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An Advanced Development Design CAE Model Utilizing *New JIT*:

Application to Automotive Intelligence CAE Methods

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**Abstract:** With a view to assisting corporations to survive in the “worldwide quality competition”, the author has proposed the “Advanced Development Design CAE Model” utilizing *New JIT*. In an effort to verify its validity, the author has created the “Automotive Intelligence CAE Methods”. Furthermore, as an extended application of these methods, the author has also established the “Automotive Intelligence CAE Management System Approach Methods”. The author has analyzed an issue of worldwide concern, the oil seal leakage mechanism on an automobile transaxle, and has created the “Intelligence CAE Software - Oil Leakage Simulator” that incorporates CG Navigation in order to ensure high quality assurance.

**Keywords:** *New JIT*, Advanced Development Design CAE Model, Automotive Intelligence CAE Methods, CG Navigation, Intelligence CAE Software - Oil Leakage Simulator, Toyota and NOK

1. **Introduction**

At present, advanced companies in both Japan and overseas in the automobile industry and others are endeavoring to survive in today’s competitive market by expanding their global production while also aiming to respond to the “worldwide quality competition”. [1] Given this management situation, the author has recognized the necessity of making advancements
in the product development system. A new area of interest has arisen in the study of a design management model that realizes high quality assurance in automobile development designing.

This new area is the shift of business process management from experimental evaluation based on actual vehicles and tests, to predictive evaluation based on highly reliable CAE (Computer Aided Engineering) analysis. Given this background, the author [2] proposes an “Advanced Development Design CAE Model, ADDCM”, which strategically deploys New JIT (New Just in Time). The validity of this model has been verified by the author and it will help realize the simultaneous achievement of QCD (Quality, Cost, and Delivery). Furthermore, by deploying ADDCM the author has created and verified the effectiveness of the “Total Quality Assurance (QA) High Cycle-ization Business Process Method” and the “Stratified Intelligence CAE Management System Approach Method”.

These methods are both a part of the “Automotive Intelligence CAE Methods” that the author has also created in an effort to reform the automobile development design process. Stated in more concrete terms, the author has invented the “Automotive Intelligence CAE Management System Approach Methods” and with the cooperation of the Toyota and NOK corporations has used these methods to investigate the transaxle oil seal leak mechanism that has been a bottleneck technological problem for the world’s automobile manufacturers. [2, 3]

At the implementation stage, the author developed a “visualization device” that could capture the dynamic behavior of the oil leak. This knowledge was then combined with the “CG Navigation” function that employs computer graphics technology to create the “Intelligence CAE Software - Oil Leakage Simulator” and this made highly reliable CAE analysis possible. As a result of this outcome, precise improvement of designs and process management could be implemented. This then led to an even more dramatic effect, the achievement of “transaxle high quality assurance” in the marketplace.
2. Expectations for Automotive Development Production and Simulation Technology

For manufacturers to be successful in the future global market, they need to develop products that make strong impressions on consumers and then supply such products in a timely fashion through effective corporate management. The mission of the automotive manufacturers in this environment of rapidly changing management technology, is to be prepared for the “worldwide quality competition”, so that they are not pushed out of the market and to establish a new management technology model that enables them to offer highly reliable products of the latest design that are also capable of enhancing the value to the customer. [2, 4]

In the field of management technology for the automobile development and production processes that are being considered here, excessive repetition of “prototyping, testing, and evaluation” is being carried out to prevent the “scale-up effect” in the bridging stage between testing and mass production. This has resulted in an increase in the development period and cost. Therefore, it is now necessary to reform the conventional development and production method. [2] More specifically, it is increasingly vital to realize the “simultaneous achievement of QCD” (Quality, Cost and Delivery) that satisfies the requirements of developing and producing high quality products, while also reducing the cost and development period through incorporation of the latest simulation technology “CAE” (Computer Aided Engineering) and statistical science called SQC (Statistical Quality Control). [5, 6]

In the vehicle development process employed in the past, after completing the designing process, problem detection and improvement were repeated mainly through the process of prototyping, testing, and evaluation. In some current automotive development, a prototype of a vehicle body is not manufactured in the early stage of development due to the utilization of CAE and SE (Simultaneous Engineering) activities, and therefore the development period has been substantially shortened (first from four years to two years, and then to one year at
present). [2] Given this background, it is clear that the conventional development process of repeated evaluation using prototypes is no longer capable of handling this task. Collaboration between CAE and SE activities, which are now faster and more precise, will be indispensable for fully utilizing the accumulated knowledge database. As discussed so far, expectations are high for the realization of super short-term development, which would be done through utilization of CAE. In other words, there will be a conversion from the so-called “development through real object confirmation and improvement” to “prediction evaluation oriented development”. [3, 6, 7]

3. Proposal of the Advanced Development Design CAE Model Utilizing New JIT

The author will apply “New JIT”, a new principle of next generation management technology, in order to create and propose the “Advanced Development Design CAE Model” in an effort to reform the business process of development design.

