VEHICLE DURABILITY AND COMPULSORY INSPECTION AND MAINTENANCE

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ABSTRACT

Vehicle inspection and maintenance (I/M) are generally considered to be indispensable for traffic safety and low environmental damage. Many countries have been managing compulsory I/M programs. However I/M program is not free of cost and drivers must bear the large part of its cost. Therefore, it has been argued repeatedly whether regulations relevant with I/M programs should be tightened or reduced. In this study, we estimate the deterioration curve of vehicles and assess the impact of regulatory reform of Japan's I/M programs. The most distinguished point of this study is estimating the deterioration curves of 67 items comprising vehicles. The results show that the previous estimation results of the social impacts of regulatory reform of Japan's I/M programs by the government committee are possibly overestimation.

Keywords: vehicle inspection and maintenance, failure rate, deterioration, hazard model

INTRODUCTION

Vehicle inspection and maintenance (I/M) programs have two objectives. One is traffic safety and the other is low environmental damage. I/M programs are thought to be indispensable in our highly motorized society. Many countries make periodic I/M compulsory. Japan's I/M program started in 1952 and it has a long history. Under the current program, private vehicles must be inspected at three years age, then every two years under ten years age and every year over eleven years age. Whenever inspected and maintained, drivers must pay out the expenses. Although the expenditures are dependent on the vehicle type and the degree of soundness of the inspected vehicle, the average expenditure for the standard type vehicle reaches to about five hundred dollars. Most drivers are dissatisfied with the expenditure. Although car technology made great improvements past half century, Japan's

I/M programs has been revised only two times if we do not count minor revisions. Therefore, it has been argued repeatedly whether regulations relevant with I/M programs should be reduced or not. Since revising the I/M program have a huge and various impacts on our society, scientific and comprehensive evaluation of the social impacts is needed.

Sumitomo Life Research Institute (1999) and Cabinet Office's Director-General for Policy Planning (2007) conducted post-evaluation of the revision of Japan's I/M program in 1995. One of the major aims of the revision was to make the vehicle maintenance industry more competitive. Sumitomo Life Research Institute estimated that the competitive policy reduced the drivers' burdens in 1996 and 1997 by about five billion dollars per year. On the other hand, Cabinet Office's Director-General for Policy Planning estimated that they reduced the burden by between 3.9 billion and 8.6 billion dollars per year from 1995 to 2005. These researches show how huge rents were transferred from the car maintenance industry with the vested interests to the general drivers. However they did not consider the negative effects such as the increase in traffic accidents and that of environmental damages. Of course, assessment of the negative impacts is also needed for a better decision.

The negative effects caused by road transportation are affected by many factors. It is not easy to assess their relationship with I/M programs. There are many empirical researches in the United States (cf. Colton and Buxbaum, 1966; Buxbaum and Colton, 1966; Schroer and Payton, 1979; Little, 1971; Crain, 1980; Garbacz and Kelly, 1987; Loeb, 1985; Loeb, 1987; Fowles and Loeb, 1989; Loeb and Gilad, 1984; Loeb, PD, 1990; Saffer and Grossman, 1987; Garbacz, 1990; Leigh, 1994; Fowles and Loeb, 1995; Merrell, Poitras and Sutter, 1999; Sutter and Poitras, 2002; Crain and Kimensyi, 1991; Keeler, 1994). On the other hand, the empirical researches are few in other countries (cf. White, 1986; Fosser, 1992; Saito, 2009). This is because, in the United States, I/M programs are different in each state and many data for the empirical analysis are available, but in most countries available data are limited because of the homogeneity of domestic I/M programs. The conclusions on the relationship between negative effects and I/M programs differ among the researches. Some show that the introduction of an I/M program decreases the number of fatal accidents, but others show that there are no correlation. Further development of the methodology is needed.

In 2004, the revision of Japan's I/M program became the political agenda. At that time, the Road Transport Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (MLITT) organized a committee and entrusted it to evaluate the social impacts of the revision. The impacts the committee estimated are following three: the increase in the number of traffic death toll, the increase in the traffic congestion length due to the increased traffic accidents, and the increase in the emission of exhaust gases. Each impact was estimated to be a 6.5%, 9.9% and 0.4-0.9% increase, respectively. From these results, in the final report, the committee concluded that the revision of the I/M program causes huge negative social impacts and that the current I/M program should not be revised (Basic Survey Committee on the Vehicle Inspection and Maintenance, 2005).

The estimation by the committee consists of two parts; first is the estimation of the failure rate curve of vehicles and that of the increase in the number of vehicles with failure due to the revision of I/M program; second is the estimation of the relationship between the number of vehicles with failure and the size of negative effects caused by road transportation, and the estimation of the increase in the negative effects due to the revision of I/M program. Though we do not mention in detail, both parts have some critical problems. Most of the problems in the first part are relevant with the statistical analysis. Since the dataset used in that part has many samples (a half million samples!) and is very rich in information, if the problems in the statistical analysis can be removed, the failure rate curve should be estimated with high accuracy. On the other hand, the problems in the second part have roots in the lack of available dataset. To make the estimates more accurate, we must start designing the appropriate survey method to collect the necessary data. Removing the problems in both parts is highly important for a better decision on the revision of I/M program.

