; 2) issue number; 3) periodical, 4) publisher, 5) source and 6) year of publication. In doing so, the articles can be analysed according to the year they were published and what are the discussion patterns according to the year. The total articles finalised into the final documents in the ATLAS.ti 9 was 49 documents.

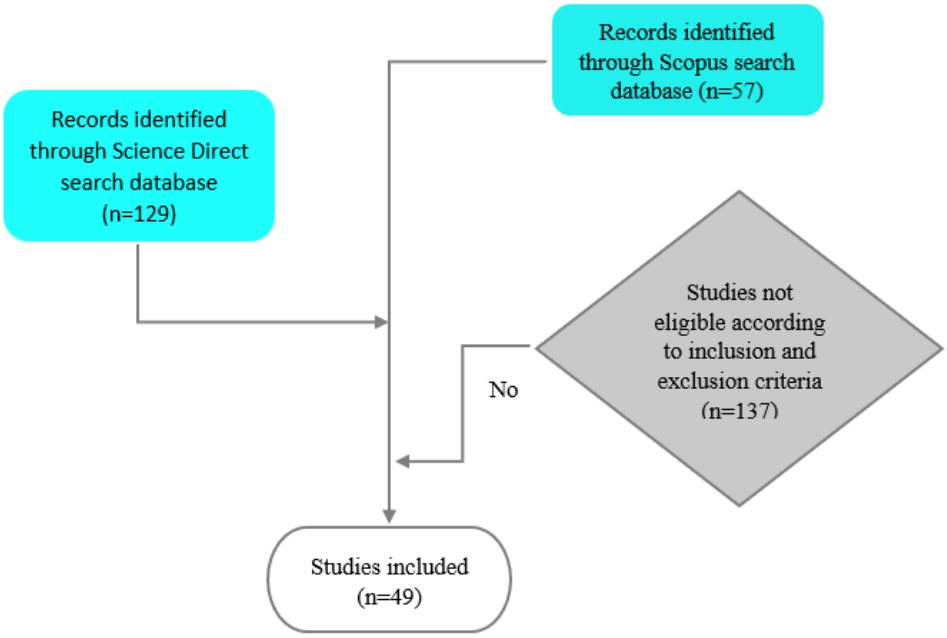

Figure 1. Inclusion and Exclusion criteria in the thematic review (adapted from Zairul [11]).

3. FINDINGS

The findings are described in two sections: i) Quantitative and ii) Qualitative. Words cloud generated in the quantitative part were establish from the 49 documents selected from Scopus and Science Direct databases (see Figure 2). The biggest word in the cloud is the largest frequency of keywords reflecting as the possible subject matter discussed in the selected articles. The words 'control' and 'throttle' are among the commonly used word that cannot be neglected in considering the themes for this review article. This indicates that control had significant impact in the focus themes of this paper on TB design.

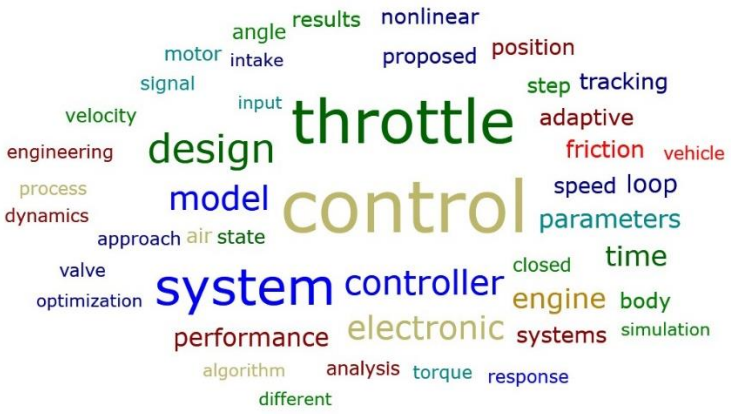

Figure 2. Word cloud on word frequency generated from 49 articles.

Despite the increasing trend, there are no review paper done elaborating specifically on the TB design study. A study protocol was created, with data collection, preparation, and interpretation specified in a logical sequence based on the past research. From the analysis of word cloud, the word 'control' was mentioned 1101 times, followed by 'throttle' at 894 times, while 'system' and 'design' were mentioned 713 and 510 times respectively. The trend of publication is seen increasing over the years (see Figure 3). Beginning with 4 articles published in the year 2011 to 2013, it falls to only 1 article published in year 2014 and 2 articles published in year 2015. Five articles were then published in year 2016 to 2017 and 8 articles in year 2018 which are the largest frequency recorded in a year. For year 2019 and 2020 the articles published were 6 and 7 respectively. As for year 2021 there are already 3 articles published at the time this article being written. The reason why the literatures for this study starts from 2011 is to focus on the latest publications within the recent 10 years and to observe the trend towards 2021. Authors would like to highlight that this analysis is systematically done focused on search strings, indexes, and exclusion criteria that reflects the literatures based on the research question (see Table 1).

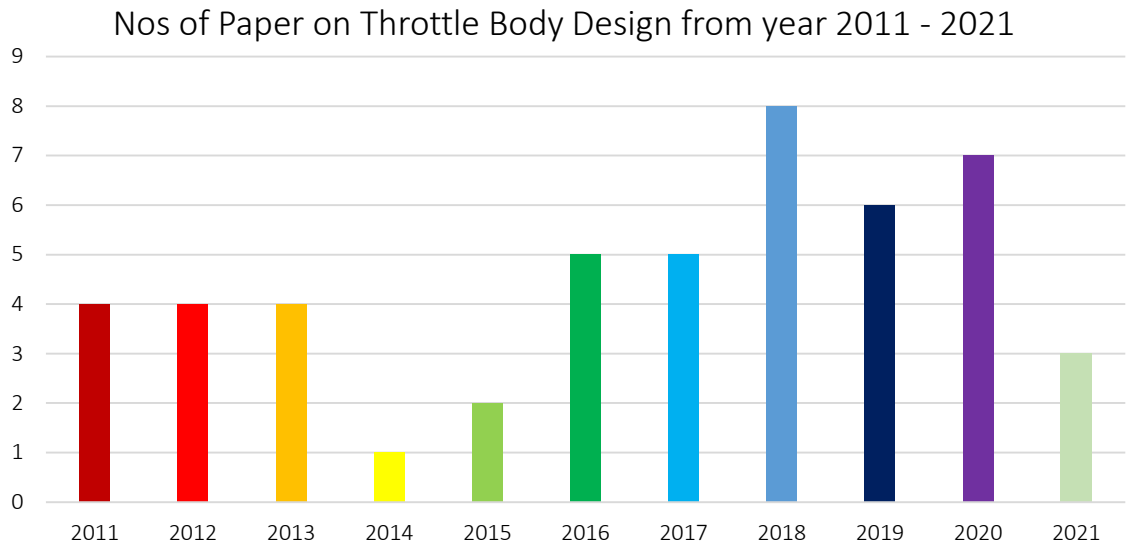

Figure 3. Papers breakdown according to the year of publication.