3.1 Concept of “New JIT” for Innovating Management Technology

The “new deployment of global marketing” for prevailing in today’s “global quality competition” is the most important issue for the manufacturing industry. Particularly for Japanese manufacturers, in order to survive in the global market, the urgent management issue is “global quality and simultaneous launching (optimal production), in other words, the simultaneous achievement of QCD, which is a prerequisite for succeeding in global production. [1, 2]

In order to create attractive products that are also superior in QCD, it will be vital for each of the business/sales, development/designing, and production divisions to carry out management in such a way as to link the entire organization of their own divisions. Therefore, what is needed is a strategic, next generation management technology that can become a unifying force for optimizing (strongly linking) the business process cycles of all divisions, in
other words, creating a new organizational and systematic behavior principle. Given this background, the author [8] hereby proposes a new management technology principle, New JIT, as indicated in Figure 1.

New JIT is the Just in Time (JIT) system [9, 10] not only for manufacturing, but also for customer relations, sales and marketing, product planning, R&D, design, production engineering, logistics, procurement, administration, and management. It will enhance the innovation of the business process and the introduction of new concepts and procedures. New JIT contains hardware and software systems for accelerating the optimization (high linkage) of work process cycles of all the divisions and aims to strengthen management technology so that it reaches the level of management strategy as shown in Figure 2.

The hardware system of this strategic management technology system (New JIT) is made up of three core principles: TDS (Total Development System), TPS (Total Production System), and TMS (Total Marketing System). The aim of New JIT is to organically link these three core principles of TDS, TPS, and TMS in order to unify the entire business process from development design technology to control technology and finally to sales, and thereby reform management technology.

These three core systems are each a core technology required for establishing the new
management technology in each of the divisions: business/sales, development designing, production engineering/production, and general affairs/management. For the software system of this strategic management technology system, the author [11, 12] proposes a new principle of quality management, Science TQM (TQM promotion incorporating Science SQC) which is called TQM-S. This has been done in order to improve the business process quality of all divisions depicted in the figure.

More specifically, this is an operation strategy for next generation quality management that was developed to promote a more scientific approach, and its validity has been demonstrated in recent years. The aim is to rationally systemize and organically organize the application of new quality management through parallel use of Information Technology (IT) and Science SQC. At present, New JIT, which will allow management technology to evolve into a management strategy, has proved effective in a number of cases at Toyota and other companies and will now be introduced to a number of countries.

Figure 2 New JIT Strategy, High-linkage Cycle for Improving Business Processes
3.2 The Importance of “Highly Reliable CAE Analysis” Utilizing New JIT

Next, the author will attempt to grasp the need for and importance of “highly reliable CAE analysis” that utilizes New JIT. This will be done from the standpoint of “high quality assurance manufacturing – the simultaneous achievement of QCD”. In order to do this the author investigated the utilization status, problems, and validity of CAE throughout the entire work flow (from development/design, to production and sales) at automotive companies (body manufacturers and parts suppliers).

This is summarized in Figure 3. In the case studies (1 to 3) conducted by the author [2, 5, 6] up to now, the progress of the CAE analysis technology has been illustrated, but it has become clear that its systematic and organizational application is still inadequate. The first CAE application problem is (i) that the mechanism of technical problems that are expected to be clarified through CAE analysis is not well understood and implemented in the CAE model. The second application problem (ii), is that the CAE analytic method has not been shown to be capable of reliable prediction and control to the point that CAE can replace the prototyping and testing evaluation process. The desired gap (analysis error) between the real machine (actual vehicle) evaluation data and the CAE data should be in the order of only a few percent.