The purpose of this study is to re-examine the previous estimation by the committee and improve it. We focus on the improvement of the statistical analysis of the failure rate curve of vehicles. The most distinguished point of this study is that the deterioration curves of 67 items of inspection are estimated using the same data as used by the committee, and from these results, failure rate curve is estimated more accurately. As far as we know, there are no existing researches that estimate the failure rate curve of vehicles as in detail as this study. We also estimate how much the ratio of vehicles with failure will increase if the current I/M program were revised, and point out that the previous estimates by the committee are possibly overestimation.

The structure of this paper is as follows. In this section, as already mentioned, the background and purpose of this study is explained. In Section 2, the method of estimation by the committee is explained and the direction for its improvement is discussed. In Section 3, a new empirical analysis of estimating the failure rate curve of vehicles under the revision scenario of the current I/M program. Section 4 summarizes the results and discusses what to be done.

RE-EXAMINATION OF THE COMITTEE’S ESTIMATION

In this section, we explain the estimation method used by the committee in detail and re-examine the way to improve it. As we have mentioned in Introduction, the methods consists of two parts. First, the failure rate curve under the revision scenario is estimated. The scenario is that the interval of inspection would be extended from three years to four years only for the first-time inspection. In the analysis, the vehicle with failure is defined as that at least one of the 67 inspected items does not meet the inspection standard is estimated.

Since the failure rate depends on the vehicles age, it is not the failure rate, but the failure rate curve must be estimated. The increase in the number of vehicles with failure under the revision scenario is estimated from the estimated failure rate curve. Second, the relationship between the number of vehicles with failure and the negative effects, more concretely, the number of traffic death toll, the traffic congestion length, and the emission of exhaust gases, are estimated. Then, using the estimated relationships, the increase in the negative effects caused by the revision of I/M program is estimated. In what follows, we look at the method of estimating the failure rate curve under the revision scenario in more detail.

Method of failure rate curve estimation

The committee estimated the failure rate curve using the data collected by MLITT between 2000 and 2003. This data was gathered from the official maintenance factories across the whole country. Under Japan's I/M program, most vehicles are checked by a qualified mechanic of the official maintenance factories, before being officially inspected, whether they meet the standards of inspection or not. In other words, before proceeding to the inspection, most vehicles are checked whether they can pass the inspection without being maintained. The dataset used in the estimation are the records of those check. Since the sampled vehicles were surveyed at the timing of inspection, the ages of vehicles in the dataset are each of three, five, seven, nine, eleven, thirteen, fifteen, and so on (Note: the sampled vehicles over eleven years of age were inspected every two years. They were not following the current I/M program but the previous I/M program). The dataset has about 730 thousands sample, and about 510 thousands samples of which are relevant with private vehicles. This

Table I – Data attributes

attributes	number of classification	type of classification
inspected year	4	2000, 2001, 2002, 2003
registered year	-	
vehicle type *	3	normal, compact, light
manufacturer	36	Toyota, Honda, Nissan, et al.
model	-	
shape	6	box, station wagon, et al.
weight	-	
total running distance	-	
previous regular check	2	checked, not checked
front brake	3	dram, disk, other
rear brake	3	dram, disk, other
power steering	2	with, without
drive system	4	FR, FF, RR, 4WD
Transmission	3	AT, MT, other
item1	3	meeting, likely to be not meeting, not meeting
:	:	
item67	3	

* The classification by Japan's "Road Trucking Vehicle Law;" normal: more than 2,000 cc; displacement; compact: between 660 cc and 2,000 cc displacement; light: less than 660 cc displacement

Table 2 – Inspected items and proportions of sampled vehicles not meeting the inspection standards