Table 1 Search Strings from Scopus and Science Direct

SCOPUS	TITLE-ABS-KEY ("throttle body" AND "design") AND PUBYEAR > 2010	57 Results
Science Direct	"throttle body" AND "design" Doctype (Article) Year: 2011 - 2021	129 Results

3.1 Quantitative Findings

Based on this analysis there are a number of journals can be chosen by scholars working on TB design wishing to publish their findings. According to the list, SAE Technical Papers and IFAC-PapersOnLine are the top two preferable journals among the TB design researchers. As justified by the authors earlier, if the word search for this search only stated 'throttle body', the numbers of results will be humongous. However, by focusing to 'throttle body' AND 'design', the results show significant decline and more focused indicating that deeper exploration can be done in the future. Nevertheless, increasing interest on TB design can be observe from the pattern shown by numerous articles as per Table 2.

Table 2 Journal-Based Articles According to Year of Publish for Study Review

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
2018 Annual IEEE International Systems Conference (SysCon)	-	-	-	-	-	-	-	1	-	-	-
Aerospace Science and Technology	-	-	-	-	-	-	-	-	1	-	-
American Society of Mechanical Engineers, Internal Combustion Engine Division (Publication) ICE	1	-	-	-	-	-	-	-	-	-	-
Applied Condition Monitoring	-	-	-	-	-	-	-	-	1	-	-
ASME 2015 Dynamic Systems and Control Conference, DSCC 2015	-	-	-	-	1	-	-	-	-	-	-
ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)	-	1	-	-	-	-	-	-	-	-	-
COMPEL - The International Journal for Computation and Mathematics in Electrical and Electronic Engineering	-	-	-	-	-	-	-	-	-	1	-
Computers in Industry	-	-	-	-	-	-	-	-	1	-	-
Control Engineering Practice	-	-	1	-	-	-	-	-	-	1	-
Energy Conversion and Management	-	-	-	-	-	-	-	-	1	-	-
Engineering for Rural Development	-	-	-	-	-	-	-	-	-	1	-
Evergreen	-	-	-	-	-	-	-	-	-	-	1
FISITA 2016 World Automotive Congress - Proceedings	-	-	-	-	-	1	-	-	-	-	-
IECON Proceedings (Industrial Electronics Conference)	-	-	-	-	-	-	-	-	1	-	-
IEEE Transactions on Control Systems Technology	1	-	-	-	-	-	-	-	-	-	-
IEEE Transactions on Industrial Electronics	-	-	-	-	-	-	-	-	-	1	-
IFAC Proceedings Volumes	1	1	1	-	-	-	-	-	-	-	-
IFAC Proceedings Volumes (IFAC-PapersOnline)	1	-	-	-	-	-	-	-	-	-	-
IFAC-PapersOnLine	-	-	-	-	-	-	-	3	-	-	-
Indian Journal of Engineering and Materials Sciences	-	-	1	-	-	-	-	-	-	-	-
International Journal of Applied Engineering Research	-	-	-	-	-	1	-	-	-	-	-
International Journal of Chemical Sciences	-	-	-	-	-	1	-	-	-	-	-
International Journal of Numerical Modelling: Electronic Networks, Devices and Fields	-	-	-	-	-	1	-	-	-	-	-
International Journal of Vehicle Structures and Systems	-	-	-	-	-	-	-	-	-	-	1
International Review of Mechanical Engineering	-	-	-	1	-	-	-	-	-	-	-

IOP Conference Series: Materials Science and Engineering	-	-	-	-	-	-	1	-	-	-	-
ISA Transactions	-	-	-	-	-	-	-	-	-	-	1
Journal of Physics: Conference Series	-	-	-	-	-	-	1	-	-	-	-
Journal of Process Control	-	-	-	-	-	-	-	1	-	-	-
Lecture Notes in Mechanical Engineering	-	-	-	-	-	-	-	-	-	1	-
Materials Today: Proceedings	-	-	-	-	-	-	-	-	-	1	-
Mechatronics	-	-	-	-	-	-	-	1	-	-	-
Modelling, Simulation and Identification / 841: Intelligent Systems and Control	-	-	-	-	-	1	-	-	-	-	-
Proceedings - 2012 9th International Conference on Fuzzy Systems and Knowledge Discovery, FSKD 2012	-	1	-	-	-	-	-	-	-	-	-
Proceedings - 2018 12th France-Japan and 10th Europe-Asia Congress on Mechatronics, Mecatronics 2018	-	-	-	-	-	-	-	2	-	-	-
SAE International Journal of Commercial Vehicles	-	-	-	-	-	-	1	-	-	-	-
SAE Technical Papers	-	1	1	-	1	-	2	-	1	1	-

Next, looking to the geographical dispersal (see Figure 4), TB design related studies have been contributed the most by French researchers with 11 published articles exploring the study related to TB as a mechatronic device. This can be seen from Ammar *et al*. [14] that discussed Set-Based Concurrent Engineering (SBCE) concept for mechatronic systems with further exploration on simulation model using Modelica done by Ammar *et a*l. [15]. Other than that, Borchani *et al*. [16] extended the approach by adding Model-Based Systems Engineering (MBSE) while Giani *et al*. [17] explored clutch-based launch controller design for motorcycles. Collaborative design process and knowledge sharing concept had been discussed comprehensively to make sure the smooth flow of design and development of TB [18]–[23].

Research works from China is ranked second with 9 published articles contributed by Feng *et al*.[24] who discussed on the parameter identification and nonlinear compensation control design of electronic throttle and followed by the study related to control system strategy for an electronic TB by [25]–[30]. Xinjie,[31] dived in a different area of research that related to the manufacturing of TB bracket which also gave significant impact on the performance of TB.