Figure 3 Issues When Applying CAE to Development Design Reform
At present however, the “development of CAE software performing within the error limitations and establishment of its usage” are not satisfactory. As a result, it has been surmised that despite its expanded usage, CAE is not yet sufficient for the simultaneous achievement of QCD or for reducing the length of the development period. The main focus of CAE utilization by development and designing engineers is first, structural modeling and estimation for prediction. Second is control, and third is factor (cause) analysis. Particularly in the case of highly reliable CAE analysis for “prediction evaluation based development”, when a highly precise absolute value evaluation is expected to be able to match the actual vehicle and testing evaluation results, then the modeling for prediction and control must inquire into the strict cause and effect relationship. In this case a physical-chemical, universal structural model is required, and advanced unique technology (such as elucidation of the “mechanism” that is causing the problems to occur) holds the key to successful development.

3.3 Proposal of the Advanced Development Design CAE Model “ADDCM”

At present, in the business process from automobile development design through to production and sales, the “high cycle-ization of development design” in particular, is becoming a pending problem. [2, 13] In general, to achieve the “scale-up effect” during the bridging stage between the actual vehicle (prototypes and testing) and mass production, a process of successive prototyping, testing, and evaluation must be carried out repeatedly. This results in higher costs and longer development periods. Therefore, in order to break out of this pattern it is now vital to reform the conventional development design method.

In an effort to deploy a global production strategy that employs New JIT, it is urgent to leave behind the conventional development design process of low intelligent productivity in which prototyping and testing are repeated on a trial and error basis. This is especially the case for design activities that ultimately aim to result in product commercialization. Instead, it
is necessary to concentrate accumulated design knowledge through a strategic collaboration between the related departments in order to conduct “highly reliable CAE design” that makes full use of the latest simulation technology “CAE analysis” capabilities. [7, 14]

Therefore, in order to break away from the old-fashioned product development method, in an aim to establish a high-cycle, next generation development design process, the author [2] proposes the “Advanced Development Design CAE Model, ADDCM”, as shown in Figure 4.

The mission of ADDCM is the simultaneous achievement of QCD. This is the basis for high quality assurance manufacturing and is also essential for the realization of CS (Customer Satisfaction), ES (Employee Satisfaction), and SS (Social Satisfaction). In order to create this model, digitized design (A) will be used in an effort to reform the development design system (B) and promote the shift to a super-short-term development process system (C). Furthermore, it will be necessary to realize the “sharing of intelligent technology” among the development designers (D).

The necessary parts to make this model into a reality are shown in the figure above. The objective of this model is to (I) scientifically interpret (convert into explicit knowledge) the

![Diagram of Advanced Development Design CAE Model](image-url)

Figure 4 Advanced Development Design CAE Model “ADDCM”
customer’s wants (implicit knowledge) that are drawn out by “Customer Science” [15] through incorporation of “Science SQC”. The second objective is to innovate and upgrade the model to (II) a highly reliable development design system that reflects the results obtained in the first step. What makes this possible is (III) “intelligent simulation” by means of creating “highly reliable CAE analysis software” that is capable of shortening the development period through accurate prediction and control. To implement this, it will be vital to (IV) introduce an “intelligent technically integrated network system” called “TTIS” (Total SQC Technical Intelligence System) [11, 16] where the accumulated know-how and latest technical information of all departments are commonly shared, and then to systematically and organizationally operate this system.

In the next chapter “Automotive Intelligence CAE Methods” will be proposed that will become the concrete deployment method for the proposed “ADDCM”.

4. Application of the “Automotive Intelligence CAE Methods” Utilizing ADDCM

In an effort to deploy “ADDCM” and reform the process of automobile development design, the author proposes the “Total Quality Assurance (QA) High Cycle-ization Business Process Method” and the “Stratified Intelligence CAE Management System Approach Method” as a part of the “Automotive Intelligence CAE Methods” mentioned above.

4.1 Total QA High Cycle-ization Business Process Method

As the first step, the author proposes the development design business process approach method. This is done from the standpoint of Verification/Validation (divergence of CAE from theory and divergence of CAE from testing) in order to make highly reliable CAE analysis possible that is consistent with the market – testing – theory profile. The author [2, 11] therefore recommends the introduction and utilization of the “Total Quality Assurance High Cycle-ization Business Process Method” which systematically and strategically realizes high quality assurance by incorporating the analysis made via the core technologies of Science
SQC and Management SQC as shown in Figure 5.

