Blucher Design Proceedings
Dezembro de 2014, Volume 1, Número 8
www.proceedings.blucher.com.br/evento/sigradi2014

The Evolutionary Changes of the Streamlined High-speed Locomotives

The quantitative analysis to reveal the changes of bullet motif locomotive design criteria

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Abstract

In this research, we develop the quantitative design analysis method for the atypical nose shape of bullet motif high-speed trains. And we trace the design changes and reveal the changes of design criteria that are shown in the evolutionary process of the Shinkansen high-speed trains by the quantitative method. To do this, first, we define the corpus of Shinkansen high-speed train designs. Second, the landmarks – sub-features – that comprise a nose shape of high-speed train are defined. Third, the locomotives of the corpus are quantitatively analysed by the morphometrics: a method of geometric shape analysis. Finally, the design changes are traced by the result of the analysis and the changes of design criteria will be revealed.

Keywords: Shape Study; Style Analysis; Geometric Shape Analysis; High-speed Train Design

Introduction

The bullet motif of steam locomotives opened the new era of streamlined trains (REF). The movement for efficiency in industrial vehicle design had promoted the exterior outcomes that are not only aesthetically futuristic but also functionally superior (REF). The corpus, so called streamlined trains, was formatted by this design trend appeared in the market as a new locomotive design solution (REF). This international movement was an opportunity that made possible to commercially operate streamlined locomotives in many countries of Europe, America, and Asia (REF). In the level of brand, various manufacturers designed streamlined locomotives and they released these into the market. This trend could be a starting point of the long-term evolution of a streamlined nose – the front head of a train – shape because the design concept was a symbolic representation of futuristic modern identity. In addition, it was functionally suitable to deal with exponentially growing demand for long-distance transportation (REF). Fortunately, there were many technical supports; the fluid dynamics contributed outstanding portion at the transition of locomotive nose exterior design (Hucho, 1998). Technical knowledge gained through manufacturing fighters and commercial airplanes had made a foundation to design an exterior shape that would reduce aero resistance (REF). The design method of streamlined nose shape was developed at a time when aerodynamic designers were developing design methods and shape evaluation methods.

After a long time, finally, the designers of a commercial locomotive could break the barrier of 200km/h with the new locomotive of the Shinkansen 0 series that is known as the first high-speed train in the world (REF). But interestingly, the nose shape of the locomotive was designed by following the old bullet motif. There is no doubt, until the first commercial high-speed train finishes its trial run, that technology of fluid dynamics had a profound progress. The progress supported even the aerospace industry to play a major role in the great achievements of a human history. The point is that the nose shape of the first high-speed train was a faithful design of the original bullet motif used for the early period streamlined shape (REF). What we want to see in this paper is the evolutionary progress of the nose shape of high-speed train starting from the first commercial high-speed train. In the perspective of the market, the evolution was inevitable by the increasingly excessive competition for the maximum speed of locomotives; the evolutionary progress is related to the efforts to design enhanced nose shape of locomotive to reduce air resistance (REF). If we look back at the first commercial high-speed train design at the level of design process, the decision for the original bullet motif would be postulated as inarguable for the high-speed vehicles. However, the posterior evolutionary progress of high-speed locomotives had raised a question regarding the bullet motif. Of course, an existence of the posterior progress is the counterevidence of it. Moreover, the special driving conditions of a high-speed train have been reconsidered with further findings as an adequate provision that attends the progress (Hucho, 1998). The design changes become clear by tracing the successors of Shinkansen 0 series: the first commercial high-speed train.