The third rank is research work from India with accumulated 8 publications. Several scholars initiated the study related to the usage of CFD analysis to evaluate airflow across TB [32]–[34] while Krishnan *et al*. [35] investigated the flow of exhaust gas into a TB in the exhaust gas recirculation (EGR) system. Coherently, some researchers were involved in the study related to the formula SAE competition which focussed on achieving a better engine performance [36], [37]. Cherian *et al*. [38] proposed a control system strategy and Balaji *et al*. [39] investigated the effect of different TB shaft configuration on the airflow across TB.

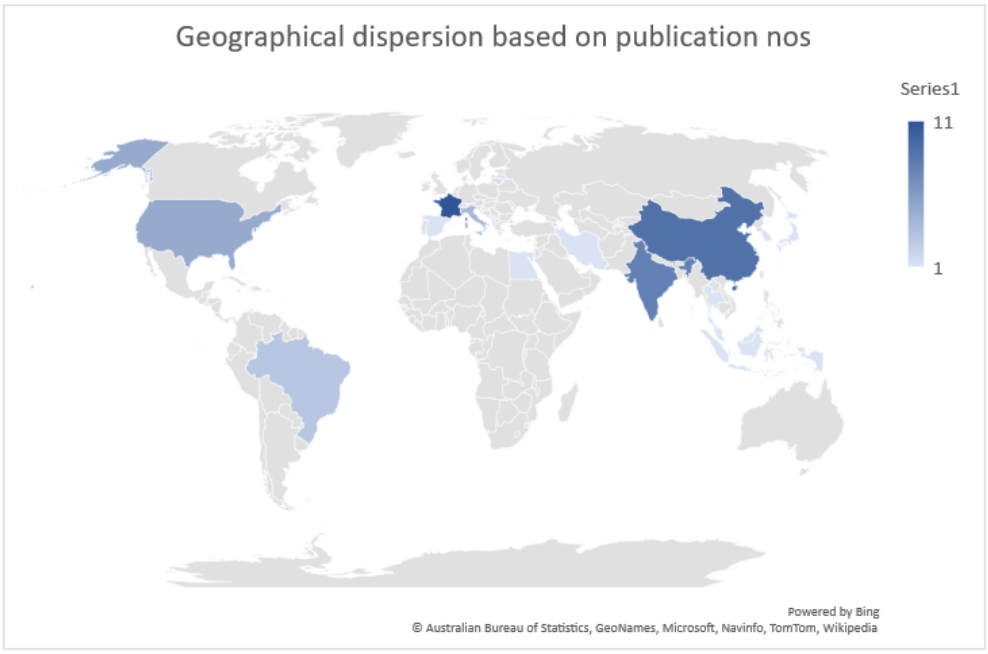

Figure 4. Geographical dispersion based on publication.

Next in line is the research works from United States with 5 published articles where Amini *et al*. [39] and Santillo *et al*. [40] made the effort to enhance the control system strategy of electronic TB while Morton & Narasingamurthi, [42] studied the airflow in the context of marine engine that experienced a different environment of engine operation. Besides these, a new approach of operation mechanism for TB was elaborated by Jawad & Arslan, [43] and Jawad *et al*. [44] explored a possible approach to achieve better performance to comply with the regulation formula SAE competition.

Researchers from Italy published 4 papers that discussed on the control system as contributed by [45]–[47] who discussed on the adaptation of TB control system applied to motorcycles engine while Di Bernardo *et al*. [48] dealt with the implementation and performance analysis of controlling an electronic TB in automotive engineering.

Research work from Brazil is ranked 6 with accumulation of 3 published articles where Vaz *et al*. [49] explored the opportunity to enhance engine performance according to regulation of the formula SAE competition while Silva *et al*. [50] put an effort to analyse runners length of the intake manifold of a 4-cylinder spark ignition engine. Delatore *et al*. [51] elaborated the idea to improved teaching and learning of subject Automotive Mechatronic System.

Nine countries with researchers published one article on TB design are Egypt [52], Indonesia [53], Iran [54], Japan [55], Latvia [56], Malaysia [57], Republic of Korea [58], Spain [59], and Thailand [60] (see Table 3). Articles from Malaysia, Indonesia, and Iran were focussed on the study of throttle body design related to performance while articles from Japan, Republic of Korea, Spain, and Thailand were focussed on the study related to the design of control system. Articles from Egypt and Latvia were investigating on a new design approach for TB and a paper from Tunisia elaborated on the design process of a mechatronic device. Figure 5 shows a broader view of published articles by country and year of publish.

Table 3 Nos of Papers Publish by Country According to Year

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Brazil	-	-	-	-	-	1	1	-	1	-	-
China	-	1	-	-	-	2	-	3	-	1	2
Egypt	-	-	-	-	-	-	1	-	-	-	-
France	-	-	1	-	-	-	-	4	3	3	-
India	-	-	1	1	1	1	1	-	1	2	-
Indonesia	-	-	-	-	-	-	-	-	-	-	1
Iran	-	-	-	-	-	-	-	-	1	-	-
Italy	3	-	1	-	-	-	-	-	-	-	-
Japan	-	1	-	-	-	-	-	-	-	-	-
Latvia	-	-	-	-	-	-	-	-	-	1	-
Malaysia	-	-	-	-	-	-	1	-	-	-	-
Republic of Korea	-	-	-	-	-	-	-	1	-	-	-
Spain	-	-	-	-	-	1	-	-	-	-	-
Thailand	-	1	-	-	-	-	-	-	-	-	-
United States	1	1	1	-	1	-	1	-	-	-	-