For example, in order to solve the pending issue of a technology problem in the market, it is necessary to create a universal solution (general solution) by clarifying the existing six gaps (1 to 6 in the figure below) in the process consisting of Theory (technological design model)–Experiment (prototype to production) – Calculation (simulation) – Actual Result (market) as shown on the lower left of Figure 5 below. To accomplish this, the clarification of the six gaps (1 to 6) in the business processes across the divisions, shown on the lower right of Figure 5 below, is of primary importance. By taking these steps, the intelligent technical information owned by the related divisions inside and outside the corporation will be totally linked, thus reforming the business process of development design. In this way the rational deployment of “Customer Science”, which is a key to the realization of the “highly reliable development design system”, will also be achieved.

4.2 Stratified Intelligence CAE Management System Approach Method

Next, as the second step, the author [2] proposes the “Stratified Intelligence CAE Management System Approach Method” shown in Figure 6. This method contributes to “high
Among many of the automotive manufacturers there is a gap between the actual vehicle testing results and the CAE analysis results in the development design stage, as shown in Figure 6. Due to a lack of confidence in the CAE evaluation results, they tend to heavily rely on survey tests (Step I). Even among advanced manufacturers, the utilization of CAE stops at relative evaluation (Step II). The author recognized the dilemma that the utilization ratio of CAE compared to actual vehicle (prototype) and testing evaluation is about 25% for survey purposes and about 50% for relative evaluation. In other words, the effectiveness of CAE for the purpose of reducing the length of the development period has not been proven. This also revealed that the usual solution for technical problems, that are difficult to solve theoretically, is actual vehicle (prototype) and testing evaluation based on empirical or CAE evaluation conducted by trial and error using a makeshift modeling process.

To help improve this situation, the author [11, 16] clarified the mechanism causing the problem by means of the research results accumulated in the “intelligent technological integration system”, in other words, the combination of visualization technology and Science SQC. Then, drawing on that knowledge, further studies focused on improving the precision of quality assurance and the simultaneous achievement of QCD”.

Figure 6 Stratified Intelligence CAE Management System Approach Method
the CAE analysis. As a good example of CAE utilization, attention was focused on the effectiveness of “SQC Technical Methods such as, N7 (New Seven Tools), RE (Reliability), SQC (Statistical Quality Control), MA (Multivariate Analysis), and DE (Design of Experiments)” [21]. These are capable of taking a functional approach to variable factor analysis of the real machine (actual vehicle) testing data and then feeding it back to the CAE analysis software through a deductive methodology in order to derive general solutions.

Next, in Step III the mechanism causing the pending technological problem was clarified by using “visualization technology”. Then, by creating a “general model”, the “absolute evaluation” (III) was made possible, an “intelligent simulation” could be realized, and the prediction and control of the mechanism could be made highly precise through the use of CAE analysis [15]. Based on this knowledge, in Step IV a “robust design” method was employed to eliminate the reliance on actual vehicle and testing results. This method allowed for a “parameter study” to be made in which the influential factors and their effects, which are important to achieving “optimal design”, were reflected. Furthermore, this also led to prevention of the “scale-up effect” at the mass production stage and the realization of a rise in the CAE utilization rate. In the next chapter the validity of the “Automotive Intelligence CAE Methods Utilizing ADDCM” will be verified.

5. Application Example: Analysis of Oil Seal Leakage and Development of Highly Reliable CAE Software

In this chapter the “Toyota and NOK cooperative task team activity - Reliability improvement of the transaxle oil seal” case study will be presented. This case study applied the “Automotive Intelligence CAE Methods” and the validity of the “Advanced Development Design CAE Model” proposed by the author was also verified.

5.1 Oil Seal Function
An oil seal on an automobile’s transaxle prevents the oil lubricant within the drive system from leaking from the drive shaft. It is comprised of a rubber lip molded onto a round metal casing. The rubber lip grips the surface of the shaft around its entire circumference, thus creating a physical oil barrier. In this case the sealing ability of microscopic roughness on the rubber surface is of primary importance. [17] The parameters for the sealing condition of the oil film involve not only the design of the seal itself, but also external factors such as shaft surface conditions, shaft eccentricity, and so on. Contamination of the oil by minute particles was found to be of particular importance to this problem since these are technical issues which involve not only the seal, but also the entire drive train of the vehicle. [18]

5.2 Automotive Intelligence CAE Management System Approach Methods

In general, experienced development design staff and CAE engineers understand the mechanism that is causing the “oil seal leak” as implicit knowledge. The formulation of this “implicit knowledge and know how that is dependent on individual expertise” is an essential step to refining CAE analysis as a problem-solving method. It is also a “problem solving approach that utilizes empirical rules and knowledge”. The creation of “highly reliable CAE software” will allow this valuable “implicit knowledge” to be turned into “explicit knowledge” and is why creating this software is so important. [2, 7, 9]