The current design method used for the bullet motif nose shape is quite predictable and reproducible as shown in the research paper of Raghunathan et al. (2002). Even though the method is predictable and reproducible, the diversity of outcomes producible by the design method is inadequate. In particular, after few successors, the complex shapes that were not producible by the current design method have been released onto the market (REF). The appearance of these innovative designs that are not a part of the corpus of the current design method is the obvious evidence for the current methodological limitations. Therefore, it implies the needs of a new method that would surmount the limitations. Although the designers have developed the complex shapes out the corpus group, the new systematic method or even the quantitative trace about the changes could not be developed and studied; thus making the understanding of evolutionary progress difficult. The evolutionary progress of the nose part of high-speed locomotives cannot be reapplied to a new design due to a lack of the quantitative method. Therefore, in this research, we develop a systematic method to quantitatively trace the design changes and reveal the changes of design criteria from the set of successors.

In this research, we develop the quantitative design analysis method for the atypical nose shape of bullet motif high-speed trains. And we trace the design changes and reveal the changes of design criteria that are shown in the evolutionary process of the Shinkansen high-speed trains by the quantitative method. To do this, first, we define the corpus of Shinkansen high-speed train designs. Second, the landmarks – sub-features – that comprise a nose shape of high-speed train are defined. Third, the locomotives of the corpus are quantitatively analysed by the morphometrics: a method of geometric shape analysis. Finally, the design changes are traced by the result of the analysis and the changes of design criteria will be revealed.

Streamlined Trains and the Bullet Motif

The vehicle advancement plan for the new era of Japanese rail system could get on the track in the same vein as similar revolutionary plans of other developed countries. These attempts and efforts of 1920s were not the result of unilateral factor: technological advancement. The driving force of the situation was quite cultural and sometimes political as much as the attempts were possible by technological advancement. And even some of the attempts of streamlined vehicles could not completely supported by engineering because of the insufficient tools and methods; in the perspective of optimization, many locomotives had been designed in the opposite direction. Of course we cannot judge all the efforts as the consequences of blind obedience to cultural trend or political propaganda. However, at least, the purpose of designing bullet motif shape for a steam locomotive was ultimately on delivering symbolic meaning of streamlined shape itself rather than pursuing aerodynamic efficiency. The fact was conjunct with the imperial consciousness of the period; Japanese imperialism promoted some kind of a conceptual connection between the futuristic streamlined shape (e.g. bullet motif) and the new political agenda of advance into continent (Manchuria) and its development. Thus, the termination of war and the followed collapse of old monarchy of empire dealt a deathblow to those movements of innovative public design transformation. Consequentially, the next generation of streamlined locomotive could not be made until revival of economic vitality. The next generation of Japanese streamlined trains opened a new era of 1960s electric locomotives, while the first generation was the grand finale of the era of steam locomotives.

The representative starter of streamlined electric locomotives – 3000 series of Odakyu Electric Railway Co. (1957) – followed the tradition of bullet motif; the nose shape was the direct inheritor of western bullet motif locomotives that was popular since before WW2. And another representative – 0 series of Tokaido Shinkansen – that began to start its first commercial driving in 1964, had a bullet like nose shape. It showed different degrees of roundishness and length but basically the shape was designed with bullet motif. More specifically, the engineers of the locomotive had got many unacquainted problems to design a new high-speed train that commercially drives over 200km/h; the design goal was totally advanced because there was no successful design case yet. To accomplish the design goal, a nose shape for the locomotive was also considered as an important factor. And finally the engineers delivered the advanced bullet motif shape; at that time, many technical bases of the nose design had been borrowed from the domain of aerospace engineering. That is why 0 series Shinkansen locomotive has similar nose shape to the very front part of airplane. Very successful debut of the new high-speed train system and the acceptable result of the unique bullet motif nose shape of the locomotive had promoted further development for newly settled goal.