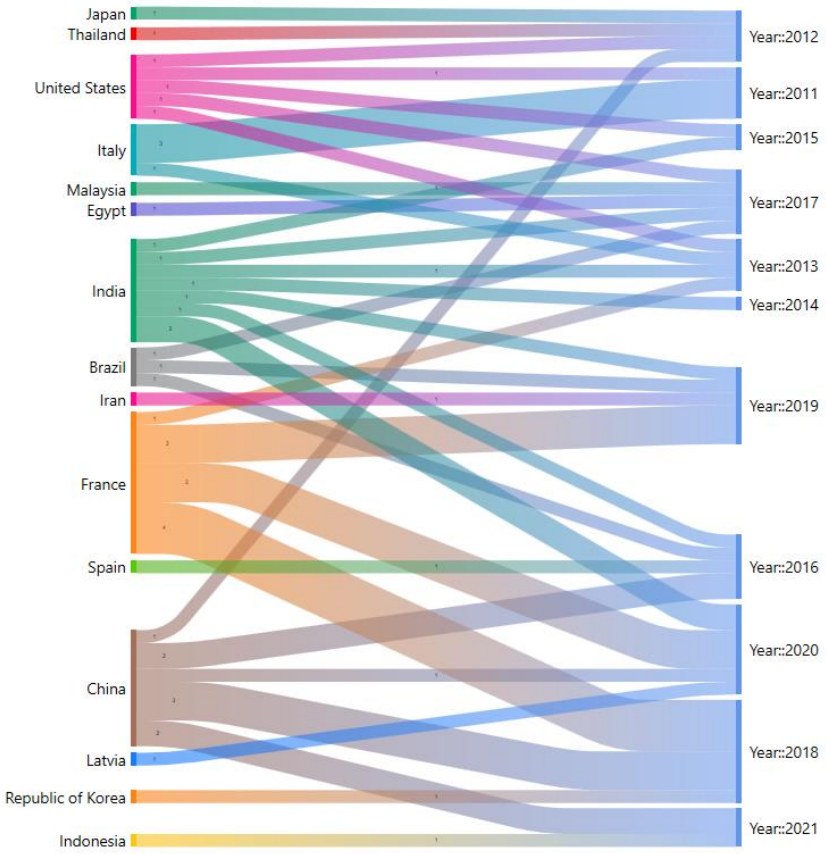

Figure 5. Sanky diagram for country and years.

3.2 Qualitative Findings

In the qualitative findings section, this paper will elaborate the themes being addressed to answer the research question. Six themes are established based on directions and subject of the articles (see Table 4). Listed are the themes from the selected publications: airflow study (6); control system design (20); design process study (10); manufacturing/production (1); new approach TB (4); and performance study (8). The main themes are not independent, but rather overlap between articles presented in this review. It is common for some articles to adopt several themes and vice versa. In the first round, the initial coding resulted to nine issues and elements discussed by authors in the study of throttle body design as shown in Figure 6. After theme reviewed, the issues were clustered into final six themes that anchor this paper review purpose (see Figure 7). In the following section the themes will be discussed separately and more in depth to answer the research question, what are the trends on throttle body design discussed in the literature from 2011 to 2021?

Table 4 Author According to Themes.

	Theme 1	**Theme 2**	**Theme 3**	**Theme 4**	**Theme 5**	**Theme 6**
Author \ Theme	**Airflow Study**	**Control System Design**	**Design Process Study**	**Manufacturing / Production**	**New Approach TB**	**Performance Study**
Amini *et al*. [40]	-	/	-	-	-	-
Ammar *et al*. [14]	-	-	/	-	-	-
Ammar *et al*. [15]	-	-	/	-	-	-
Ashraf *et al*. [52]	-	-	-	-	/	-
Balaji *et al*. [39]	-	-	-	-	/	-
Banis [56]	-	-	-	-	/	-
Borchani *et al*. [16]	-	-	/	-	-	-
Cherian *et al*. [38]	-	/	-	-	-	-
Corno *et al*. [45]	-	/	-	-	-	-
Delatore *et al* [51]	-	-	/	-	-	-
Di Bernardo *et al*. [48]	-	/	-	-	-	-
Fauzun & Yogiswara [53]	-	-	-	-	-	/
Feng *et al*. [24]	-	/	-	-	-	-
Fradi *et al*.[18]	-	-	/	-	-	-
Gao *et al*. [29]	-	/	-	-	-	-
Giani *et al*. [17]	-	/	-	-	-	-
Hassantabar *et al*. [54]	-	-	-	-	-	/
Jansri *et al*. [60]	-	/	-	-	-	-
Jawad & Arslan [43]	-	-	-	-	/	-
Jawad *et al*. [44]	-	-	-	-	-	/
Jiao & Shen [28]	-	/	-	-	-	-

Jiao *et al*. [27]	-	/	-	-	-	-
Jimbo & Nakayama [55]	-	/	-	-	-	-
Krishnan *et al*. [35]	/	-	-	-	-	-
Mcharek *et al*. [20]	-	-	/	-	-	-
Mcharek *et al*. [61]	-	/	-	-	-	-
Mcharek *et al*. [23]	-	-	/	-	-	-
Mcharek *et al*. [19]	-	-	/	-	-	-
Mcharek *et al*. [22]	-	-	/	-	-	-
Mcharek *et al*. [21]	-	-	/	-	-	-
Mo *et al*. [30]	-	/	-	-	-	-
Morton & Narasingamurthi [42]	/	-	-	-	-	-
Norizan *et al*. [57]	-	-	-	-	-	/
Panzani *et al*. [47]	-	/	-	-	-	-
Panzani *et al*. [46]	-	/	-	-	-	-
Pujol *et al*. [59]	-	/	-	-	-	-
Rajendran & Purushothaman [33]	/	-	-	-	-	-
Ramachandra & Nagalapura [32]	/	-	-	-	-	-
Ranganathan *et al*. [37]	-	-	-	-	-	/
Santillo *et a*l. [41]	-	/	-	-	-	-
Sharma *et al*. [36]	-	-	-	-	-	/
Silva *et al*. [50]	-	-	-	-	-	/
Suresh Kumar *et al*. [34]	/	-	-	-	-	-
Vaz *et al*. [49]	-	-	-	-	-	/
Xinjie [31]	-	-	-	/	-	-
Xu & Cho [62]	/	-	-	-	-	-
Xue *et al*. [26]	-	/	-	-	-	-
Xue & Jiao [25]	-	/	-	-	-	-
Yang *et al*. [58]	-	/	-	-	-	-