equipment	inspection item		normal	compact	light
steering equipments	handle	handling trouble	0.00051	0.00050	0.00045
	gear box	loose attachment	0.00050	0.00048	0.00024
	rod, arm	looseness, backlash, damage	0.01492	0.00682	0.00578
		crackes in dust boots of pole joint	0.01352	0.03307	0.01268
	side slip		0.02322	0.02502	0.03278
	power steering	looseness, damage *	0.10010	0.10897	0.05767
		oil leak and volume	0.01389	0.00966	0.00163
		loose attachment	0.00035	0.00033	0.00029
control equipments	brake pedal	allowance, clearance *	0.00064	0.00141	0.00170
		brake performance *	0.00054	0.00082	0.00126
	hand brake	allowance *	0.00701	0.00879	0.00801
		brake performance *	0.00149	0.00198	0.00145
	hose pipe	leak, damage, attachment *	0.00862	0.01141	0.00160
	master cylinder	function, wear, damage	0.00319	0.00334	0.00195
		leak *	0.00388	0.00606	0.00680
	wheel cylinder	function, wear, damage	0.00451	0.02109	0.04151
		leak *	0.00947	0.04245	0.08617
	disk caliper	function, wear, damage	0.01054	0.01099	0.01060
		leak *	0.00474	0.00645	0.00522
	brake dram and shoe	gap between dram and lining *	0.00126	0.00556	0.00661
		sliding shoe wear, lightning wear *	0.00416	0.03255	0.02673
		brake dram wear, damage	0.00016	0.00089	0.00076
	brake disk and pad	gap between disk and pad *	0.00377	0.00330	0.00312
		brake pad wear *	0.13822	0.11869	0.09948
		brake disk wear, damage	0.00993	0.00713	0.00446
driving equipments	wheel cylinder	air pressure in tire *	0.01852	0.02292	0.02526
		crack, damage *	0.00599	0.00806	0.00716
		tread wear, unusual wear *	0.03471	0.04518	0.04573
		looseness of wheel nut and bolt *	0.00270	0.00273	0.00265
		backlash of front wheel bearing	0.00450	0.00355	0.00511
		backlash of rear wheel bearing	0.00097	0.00291	0.00442
buffering equipments	attaching and connection porti	looseness, backlash, damage	0.01259	0.00765	0.00622
	shock absorber	oil leak, damage	0.00733	0.00666	0.00359
power transmission	clutch	allowance, clearance *	0.00076	0.00270	0.00143
	transmission	oil leak, oil volume *	0.01664	0.01467	0.01163
	transfer	oil leak, oil volume *	0.00191	0.00116	0.00133
	propeller shaft	loose attachment *	0.00091	0.00047	0.00018
	drive shaft	loose attachment *	0.00038	0.00084	0.00184
		crack in joint dust boots, damage	0.02414	0.07100	0.09922
	differential	oil leak, oil volume	0.00825	0.00437	0.00528
electric device	ignition device	spark plug *	0.04228	0.07687	0.08791
		ignition timing *	0.00016	0.00031	0.00061
		distributer cap *	0.00111	0.00131	0.00174
	battery	terminal connection *	0.00647	0.00682	0.00688
	electric wiring	loose attachment and damage	0.00163	0.00170	0.00206
engine	main unit	air cleaner element *	0.10514	0.09741	0.07911
		air ventilation *	0.00027	0.00048	0.00066
	lubricating device	oil leak *	0.03521	0.04879	0.05290
		fuel leak	0.00278	0.00305	0.00074
	cooling device	looseness of fan belt, damage *	0.13125	0.12692	0.16875
		water leak *	0.02468	0.02653	0.02962
exhaust gas control equipments	blow-by gas reducing device	metering valve	0.00008	0.00018	0.00076
		pipe damage	0.00026	0.00052	0.00023
	fuel evaporative emission redu	pipe damage	0.00008	0.00038	0.00009
		clog of charcoal canister, damage	0.00004	0.00004	0.00004
		check valve	0.00002	0.00004	0.00005
	carbon monoxide emission red	joint looseness of catalytic exhaust gas reduction device, damage	0.00038	0.00022	0.00030
		secondary air supplier	0.00009	0.00010	0.00003
		exhaust gas recirculation device	0.00010	0.00010	0.00009
		exhaust gas reduction during deceleration	0.00004	0.00004	0.00011
		pipe damage, connection	0.00012	0.00046	0.00028
	exhaust gas	CO	0.00057	0.00191	0.00400
		HC	0.00041	0.00098	0.00170
		graphite	0.00077	0.00065	0.00000
noise control equipments	exhaust pipe and muffler	loose attachment and damage *	0.00789	0.00980	0.01106
		muffler function	0.01048	0.01498	0.02950
body	body	looseness, damage	0.00183	0.00211	0.00274
number of samples			160,162	271,812	79,904

sample size is roughly equivalent to one percent of all the vehicles in Japan. Data attributes are summarized in Table 1. Each of the 67 inspected items is classified into three categories: meeting, likely to be not meeting, not meeting. “Meeting” means that it can pass the inspection even if it proceeds to the inspection without being maintained. “Likely to be not meeting” and “not meeting” are the same. Table 2 summarizes the list of items of being inspected. The figures in the table are the proportions of the sampled vehicles that were classified into the category of “not meeting” the inspection standards of the relevant inspected items. We can see that the proportions are greatly different among inspected items. The maximum proportion is 0.16875 for the engine cooling device of the light vehicle type. On the other hand, for all the inspected items of exhaust gas control equipments, the proportions are less than 0.01. These differences imply that we must estimate the failure rate curves for each inspected item separately.

The committee’s estimation of the failure rate curve under the revision scenario consists of two steps. First, the failure rate of the vehicles four years of age and below, and of average annual running distances, is estimated (Step-1). Then, the failure rates of the vehicles of more than four years of age are estimated (Step-2). In Step-1, the observed failure rate of vehicles three years of age thirty thousand kilometres total running distance is set as the base rate. Then, two kinds of correction are made to the base rate, and the failure rate of vehicles four years of age average annual total running distance is estimated. One of the two corrections is to consider the effect of age deterioration, and the other is to consider the effect of running deterioration. The size of each correction is calculated from the difference between two observed average failure rates. As shown in Figure 1, the size of running correction is calculated as the difference between the average failure rates of vehicles aged three years with about 30,000 kilometer total running distances and of those with about 40,000 kilometers total running distances. The size of age deterioration is calculated as a half of the difference between the average failure rates of vehicles with about 30,000 kilometer total running distances aged three years and those aged five years.