The importance of nose shape improvement had kept rising as other mechanical parts and control systems go close to the optimal solution. Even the degree of exterior noise and vibration generated when train drives has been increased exponentially, as a result of progress on maximum velocity spec. Although the aerodynamics – specifically, the domain of high-speed train design – could examine the major causes of the inevitable energy loss (noise and vibration) still the effect of the most important factor, a nose shape, cannot be defined mathematically. The mechanism of noise generation by a nose shape remains as a black box. The design methodology had been systematized and quite simplified at the intermediate level to guarantee both predictability and generalness. Here, the shape generation methodology had to cover many shape solutions as possible in general. But a simplification was unavoidable because the predictability has been gained by mathematical modeling. Thus the shape alternatives difficult to be modeled in rational expression could not be covered with the methodology.

Here, the design methodology had to inform any mathematical variables that control the morphology to designers. Then designers could generate many alternatives and examine the pros and cons. Meanwhile, the shape generation methodology had to cover many shape solutions as possible in general. The design methodology could inform some mathematical variables that control the morphology to designers. Then designers could generate many alternatives and examine the pros and cons; the evaluation was made by criteria of aerodynamic traits. In spite of limited kinds of solution, at least the methodology could guide designers to the final solution that is locally optimized. However, new market demands and solutions provide counterevidence of this equilibrium. Most design cases released recently have complex streamlined nose shape those are difficult to be rationally expressed in general. It represents a practical limitation of current methodology. The solution space of the methodology is not sufficient, even if it guarantees both predictability and generalness. A new methodology is needed to increase generalness and solution space; meanwhile the predictability should be maintained.

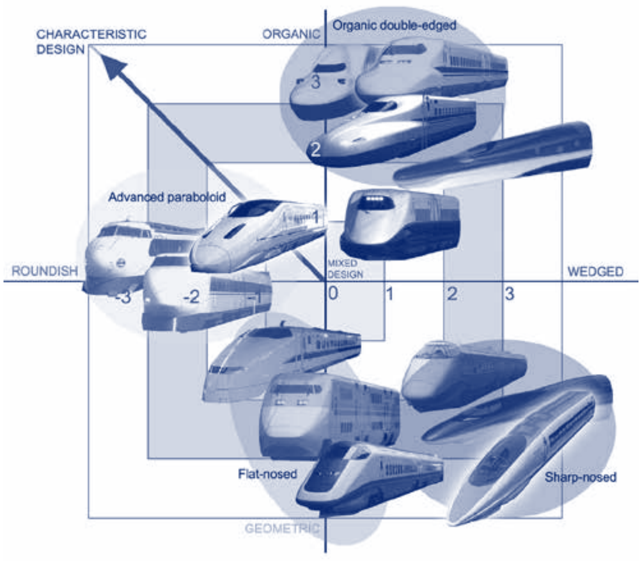
By this time, commercial driving of Shinkansen high-speed train system was operated by 16 series of locomotives: 0, 100, 200, 300, 400, 500, 700, N700, 800, E1, E2, E3, E4, E5, E6, and E7 series. Researches on high-speed train have never been stopped by the lead of operation companies of Shinkansen rail lines even after the government-owned Japanese National Railways was divided into several for-profit corporations by the reason for enhancing management effectiveness. Of course the first generation of Shinkansen locomotive was developed by the project of Japanese National Railways. But the corporations have accumulated the knowledge regards to high-speed train design, manufacture, maintenance, operation etc. The next generations of Shinkansen locomotive are the result of development. The corporations are currently collaborating to develop new generation of locomotive.

Style Studies for High-speed Train

In this research, the evolutionary changes of the nose shapes of Shinkansen locomotives are quantitatively analyzed to figure out new design criteria that cannot be explained by the current design methodology. As mentioned above, the current methodology only provides locally optimized solution because the methodology cannot cover complex shapes alternatively applied on nose part of high-speed locomotive. That is why a general shape study method should be developed before a new shape generation methodology is settled. Many shape studies regard to nose part of high-speed train are categorizing and tracing series of designs. And most of the results explain trend of streamlined nose design or some cultural aspects. Their future goal is making a systematized methodology to generate morphological identity of nose design by current design trends or social aspects. In other words, that was a matter of understanding brand identity of the nose part. However, very simply, the fashion is not a complete factor to describe the traits of nose morphology at least the nose shape is the most major feature in improving the aerodynamics of locomotive. Nonetheless, the researches imply very significant background of Shinkansen style study.