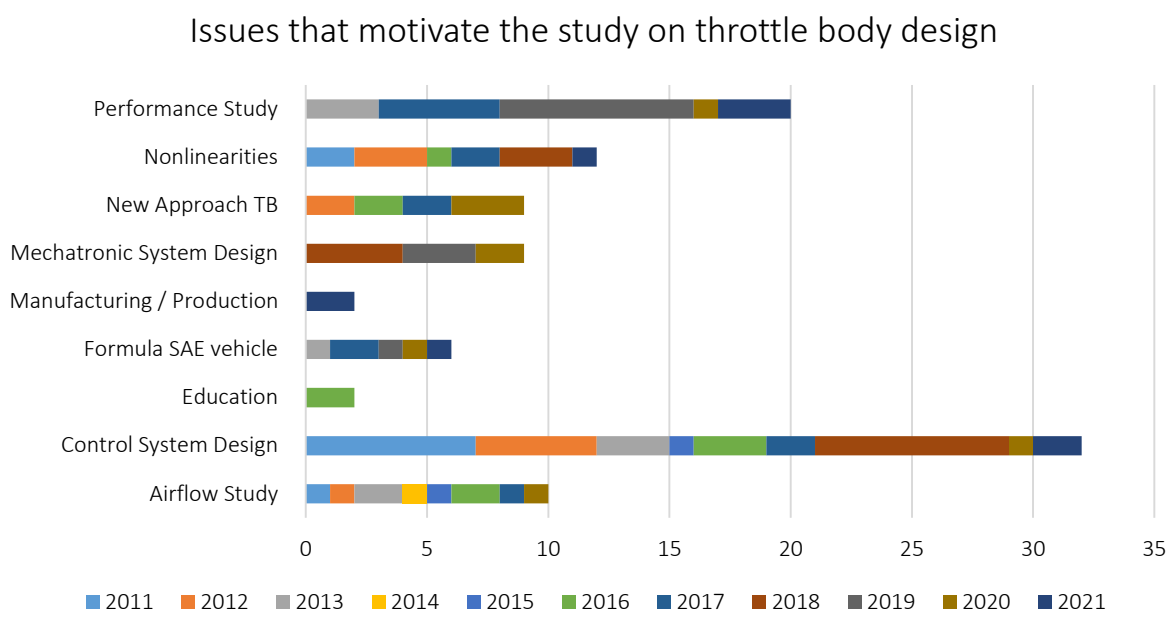

Figure 6. Type of issues discussed in the literature.

What are the trends on throttle body design discussed in the literature from 2011 to 2021?

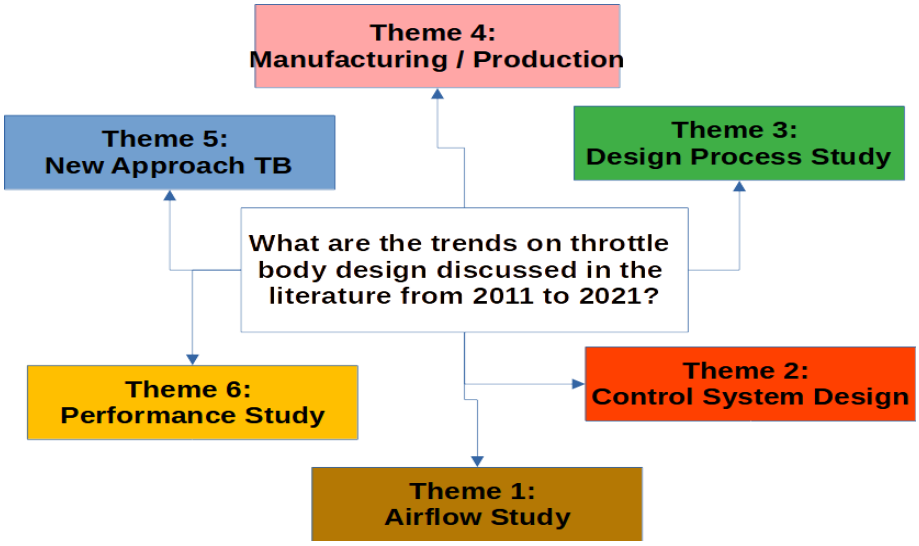

Figure 7. Overall network reflecting to research question.

3.2.1 Theme 1: Airflow Study

Airflow had become one of the themes that motivated the study on TB design. Mainly the studies on airflow were focused on the application of Computational Fluid Dynamics (CFD) simulation to understand and improve the airflow characteristic across the butterfly TB in the intake system [32]–[34], [62]. Besides the intake airflow, Krishnan *et al*. [35] in their study on the flow of exhaust gas in the Exhaust Gas Recirculation (EGR) System which affected the TB condition and performance was elaborated. Airflow study on a marine engine was also taken into consideration by Morton & Narasingamurthi [42] who highlighted the challenges of engine operation in warm environment due to the sealed cowl wrapped around the engine to prevent from water droplet entering the ICE.

From this theme, it can be seen that many efforts had been undertaken by scholars to study TB design in the context of airflow (see Figure 8). Considering ICE has been widely used in various condition and environment, future research can still be proposed to be explored and thus contribute to this theme of study.

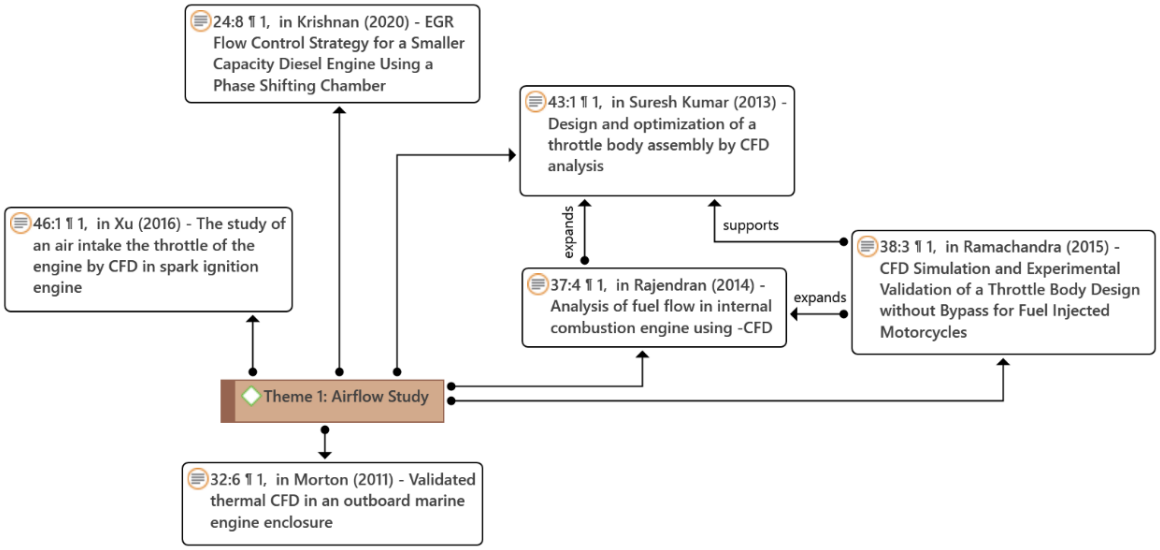

Figure 1. Airflow study network theme.