Therefore, the author [2] applied the previously mentioned “Automotive Intelligence CAE Methods” and developed highly reliable CAE software in an effort to help solve the “automobile transaxle oil seal leakage problem” that had become a global technological issue. As an intelligent application method of this software, the author proposed the “Automotive Intelligence CAE Management System Approach Methods”, as shown in Figure 7. In the case of the “oil seal leakage”, this was a pending problem where no progress was being made in the reduction of claims from the marketplace or the functional fault. At the time, no one knew
where exactly the fault was occurring or what mechanism was causing it. It was important to search out the “root cause” in order to solve this technological problem. [20, 21]

To accomplish this, first, it was important to “visualize the dynamic behavior of the problem” by using actual vehicles and carrying out testing (A). At this point the expertise of specialists from both inside and outside the company was brought together through “partnering” activities. The most advanced SQC methods were used to analyze and investigate the complex cause and effect relationships. It was vital to “deduce the fault mechanism”. Next, in order to carry out (B) a precise fault analysis and factor analysis, N7, SQC, RE, MA, and DE were combined and utilized to “search out and identify previously unknown or overlooked latent causes”. In this way a logical thinking process was used to carry out a logical investigation into the “cause of the fault mechanism”.

Furthermore, all of this knowledge and information was then unified through (C) the creation of “CAE Navigation Software” (CAE-CG-NS) that employs computer graphics (CG) to reproduce the “visualization” of the actual vehicle and testing data so that it can be made...
consistent on a qualitative level. At this stage, where “CAE-CG-NS” is being created, it was important to carry out actual vehicle and testing work so that a model (qualitative model) could be made for the cause and effect relationships of the unknown mechanism. It would then become extremely important to use this model to reduce the divergence (gap) between the results from the actual vehicle testing and the CAE “absolute value evaluation”.

In addition, at the stage of developing the highly reliable CAE software (D), exhaustive actual vehicle testing was carried out in order to convert the leak mechanism from “implicit knowledge” into precise “explicit knowledge”. The information gained from these work processes would then be unified and a “highly credible numerical simulation (quantitative model)” would be carried out to make absolute value prediction and control possible. In the final stage (E), the CAE analysis results are then verified by comparing them to the actual vehicle testing results. In the case of a decentralized organization and business process (such as shown in Figure 7) it is essential that the specialists in the fields of design, testing, CAE analysis, CAE software development, and SQC, carry out cooperative team activities, “partnering” (◎Main, ○ Sub, △Support) at each stage of the work process (A to E).

The author [24, 28] acted as the coordinator to promote integration of the Toyota and NOK cooperative team and as a result dramatic improvement in the number of claims from the market were achieved as illustrated in the following chapter.

5.3 Understanding of the Mechanism through Visualization

According to NOK, the oil leaks occurred due to wear. The result of a wear test on the oil seals indicated that a running distance of 400,000 km (equivalent to 10 years or more of vehicle life) is regarded as sufficiently reliable for the oil seal design. [22] However, according to Toyota’s fault repair records for parts that had market claims, which makes use of DAS (Dynamic Assurance System) [23], there were sporadic cases of the oil leak problem
occurring in vehicles that had not even reached half of the running distance set by NOK. [18]

Judging from the survey and analysis of parts returned from customers due to claims, the cause of the failure was identified as being due to the accumulation of foreign matter between the oil seal lip and the contact point with the transaxle shaft, resulting in insufficient sealing. Oil leaks were found not only during running, but also in new vehicles at rest. Thus, it was determined that the cause is poor foreign matter control during the manufacturing process, and that it is vital to improve the production quality in this process.

The established theory used to be that fine metal particles (on the order of microns in size) would not adversely affect the lip sealing effect. [24] However, when these particles combine to produce relatively larger particles, do they then affect the sealing effect? Also, what about the effect of alignment between the drive shaft and the oil seal (fixing eccentricity) during assembly? In addition, if oil leakage occurs due to foreign matter accumulation on the oil seal lip during transaxle assembly, what is the minimum particle size that causes the problem? The answers to these questions were all unknown since the dynamic behavior of the oil leakage had not yet been visualized. This meant that the true cause also had yet to be clarified.