To examine and release a newly developed high-speed locomotive, advanced technologies for designing a vehicle and evaluating the prototype for a commercial driving are required and sufficient manpower, budget, and schedule are necessary. Nevertheless, the number of manufactured product is very few and very special organizations conduct the design and evaluation work. Moreover, there are terms between generations; the new locomotive design project is arranged if there are distinguishable improvements of technology or the market demands a new generation of locomotive for the opening of new Shinkansen rail line. Therefore in particular circumstances of the Shinkansen locomotives, for style studies, the individual identity in a stream of design development could be given on the each series.

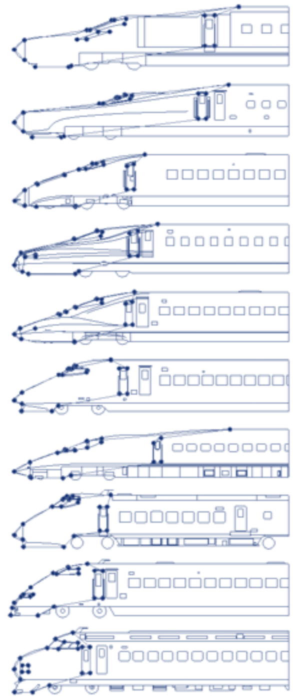
The context has made possible to understand a design generation as a successor of its parent, though the relationships were not quantitatively defined yet. Thus the opinions that conclude the socio cultural effect is useful to understand the design transformations are not totally illogical. But the necessity still remains for quantifying the morphological characters closely relevant to aerodynamics. One more noticeable thing from the previous style studies is the two-dimensional Euclidean space used for nose shape classification. In the system, one axis is 'geometric-organic' and another is 'roundish-wedged'. Of course the two-dimensional system is insufficient to quantitatively classify a complex volume of nose part. The thing implies two possible perspectives to understand the morphological characters: 1) roundness (roundish-wedged) and 2) complexity (geometric-organic). The degree of roundness is a very fundamental variable that controls a bullet motif shape. It was very necessary to conduct the style study because the design cases of Shinkansen locomotives have a same root: bullet motif streamlined shape. So, the first criterion for the classification represents a morphological trait of bullet motif noses. And the complexity factor is an evidence of efforts, as mentioned above, that have tried to overcome the limitation of current design methodology. The recent locomotives are positioned in the 'organic' group (figure). However the factor should not be understood as a criterion, but should be understood as a counterevidence of effectiveness of current design methodology.



Methodology for Shape Analysis

Stiny and Mitchell described the major purposes of the style definition. A style of artifacts must be defined and represented within a general frame. Then the purposes will become clear: quantitative explanations of similarity in a corpus, style-judging criteria for corpus discrimination, and compositional rules of members. However, even though organizing a general frame is possible, as long as the format of frame is the simplified parametric modeling, a general expression for all atypical nose shapes of high-speed train is almost impossible. In another way, the profile of a nose shape can be analyzed as the combination of curve segments. Practically the method requires distinct nodes to define a decomposition rule universal for each corpus; the distinct nodes should be common in a corpus to decompose a profile into a meaningful set of segments. But the method has a generalization issue to cover the corpus of Shinkansen noses; in general, contrary to the style studies for automobile, there are no distinct and even common nodes on profiles. Then the alternative method – elliptic Fourier analysis – is considerable under these practical constraints. Nevertheless, an important condition of the method makes hard to apply this on the nose style study. To apply the analysis method the curve must be closed, but the profile of a train nose is not represented as a closed curve. In summary, a domain specific method to represent all streamlined nose design cases is needed.