3.2.2 Theme 2: Control System Design

Control System Design is a major theme influencing the study on TB design discussed by scholars. Generally, there are two categories of study done that were focused on motorcycle's engine and also on 4 cylinders automobile engine. Inherent non-linearities in the butterfly TB such as spring, friction and backlash of gear are the main challenges in developing a control system highlighted by many scholars [24], [38], [45]. Thus Jiao & Shen [28] in their study, explored the approach of Proportional Integral Derivative (PID) Controller to manage the nonlinearities effect in electronic TB. However, Amini *et al*. [40], [58] extend the knowledge by implementing the strategy of sliding mode controller in their study while Jansri *et al*. [60] explored the fuzzy logic controller approach in their study to manage TB operation. The strategy of adaptive controller approach was also emphasizes in several studies explored by researchers [25], [27], [46], [47].

Majority of scholars involved in the study are related to this theme. This indicates the importance of this theme to the area of study (see Figure 9). Understanding that the element of control was established to cater the issues of nonlinearities in TB, future research on reducing or eliminating the nonlinearities in TB might be another opportunity to be explored rather than only controlling the nonlinearities.

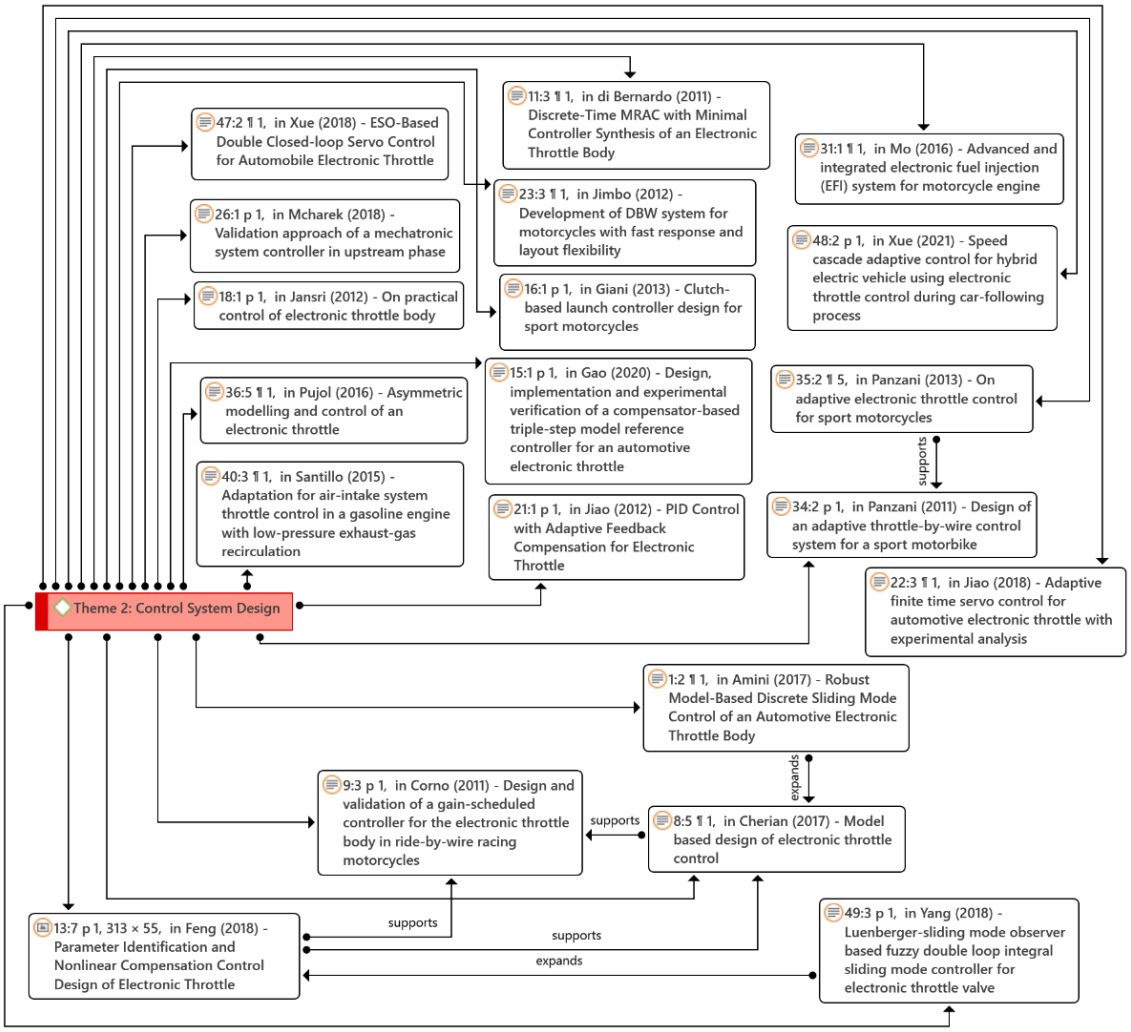

Figure 2. Control system design network theme.

3.2.3 Theme 3: Design Process Study

Another theme identified in the TB design study is related to the design process. This theme was established by scholars that considered TB as a mechatronics device. Researchers focused on the improvement of mechatronics design of the electronic TB that involved multidisciplinary collaborative design process [21]–[23]. Besides that, Ammar *et al*. [15] extended the research scope by elaborating on the implementation of set based concurrent engineering concept to the case study of an electronics TB. Other than that, Delatore *et al*. [51] explored an interesting field in education related to active learning concepts applied on mechatronic system that aimed to facilitate the practical element of teaching and learning for students of Technology and Engineering Automotive, Mechatronics or Electrical courses.

Design process study is an interesting theme which explores the possibilities that contributes to improvement from the beginning of product development. This element has effect on the cost and process flow of manufacturing that are worth to be studied. Figure 10 shows various articles published by researchers discussing the theme.