Consequently, a device was developed to visualize the dynamic behavior of the oil seal lip, as shown in Figure 8, in order to turn this "unknown mechanism" into explicit knowledge. [4, 22] As shown in the figure, the oil seal was immersed in the lubrication oil in the same manner as the transaxle, and the drive shaft was changed to a glass shaft that rotated
eccentrically via a spindle motor so as to reproduce the operation that would occur in an actual vehicle. The sealing effect of the oil seal lip was then visualized using an optical fiber. It was conjectured that in an eccentric seal with one-sided wear, the foreign matter becomes entangled at the place where the contact width changes from small to large. Three trial tests were carried out to ascertain if this was true or not. Based on the examination of faulty parts returned from the market and the results of the visualization experiment, it was observed that very fine foreign matter (which was previously thought to not impact the oil leakage problem) grew at the contact section, as shown in Figure 9 (Test-1).

It was also confirmed from the results of the component analysis that the fine foreign matter was a powder produced during gear engagement inside the transaxle gear box. This fine foreign matter on top of microscopic irregularities on the lip sliding surface resulted in microscopic pressure distribution which eventually led to the degrading of the sealing performance (Figure 10, Test-2). Also, the presence of this mechanism was confirmed from a separate observation that foreign matter had cut into the lip sliding surface, thereby causing aeration (cavitations) to be generated in the oil flow on the lip sliding surface. This caused deterioration of the sealing performance, as shown in Figure 11 (Test-3). The figure indicates that cavitations occur in the vicinity of the foreign matter as the speed of the spindle increases, even when the amount of foreign matter that has accumulated on the oil seal lip is relatively small.

![Figure 10 Oil Leakage Mechanism (Test-2)](image)

![Figure 11 Oil Leakage Mechanism (Test-3)](image)
As the size of the foreign matter gets bigger, the oil sealing balance position of the oil seal lip moves more toward the atmospheric side and causes oil leaks at low speeds or even when the vehicle is at rest. This fact was unknown prior to this study, and therefore was not incorporated into the original design of the oil seals. [19, 22]

5.4 Fault and Factor Analyses

Before studying the mechanism of the oil seal leaks described in Section 5.3, both NOK and Toyota believed that the wear on leaking oil seal lips would follow a typical pattern. The empirical knowledge based on the results of individual oil seal reliability tests was that the unit axle is highly reliable, and would ensure 400,000 km or more in B10 life (the period of time in which less than 10% of the items fail). It was thought that the oil seal lip should wear gradually because of smooth contact between the oil seal lip and the rotating drive shaft, and also because of an oil film in between the two rough surfaces. [18]

As a result of the study and investigation discussed however, it was found that metal particles generated from the gears in the differential case accelerated the eccentric wear of the oil seal lip, making the expected design life unobtainable. Since the wear pattern was not simple, it had to be confirmed that the oil leak problem could be reproduced with the faulty oil seals returned due to customer claims. At this point the author [2, 3] performed a search on the research that Toyota had performed up to now using “TTIS”. The “SQC technical method” was also applied and the information obtained up to now was further classified and summarized using the N7 (affinity diagrams and association charts among others) to promote the “fault analysis” and the “factor analysis”.

First, in addition to defective oil seals, non-defective ones were collected on a regular basis to check if the oil leak could be reproduced and for comparison through visual observations. Next, transaxle units from vehicles, both with and without oil leak problems,
were also collected on a regular basis to check if the leak could be reproduced in the same way. Integrating the results from transaxles both with and without defective oil seals confirmed that the defect could be reproduced and in all of these tests, the oil leaks were reproduced as expected. Based on these test results, a Weibull analysis was then conducted as described below.

The plot of the results (based on defective items that resulted in claims) is shown in Figure 12. It clearly shows a bathtub-shaped failure rate for the oil seal failures. The three shape parameter (m) values correspond to the three different failure modes. This analysis resulted in the following new knowledge:

(1) In the initial period, the failure rate is decreasing (slope (m) < 1), in the middle period it is constant (slope = 1), and in the latter period it is increasing (slope > 1) indicating a bathtub-shaped failure rate. The failure rate in each of the three sections can be modeled by a different Weibull distribution, so that the failures can be modeled by a sectional Weibull model.

(2) The initial failures (where the failure rate is decreasing) occur up to a running distance of 50,000km. Failures in the intermediate range (where the failure rate is constant) occur up to 120,000km. Finally, failures occurring above this value (where the failure rate is increasing)
are due to wear.

(3) The B10 mode life is approximately 220,000 km, about half the value stated as the design requirement.