Similar problems have been discussed in the domain of comparative biology and evolutionary biology. And the solution is a geometric shape analysis method. Exactly, the parametric modeling method was not adequate to represent a shape into a structure of rational expression because most of comparison targets are extremely complex and atypical; even the mathematical variable does not deliver any biological meaning. And the curve decomposition method was also not universal in the domain because the profile of some species does not have distinct nodes for rigorous curve decomposition. Nonetheless, the synthetic character of a body or organism shape could be quantified by elliptic Fourier analysis method when the comparison target is a closed curve. However the numeric representation of elliptic Fourier analysis is insufficient for tracing evolutionary transformations; the method has been used to compare sub-features of a body or organism. The geometric shape analysis method is the alternative way to satisfy the conditions. For the universal representation in a corpus, the common landmarks are defined. The landmarks are representing the common sub-features that have an evolutionary meaning to be traced; the landmarks are corpus-specific. A synthetic transformation of target bodies or organisms is comprehensively traced with a holistic result of the all landmark changes. The numeric representation of the degree of deformation and synthetic visualization for the tendency are also possible through the thin-plate method. The method has been used to quantitatively 'identify' or 'justify' shapes of specimen; the corpus in comparison biology and evolutionary biology was defined by phylogenetic relationships. Interestingly the method was not only used in quantifying biological transformations of bodies or organisms but also tracing design changes of artifacts; the technique of landmark definition in an artifact style study is similar to the original but the definition of corpus is domain specific. For example, in a tough condition that only accessible excavated artifacts for an anthropological study, the cultural anthropologists have used the geometric shape analysis method to 'identify' and 'justify' the artifacts of a corpus.



Analysis Result

In the early stages of the nose designs of a high-speed locomotive, a small number of public enterprises have partaken, resulting in a lower number of design cases compared to other vehicles. Due to this reason, each design case of high-speed trains has a clear differences from generation to generation. However, the atypical characteristics of the nose shape have militated against quantitative trace and analysis since the atypical design series are difficult to define by global and local frames, and their absolute shape decomposition is also problematic. Thus, the current hierarchical methods – top-down or bottom-up methods – of design analysis are inappropriate for the set. As an alternative solution, we suggest the method of geometric shape analysis. The method has been evaluated as an appropriate solution to trace and analyse the changes of atypical and complex shapes; the morphometrics used in the evolutionary biology is representative (Cardillo, 2010). Especially, the method is useful for tracing the consecutive changes occurred in one corpus. This method has expanded the domain to artefacts helping to 'identify' and 'justify' the ancestor and the descendant of one corpus (Cardillo, 2010). In the analysis, using the morphometrics, one complex shape is represented by a set of sub-features that comprise the shape (Cardillo, 2010)[FIGURE 1]. The traces of each sub-feature – landmark – show the quantitative changes within one series of shapes (Cardillo, 2010). Fortunately, the high-speed locomotive has universal sub-features, which are concretely indicated as landmarks; the nose part consists of locomotive connection cab, lower skirt, bogie skirt, headlight, tail identification light, front window for driver's cabin, nose end, and etc [FIGURE 1].

Specifically, to apply the method for tracing the design changes and revealing the changes of design criteria from the successors of high-speed train, we define the corpus by the Shinkansen series: Japanese high-speed trains. The Shinkansen series is appropriate for applying our method because the changes are apparent in its history, and the set of series has a various kinds of successors compared to any other high-speed train systems.

Conclusions

The evolutionary progress of the nose part of high-speed locomotives could not be reapplied to a new design due to a lack of the quantitative method. Thus, we will develop the quantitative design analysis method for the atypical nose shape of high-speed trains. The morphometrics will be used as an alternative solution. The method is expected as an appropriate way to trace the design changes and reveal the changes of design criteria implied in the evolutionary process of the Shinkansen high-speed trains. Hopefully, this method is applicable for analysing design evolution of other corpus with atypical shape characteristics.

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