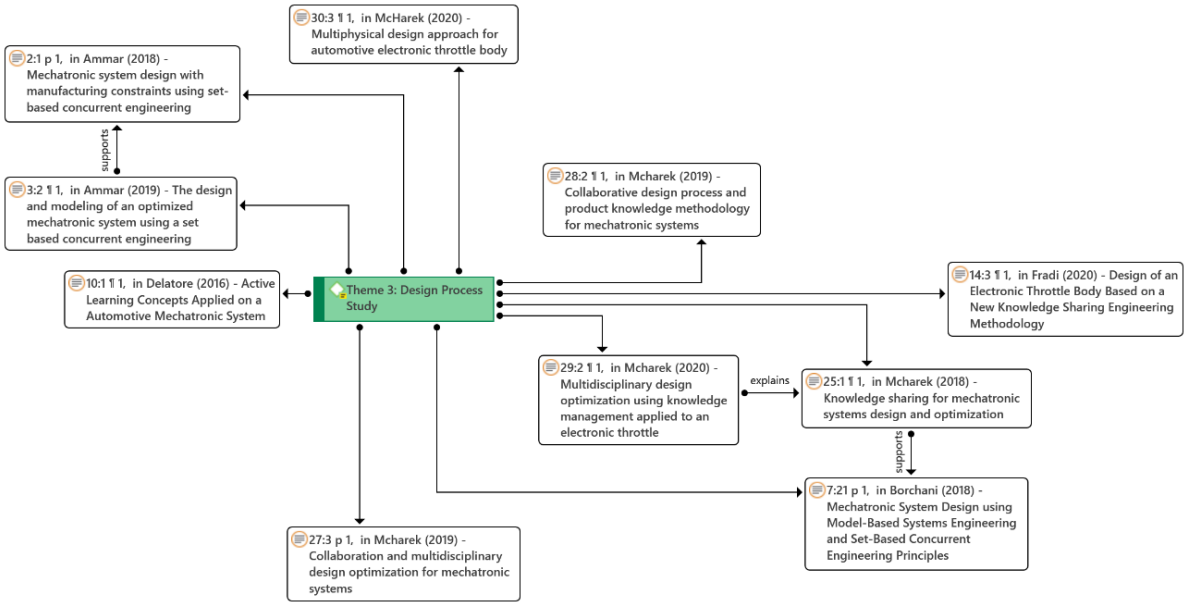

Figure 10. Design process study network theme.

3.2.4 Theme 4: Manufacturing / Production

Manufacturing/production is another theme identified to be widely studied on TB design. Xinjie [31], in his study explained how the quality of mold for the manufacturing of TB bracket had affected the performance of TB and vehicles (see Figure 11). The relation between manufacturing quality with the end product performance is an interesting area to be studied in the future. This will enlighten TB manufacturers to strive for excellent quality in manufacturing. This theme seems to be an interesting area to be extended in the future study as there are not many articles has been published in this area.

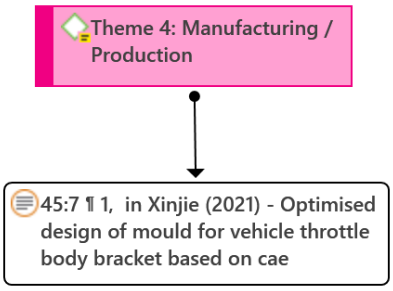

Figure 11. Manufacturing / production network theme.

3.2.5 Theme 5: New Approach TB

New approach in designing TB mechanisms is an interesting theme that has influenced TB design study. Jawad & Arslan [43] explored in their study on the new approach of cam-type pulley for throttling mechanism while Balaji *et al.* [39] investigated the effect of different TB shaft configuration to the pressure drop across the TB. This is a unique approach of improving the operation mechanism or the component of TB.

Expanding the results, Ashraf *et al.* [52] suggested barrel TB concept to replace butterfly TB. A totally new concept that contributes to a better airflow at wide open throttle. Further, Banis [56], investigated the airflow resulted at idle speed condition for a novel TB that offered no obstruction at wide open throttle.

From this theme (see Figure 12), it can be inferred that there are many possible design concepts of TB that can be explored in order to enhance TB operation. More future studies on the design concept can be proposed by scholars which can potentially contribute to the body of knowledge.

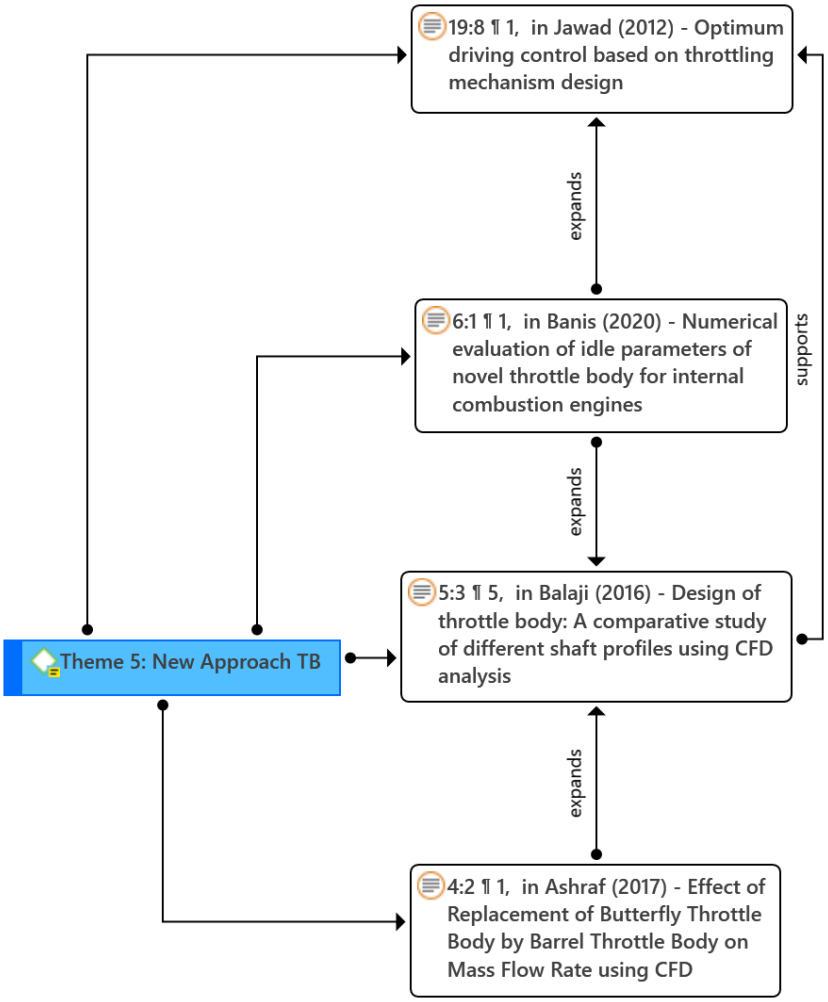

Figure 12. New approach TB network theme.