To confirm the reliability of these results, subsequent claims were analyzed using the Toyota DAS system. Within the warranty period (number of years covered by warranty), the total number of claims classified by each month of production (total number of claims from the month of sale to the current month for vehicles manufactured in the same month) divided by the number of vehicles manufactured in the respective month of production is about twice the design requirement.

This agrees with the result of the above reliability analysis. The influence of five dominating wear-causing factors (period of use, mileage, margin of tightening, hardness of rubber, and average width of lip wear) was studied by two-group linear discriminate analysis using both leaking and non-leaking parts collected in the past. The result showed high positive discriminate ratios of 92.0% and 91.7% for both group 1 (leaking parts) and group 2 (non-leaking parts). [4] From the partial regression coefficients of the explanatory variables in the linear discriminate function obtained, the most significant influence was found to be the hardness of the rubber of the oil seal lip. The influence ratios for the five factors were obtained by means of an orthogonal experimental design (L27), with three level values, which were thought technically reasonable in consideration of the non-linear effects assigned to each of them. [25]

Figure 13 shows the influence ratios of each factor contributing to the discrimination. The figure shows that the hardness factor of the rubber is highly influential. This analytical result was also convincing in terms of inherent technologies. To test the validity of this result, the lip rubber hardness and the degree of wear on the other collected oil seals was examined further.

As a result, it has been confirmed that eccentric wear is more likely to shorten the seal life
because the rubber hardness at the lip portion decreases. This result is consistent with the established theory and empirical knowledge (empirical rules) obtained up to now. This survey and analysis could not have been carried out successfully by the conventional and separate investigation activities of Toyota or NOK. [22]

5.5 CG Navigation and Intelligence CAE Software - Oil Leakage Simulator

The author combined the “CG Navigation” function that explains the dynamic behavior of the oil leak with the technological knowledge examined and acquired above, to create the “Intelligence CAE Software - Oil Leakage Simulator”. [2]

Figure 14 shows a typical example of the modeling of the sliding surface condition that has been created for the purpose of reducing the weight of the sliding surface of the oil seal.
contact part. Judging from what has been observed up to this point, it is necessary to have the sliding surface minutely irregular and the parts that are actually in contact biased toward the oil side. This is done in order to maintain a good sealing condition that will prevent oil leaks from occurring at the contact part of the oil seals.

As shown in Figure 14, the upper section of the sliding surface is the oil side and the lower section is the air side. The darkest black part indicates the areas that are actually in contact. Among the conditions of characteristic values necessary for sealing, the minute roughness of the sliding surface or the small black area representing the actual contact area can be described in this way. Next, another condition is that this black area is biased toward the oil side, which can be incorporated in the sliding surface model like this. Here, the two black areas are not completely parallel, but rather the upper ends are found to be pointing inward. This takes into account the condition of a real oil seal. The actual sliding surface of the oil seal consists of countless tiny projections, which are represented by the black area, pointing in random directions. However, statistically speaking, the directional orientation of these projections shows counterbalancing characteristics.

In this model such factors have been taken into consideration. In other words, the two model projections representing the random projections are arranged to face each other at the same angle, so that a directionless model is presented. The author [2, 24] actually photographed an oil seal reproducing this model sliding surface and observed the behavior of the oil. The upper section in the figure is the oil side and the lower section is the air side, while the rotating axis of the drive shaft (called “the shaft” hereinafter) rotates in the direction of the arrows (⭝). As the shaft rotates, a flow of oil in the same direction as the rotation is generated and it flows along the two tiny projections.

With this situation in mind, let’s consider the cross sections of the tiny projections, A-A and B-B. First of all, let’s look at the cross section A-A. At the oil inlet, the angle between the
shaft and the microscopic projection is small. Because of this, a strong, hydrodynamic wedge effect is produced, causing the oil film to become thicker and increasing the amount of flow to the oil side. On the other hand, at the cross section B-B, the angle at the oil inlet is larger. Consequently, the wedge effect is small and the oil film does not get thick, resulting in a smaller amount of flow to the air side. Comparing the inlet flow and outlet flow here, the flow rate into the oil side is larger and achieves sealing. This leak prevention phenomenon has been reproduced and confirmed by an actual oil seal having the same characteristic values as the above model, and therefore the validity of this sliding surface model has been verified.