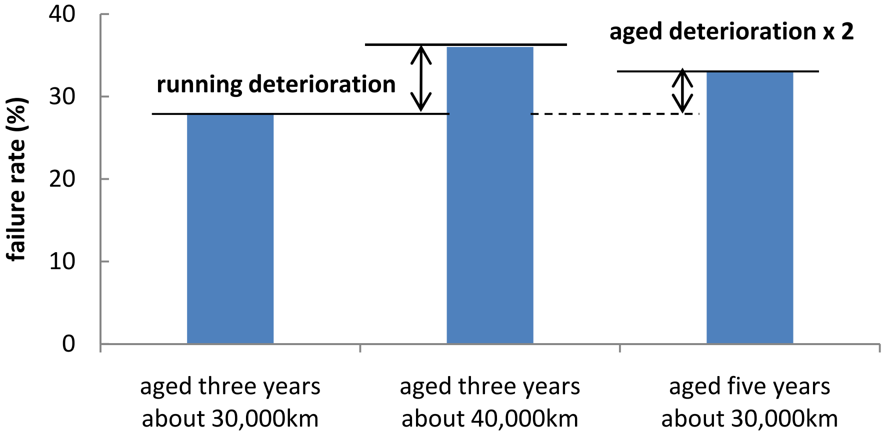

Figure 1 – Estimation of failure rate (vehicles aged four years)

Then, the two parameters of Weibull survival function, from which the failure rate curve is derived, are calibrated with the observed failure rate of three years of aged vehicles (A) and the estimated failure rate of four years of aged vehicles (B) as shown in Figure 2. The functional form of Weibull survival function is given by,

$$S(t) = \exp\left(-\frac{t^m}{a}\right), \tag{1}$$

where t is the age of vehicles and a and m are parameters. Since this function has two parameters and the number of data to be used for calibration are two (A and B), all the parameters can be determined uniquely. The failure rate curve of the vehicles four years of age and below is derived from the calibrated survival function as curve α in Figure 2.

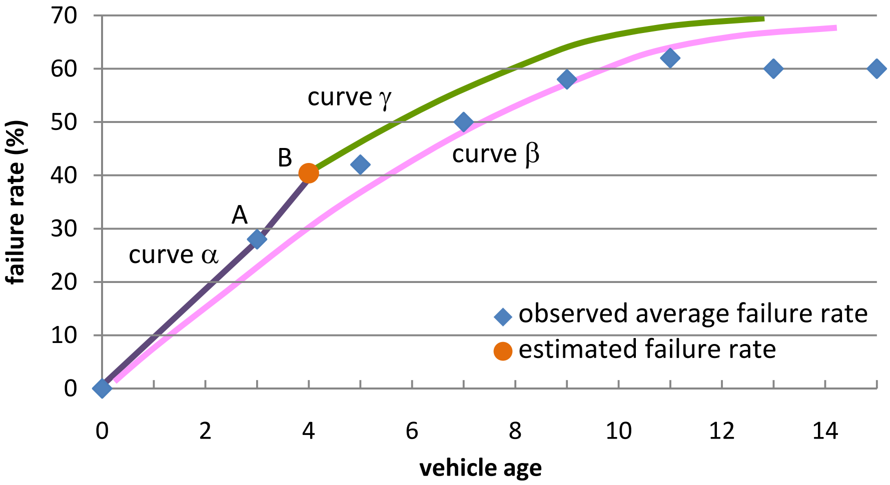

Figure 2 – Estimation of failure rate (vehicles aged other than four years)

In Step-2, the two parameters of Weibull survival function (cf. Eq.(1)) are estimated statistically with the observed average failure rate of each age. The number of data to be used for the estimation is eight in all, as shown in Figure 2. Then, the failure rate curve of the vehicles of any age under the current I/M program is derived from the estimated survival function (curve β). The failure rate curve of the vehicles aged more than four years under the revision scenario (curve γ) is derived by shifting the failure rate curve β straight leftward to connect the failure rate curve of the vehicles four years of age and below (curve α) at the point of four years of age.

Problems in the estimation of failure rate curve

We can point the following three problems in the committee's estimation of the failure rate curve. First, the definition of the vehicle with failure and the failure rate should be remedied. A vehicle consist of many parts and equipments, and their failures in the meaning of not meeting the standards are thought to be interdependent with each other. Further, as shown in Table 2, the failure rate of each item varies widely among inspected items. The committee's definition of vehicle with failure is thought to be too restrictive and may cause a large bias in the estimated failure rate curve. Since we can know from the data whether each item had met the standard or not, it is natural to estimate the deterioration curve of each item and then to estimate the failure rate curve of a vehicle.