3.2.6 Theme 6: Performance Study

Performance study is another theme investigated by researchers on TB design (see Figure 13). Majority of the studies done were related to the participation in the Formula SAE competition. The objectives were to comply with the specification set by the organizer and to achieve the best performance out of the engine [36], [37], [44], [49], [53], [57]. However, Hassantabar *et al*. [54] extended the scope of study to unmanned aerial vehicle (UAV) where the effect of engine speed and flight altitude on the performance of TB injection were investigated.

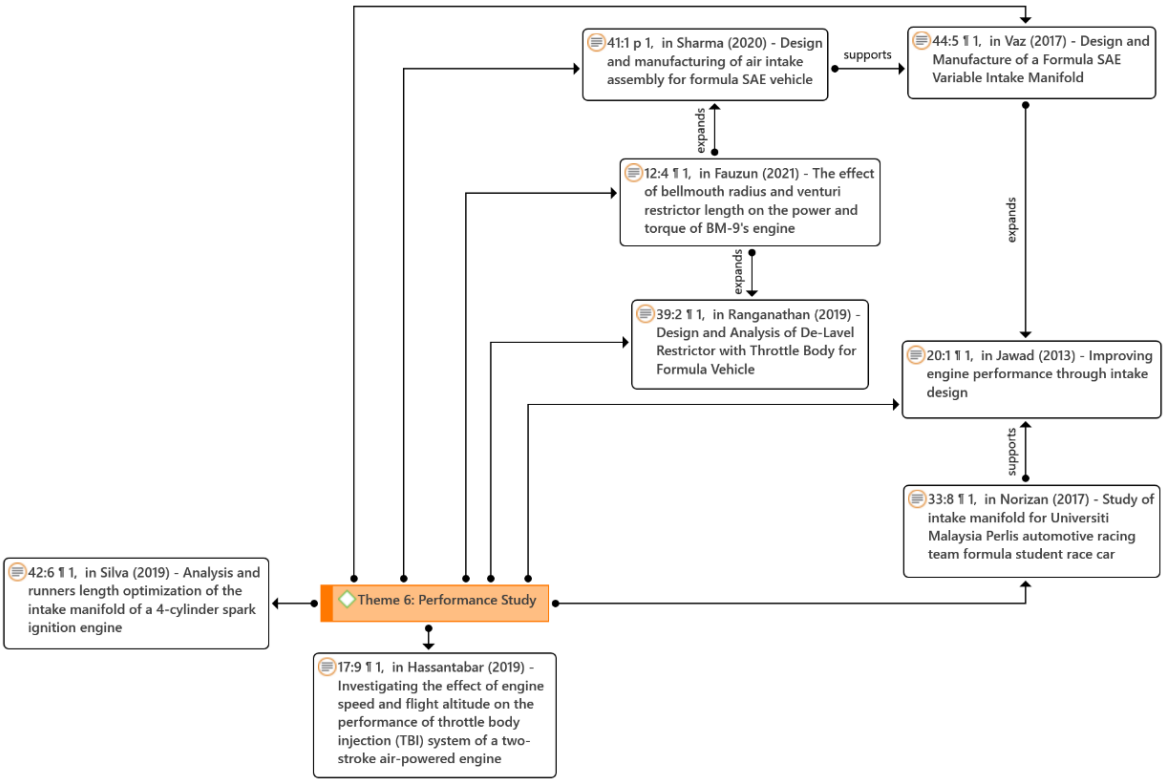

Figure13. Performance study network theme.

4. DISCUSSION AND FUTURE STUDIES

Based on the themes reviewed in this paper, it is clear that the future of TB design is much broader. Researchers can expand the knowledge towards improvement of pressure loss detected in the currently used butterfly TB. Suggesting a new design concept is one of a possible effort to develop better TB to be used for ICE vehicle.

Another opportunity to be considered is to design a more efficient operation mechanism for a new concept TB. The well-known nonlinearities in the butterfly TB need a new solution to be used and this will open a door to innovate a new control system strategy to be equipped with the novel TB.

Regarding the manufacturing process of TB, there is great potential of technological exploration as it will benefit the research and development teams in the manufacturing industries. The relationship between manufacturing quality and the actual performance of the end product could be investigated and hence contributed to a better production in the future.

Looking to the complexity of the design process for mechatronic devices highlighted in several studies reviewed in this paper, authors believe there is a great opportunity of enhancing the design process to ensure the barrier of multidisciplinary can be resolve.

Performance was always the main goals of these studies. It can be observed from the two different contexts, which are engine performance and TB performance. Investigation in the possibilities to increase engine performance can be achieved by participating in the event of formula SAE competition that was organized to expand the knowledge among young researchers. Nevertheless, TB performance will need to be expanded by the effort of exploring new design concept for example barrel TB, iris TB, and slide TB.

5. CONCLUSION

From the 49 articles reviewed in this paper, there are two approaches that were employed in this article. The first is the quantitative part, which highlighted the data that was obtained numerically from ATLAS.ti 9. Despite the growing interest in the subject, there is no review paper reported in the literature that focussed on the area of TB design. There is also a need to observe the trends in TB design to ensure continuous improvement in ICE vehicle especially with the commitment of European country to ban ICE vehicle starting the year 2030. On the qualitative part, the thematic highlighted the pattern of studies done on TB design where majority of the studies were focussed on the control system design to cope with TB nonlinearities issue. Design process theme which is ranked second in the discussion by scholars was focussed on the effort to improve process of designing mechatronic device. Performance and airflow also being discussed in several publications that motivated the study on TB design. An opportunity to enhance TB design was discussed in the publications with the theme of new approach TB while manufacturing / production of TB also being discussed.

The key contribution of this article is to analyse the literature that discussed on throttle body design. The practical contributions are to improve or introduce future opportunity for industries and researchers in exploring new approach of TB. This article highlights existing study in TB design that are crucial in contributing to the improvement of ICE performance. It is thus necessary for researchers to explore new approaches and model concepts of TB that can contribute towards better emission control and performance of ICE.

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