It is this phenomenon that creates a circulation of the oil flowing in and out of the sliding surface against the direction of the shaft rotation (V) when sealed, as shown in the figure. This circulation, which is promoted by the tiny projections, is the very factor that separates the lip sliding surface and the shaft and maintains a favorable fluid lubrication condition. This is in line with the phenomenon explained at the beginning, and explains why the wear on the oil seals is limited. The series of discussions to this point has sufficiently explained why the newly designed oil seal suffers little wear and maintains its sealing effect for a long period of time. The author has confirmed the leak proof phenomenon utilizing actual model seals. The validity of the Sliding Surface Model – Sealing Mechanism Analysis was verified against the results of actual vehicles and tests with a difference rate of 2%.

This clarified concept of Numerical Simulation by CAE – the Sliding Surface Model has been applied to the development design engineering of high precision oil seals. That is to say, as a result of incorporating the Intelligence CAE Software, the minute roughness on the sliding surface has been controlled by regulating the composition of the materials. The next factor concerning the biased distribution of roughness toward the oil side can be interpreted as the bias of contact pressure distribution toward the oil side. Therefore, this factor has been controlled by shape designing technology used for designing the seal lip.
The result obtained from incorporating “CG Navigation” and “Intelligence CAE Software for OL (Oil Leak) Analysis” has helped to identify and refine the high precision sealing mechanism of oil seals. Furthermore, the study conducted by the author has established this as a predictive engineering method for functional designing of oil seal parts.

6. Design Changes and Process Control for Improving Reliability

From the comprehensive knowledge gained in the previous chapter, “An Analysis of Oil Seal Leakage and Development of the Highly Reliable CAE Software”, the following facts were learned: (1) The result of the Weibull analysis and visualization tests showed that some gears in the transaxle units had low surface hardness, and that there was a lot of wear during meshing (causing the generation of minute metal particles) leading to an unusually short operational life. It was recognized that it was necessary to prolong the life of these gears. (2) The study confirmed that there was considerable variation in the oil seal lip rubber hardness and this also had to be controlled.

Consequently, the author [2, 3] carried out the following improvements in order to ensure high quality assurance for the transaxle.

(1) At Toyota, (i) improvement in wear resistance was achieved by increasing the gear surface hardness through changes to the gear material and heat treatment. Furthermore, (ii) for transaxles, improvements in the roundness and surface smoothness of the drive shaft (resulting in the reduction of metal particles caused by the wear of gears in the differential case) were achieved.

(2) At NOK (iii) the mean value of the oil seal lip rubber hardness was increased and the specification allowance range narrowed. This, in combination with improvements in oil seal lip production technology (including in the rubber compound mixing process to suppress deviation between production lots), led to improved process capability. In addition, (iv) the
higher coaxial centers of metal oil seal housings, the alignment of coil springs and seal lips, the contact width of the oil seal lips, and the thread profile identified during the design modifications were properly monitored and controlled during the production process to ensure the high quality of the oil seals.

(3) Furthermore, in order to control the generation of foreign matter, the new information that the oil starts leaking when fine metal particles of approximately 75 um in size are present (caused by the yarn dust from gloves during work, rubbish, powder dust, etc.) was publicized. Based on this new knowledge about when the oil leaks start, both Toyota and NOK promoted work improvements at their production sites and reduced the cases of early faults in the market.

Due to these comprehensive reliability improvements the B10 life was increased to greater than 400,000 km. As a result, the cumulative number of market claims per production month was reduced to less than 1/20th the previous level and the desired effect was achieved as shown in Figure 15.

6. Conclusion

With a view to helping corporations survive the “worldwide quality competition”, the author brought about reform of the development design business process. This reform entailed
the change from conventional development methods that use experimental evaluation based on actual vehicles and tests, to predictive evaluation based on development methods that use highly reliable CAE analysis. Given this background, the author has proposed the “Advanced Development Design CAE Model” utilizing New JIT, and has been able to present a new automobile development design method, “Automotive Intelligence CAE Methods” that utilize the “Total Quality Assurance High Cycle-ization Business Process Method” and the “Stratified Intelligence CAE Management System Approach Method.

Furthermore, as an extended application of these methods, the author has also established “Automotive Intelligence CAE Management System Approach Methods”. In order to demonstrate their effectiveness, these methods were applied to the clarification of the mechanism of the transaxle oil seal leakage problem, which was a bottleneck problem for vehicle manufacturers worldwide. In order to realize highly reliable CAE analysis, first, the author devised the “Intelligence CAE Software - Oil Leakage Simulator” that incorporated CG Navigation for the purpose of preventing oil seal leakage. This has contributed to a remarkable reduction in market claims regarding this problem, and a substantial result has been achieved in the field of ensuring high quality assurance.

References