Second, the failure rate curve should be estimated using available disaggregated data and micro-econometric techniques. In the committee's analysis the aggregated data had been used, and we cannot discuss the statistical significance of the result. If we estimate the failure rate curve using the disaggregated data, we can discuss the statistical significance of the results. In addition, we can include variables listed in Table 1 that have some relationship with the durability of vehicles such as total running distance, previous regular check and so on, and improve the statistical accuracy of the estimation.

Third, the past history of inspection and maintenance should be considered in the estimation. Even if a high aged vehicle had met all the standards of inspected items, we cannot know from the available data whether it was highly durable and had not been maintained at all in the past check or it was not durable and had been maintained before. Similarly, even if a vehicle had not met some standards, we cannot know whether it was the first time that was classified into the category of not meeting the standards or it had been classified into the same category before. The available data is not a panel data, but a cross section data. The observable and unobservable information is summarized in Figure 3. In the committee's estimation, the observability of data was not well considered, and failure rate curve was thought to be underestimated by implicitly assuming that surveyed vehicles had never been maintained before. To address this problem, the survival model either must be extended to be able to consider the unobserved past history of inspection and maintenance, or the past history must be included in the data to be used for the estimation.

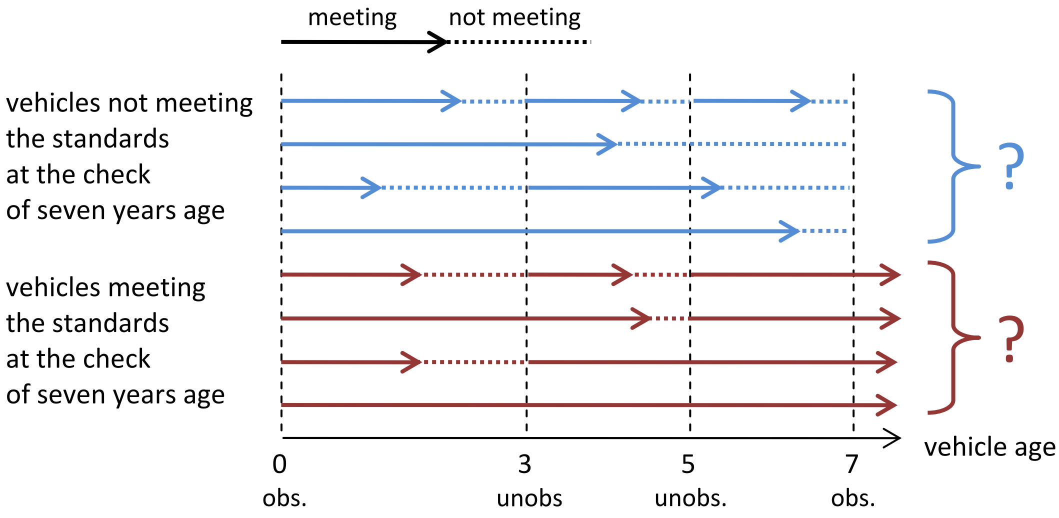

Figure 3 – Observable and unobservable information (vehicles aged seven years)

Related literature

Tajiri (2006) and Council for the Promotion of Regulatory Reform (2005) did the empirical analysis relevant with the above mentioned problems. They considered that not only the time factor but also the total running distance factor should have affected the durability of vehicles. Both studies estimated the failure rate curves (logistic regression curve) using the disaggregated data. The data was the same with that of the committee, but had been aggregated in the committee's analysis. Although the two analyses were better than that of the committee, the first and the third of above mentioned problems were still unaddressed. In the next section, we estimate the deterioration curve of each inspected item extending the survival model to make it possible to consider the past history of inspection and maintenance, and then estimate the failure rate curve of vehicles.

EMPIRICAL ANALYSIS

In this section, we estimate the failure rate curves of vehicles using the same data as used by the committee, but by a more elaborate method to address the problems mentioned in the last section. We estimate the deterioration curve separately for each inspected item (67 items) and for each vehicle type (3 types). In all, 201 deterioration curves are estimated. The deterioration mechanisms are represented by the commonly used Weibull proportional hazard model. Since the standard hazard model cannot consider the past history of inspection and maintenance, we must extend it. In what follows, first, we explain Weibull proportional hazard model. This model is used to model the deterioration mechanism of vehicles. Then, we explain how it can be extended to consider the past history of inspection and maintenance. Finally, we apply it to the same data as used by the committee and estimate the deterioration curves of each inspected item, failure rate curve of vehicles, and the increase in the number of vehicles with failure under the revision scenario of current I/M program.

Weibull proportional hazard model

We use Weibull proportional hazard model to represent the core mechanism of the deterioration of vehicles (Dobson, 2002; Klein and Moeschberger, 2003). This model is the most commonly used in survival analysis and expresses the deterioration process as a stochastic process. Since the deterioration of vehicles is uncertain, it is natural to use this kind of stochastic deterioration model.

Now, for a while, let us ignore the possibility of the past inspection and history. We suppose that vehicle i is registered for the first time at $t_i = 0$. While being used, the vehicle deteriorates progressively, and some items become off-standard of the inspection. Let us represent the time when item *j* becomes off-standard for the first time by t_{ij}. We assume t_{ij} follows Gumbell distribution given by,

$$f(t_{ij};\lambda_j,\theta_{ij}) = \frac{\lambda_j t_{ij}^{\lambda-1}}{\theta_{ij}^{\lambda}} \exp\left[-\left(\frac{t_{ij}}{\theta_{ij}} \right)^{\lambda_j} \right], \tag{2}$$

where λ_j is a parameter that represents the shape of distribution and $\lambda_j > 0$, and θ_{ij} is a parameter that represents the width of distribution and $\theta_{ij} > 0$. If we exchange parameter θ_{ij} by $\phi_{ij} = \theta_{ij}^{-\lambda_j}$, Eq.(1) can be converted into

$$f(t_{ij};\lambda_j,\phi_{ij}) = \lambda_j \phi_{ij} t_{ij}^{\lambda_j-1} \exp\left[-\phi_{ij} t_{ij}^{\lambda_j} \right]. \tag{3}$$

Then, the probability that item *j* becomes off-standard by time T_i can be given by

$$F(t_{ij};\lambda_j,\phi_{ij}) = 1 - \exp\left[-\phi_{ij} t_{ij}^{\lambda_j} \right]. \tag{4}$$

Similarly, the probability that item *j* keeps on meeting the standard until time T_i can be given by

$$S(t_{ij};\lambda_j,\phi_{ij}) = \exp\left[-\phi_{ij} t_{ij}^{\lambda_j} \right]. \tag{5}$$

From Eq.(4) and Eq.(5), hazard rate can be given by

$$h(t_{ij};\lambda_j,\phi_{ij}) = \lambda_j \phi_{ij} t_{ij}^{\lambda_j-1}. \tag{6}$$

If $\lambda_j = 1$, hazard rate is constant for any t, this is the case of exponential deterioration. If $\lambda_j > 1$, hazard rate increases as time t increases, this is the case of accelerated deterioration. Parameter ϕ_{ij} in Eq.(6) represents the difference of the speed of deterioration among vehicles. Deterioration of vehicles is thought to depend on some attributes of vehicles such as manufacturer, transmission and so on, and how much they are used. So, we represent ϕ_{ij} as $\phi_{ij} = e^{\boldsymbol{x}_{ij}^T \boldsymbol{\beta}_j}$ where $\boldsymbol{x}_{ij}$ is a vector of variables representing the attributes of vehicle *i* with relevant to inspected item *j* and $\boldsymbol{\beta}_j$ is a vector of parameters. By inserting this into Eq.(6), hazard rate can be converted into

$$h(t_{ij};\lambda_j,\boldsymbol{\beta}_j,\boldsymbol{x}_{ij}) = \lambda_j e^{\boldsymbol{x}_{ij}^T \boldsymbol{\beta}_j} t_{ij}^{\lambda_j-1}. \tag{7}$$

Since the attributes of vehicles affect the hazard rate through its proportional factor, this model is called “Weibull proportional hazard model”. In what follows, after extending it to be able to consider the past history of inspection and maintenance, we estimate the parameters in Eq.(7) statistically.

Modelling of inspection and maintenance history

Before going into the formal modelling of inspection and maintenance history, let us explain the idea behind it. We consider a binominal tree shown in Figure 4. In this figure, all the possibility of an inspected item seven years of aged vehicle is listed. Then, even if we know only the result of check at the age of seven years (and do not know those at the age of three and five years), we can calculate the probability of getting this result if we can assign a probability on each path of the tree. Here, we suppose that probabilities on the right of the terminal nodes of the tree are assigned on respective paths. $F(\bullet)$ and $S(\bullet)$ are the distribution and survival functions of Weibull proportional hazard model defined above. In this case, the probability that some item seven years of aged vehicle is categorized as meeting the standard is given by

$$\mathrm{Prob} = F(3)\cdot F(2)\cdot S(2) + F(3)\cdot S(4) + [F(5) - F(3)]\cdot S(2) + S(7) \ , \tag{8}$$

and the probability of being categorized as not meeting the standard is given by

$$\mathrm{Prob} = F(3)\cdot F(2)\cdot F(2) + F(3)\cdot [F(4) - F(2)] + [F(5) - F(3)]\cdot F(2) + [F(7) - F(5)] \ . \tag{9}$$

Once these probabilities are derived for any years of aged vehicles, applying the maximum likelihood method, we can estimate the unknown parameters in Eq.(7).

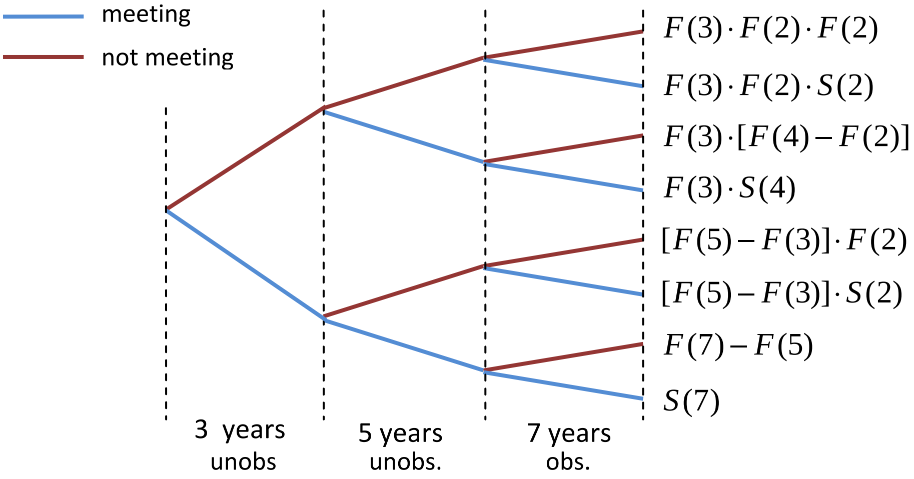

Figure 4 – Binominal tree of the history of maintenance and inspection (vehicles aged seven years)

Now, let us formulate the model of the past history of maintenance and inspection following the idea explained above. We represent the age of vehicle i contained in the data by N_i. The set of ages that vehicle i was checked before surveyed by $T_i = \{\tau_{ik}\}_{k=1,\cdots,K_i}$, where $\tau_{iK_i} = N_i$, and $\tau_{i1} < \cdots < \tau_{iK_i}$. K_i indicates the number of checks/inspections vehicle i took since first registered. Let us represent the result of k th check of item j of vehicle i by d_{ijk}. d_{ijk} is either 0 or 1. $d_{ijk} = 0$ means not meeting the standard and $d_{ijk} = 1$ means meeting it. The set of ages that item j of vehicle i was categorized as not meeting the standard by $\Delta_{ij} \in 2^{T_i}$. If $d_{ijk} = 0$ for any τ_{ik} , then $\Delta_{ij} = \{\phi\}$. If $d_{ijk} = 1$ for some τ_{ik} , then $\Delta_{ij} = \{\delta_{ijm}\}_{m=1,\cdots,M_{ij}}$, where $1 \le M_{ij} \le N_i$ and $\delta_{ij1} < \cdots < \delta_{ijM_{ij}}$. M_{ij} indicates the number of maintenance vehicle i took after having been categorized as not meeting the standard in the past check.

The probability that item j of vehicle i contained in the data is categorized as not meeting the standard can be represented as follows:

$$\Pr\left(d_{ijK_i}=1\right)=\sum_{\substack{\Delta_{ij}\in 2^{T_i}\\ :M_{ij}=K_i}}\prod_{m=1}^{M_{ij}}\left[F\left(\delta_{ijm}\right)-F\left(\delta_{ijm^-}\right)\right]S\left(t_{ijK_i}-\delta_{ijM_{ij}}\right), \tag{10}$$

where $m^- \equiv m-1$ and $\delta_{ij0}\equiv 0$. In Eq.(10), $S\left(t_{ijK_i}-\delta_{ijM_{ij}}\right)=S\left(0\right)=1$ is always satisfied since only the case of $M_{ij}=K_i$ is considered. On the other hand, the probability that item j of vehicle i contained in the data is categorized as meeting the standard can be represented as follows:

$$\Pr\left(d_{ijK_i}=0\right)=S\left(t_{ijK_i}\right)+\sum_{\substack{\Delta_{ij}\in 2^{T_i}\\ :1\le M_{ij}<K_i}}\prod_{m=1}^{M_{ij}}\left[F\left(\delta_{ijm}\right)-F\left(\delta_{ijm^-}\right)\right]S\left(t_{ijK_i}-\delta_{ijM_{ij}}\right). \tag{11}$$

Further, for the case of $\Delta_{ij}=\{\phi\}$, if we define

$$\prod_{m=1}^{M_{ij}}\left[F\left(\delta_{ijm}\right)-F\left(\delta_{ijm^-}\right)\right]S\left(t_{ijK_i}-\delta_{ijM_{ij}}\right)\equiv S\left(t_{ijK_i}\right), \tag{12}$$

then Eq. (11) is converted into

$$\Pr\left(d_{ijK_i}=0\right)=\sum_{\substack{\Delta_{ij}\in 2^{T_i}\\ :M_{ij}\neq K_i}}\prod_{m=1}^{M_{ij}}\left[F\left(\delta_{ijm}\right)-F\left(\delta_{ijm^-}\right)\right]S\left(t_{ijK_i}-\delta_{ijM_{ij}}\right). \tag{13}$$

Using Eq. (10) and Eq.(13), a likelihood function can be defined and we can apply maximum likelihood method to it.

Before going forward, we must point out some implicit assumptions made in the above modelling. There are three major assumptions. First assumption is that all the inspected items deteriorate independently. Second assumption is that all the vehicles are checked and maintained only at the timing of inspections, and only the items categorized as not meeting the standards of inspection are maintained. Third assumption is that once the items are maintained, they entirely recover and return to fresh states. Although these assumptions look somewhat restrictive (in that the correlation among deterioration of each item, the possibility of drivers' voluntary check and maintenance, and that of imperfect recovering in maintenance are ignored), if we relax them, the model become too complicated and the reliability of statistical inference may become smaller. We think, it is natural step to start our empirical analysis with a little bit restrictive assumptions.

Likelihood function

As for the explanatory variables of Weibull proportional hazard model formulated as Eq.(7), we use the following seven variables for each inspected item; 1) constant, 2) average running distance per year (is equivalent with total running distance divided by vehicle age); 3) dummy of previous regular check; 4) dummy of RF drive system; 5) dummy of FF drive system; 6) dummy of MT transmission; 7) dummy of AT transmission. The parameters to be estimated for item j are $(\lambda_j, \beta_{j1}, \cdots, \beta_{j7})$. Using Eq. (10) and Eq.(13), a likelihood function can be defined as follows:

$$L(\lambda_j, \beta_{j1}, \cdots, \beta_{j7}) = \prod_{i \in I} \Pr\left(d_{ijK_i} = 1\right)^{d_{ijK_i}} \cdot \Pr\left(d_{ijK_i} = 0\right)^{1-d_{ijK_i}} , \tag{14}$$

Further, a loglinear likelihood function can be defined as follows:

$$LL(\lambda_j, \beta_{j1}, \cdots, \beta_{j7}) = \sum_{i \in I} \left\{ d_{ijK_i} \cdot \Pr\left(d_{ijK_i} = 1\right) + \left(1 - d_{ijK_i}\right) \cdot \Pr\left(d_{ijK_i} = 0\right) \right\} . \tag{15}$$

Results of parameter estimation

Parameter estimates for normal, compact and light cars are summarized in Table 3, 4 and 5 respectively. To show the results compactly, the standard errors of parameter estimates are omitted. Instead, the results of asymptotic t-tests are given by colors. The estimates in the orange cells are significant at one percent level. The estimates in the green and blue cells are significant at five and ten percent levels, respectively. The parameter λ s are tested whether the estimates are significantly different from one, and the other parameters are tested whether the estimates are significantly different from zero. We can point out the following five points.

First, the estimates of parameter λ_j , indicating the strength of age deterioration, are significantly more than 1 for most pairs of item and vehicle type. This means that the accelerated hazard model, one specification of which is Weibull hazard model, is appropriate for the vehicle deterioration model. In contrast, for some items of exhaust gas control equipments, the estimates of λ_j are not significantly more than 1. The constant hazard models may be more appropriate for them. Anyway, for all the pairs of item and vehicle type, the estimates of λ_j are significantly more than 0, and this means that the age deterioration is occurring for any vehicles and inspected items.

Second, the estimates corresponding to the average running distance are significantly positive for more than fifty five pairs of item and vehicle type. This means that the average running distances is one of the most important factors of deterioration. As the estimates of age deterioration, the estimates of average running distance are not significantly positive for some items of exhaust gas control equipments. A running deterioration mechanism may not be occurring for them.

Third, the estimates corresponding to the previous regular check are significantly negative for about thirty pairs of item and normal or compact vehicle type. The dummy variable represents whether vehicles are checked just one year before surveyed. Under the current I/M program, private vehicles are obliged to have their vehicles checked in every middle year between inspections. The items to be checked in the middle year are marked with asterisk in Table3 - Table5. Although drivers are obliged, even if they do not have their vehicles checked, they are not punished. The rate of vehicles to be checked in the middle years is thought to be about 40 or 50 percent. The results indicate the positive impacts of the middle year check for some items, in the sense that they can decrease the cost of maintenance at the time of inspections.

Table 3 – Parameter estimates (normal vehicle)

equipment	inspection item		AIC	lambda	const	dist	insp	FR	FF	AT	MT
steering equipments	handle	handling trouble	1,343	2.09	-12.18	3.64	0.19	0.26	-0.06	0.90	1.73
	gear box	loose attachment	752	2.96	-13.86	5.09	0.04	0.03	0.19	0.48	-5.06
	rod, arm	looseness, backlash, damage	14,797	2.73	-9.36	5.70	-0.24	-0.15	-0.33	0.28	0.09
		crackes in dust boots of pole joint	19,139	4.00	-12.86	5.43	-0.06	0.01	0.52	0.44	0.70
	side slip		23,149	1.38	-5.25	2.37	-0.33	-0.23	-0.07	-0.14	0.07
	power steering	looseness, damage *	97,966	1.89	-5.38	3.75	-0.09	0.14	0.13	-0.01	-0.06
		oil leak and volume	21,402	2.48	-9.38	4.20	0.11	0.35	0.10	0.42	0.67
		loose attachment	484	3.27	-14.85	5.05	0.13	0.37	0.63	-0.28	0.56
control equipments	brake pedal	allowance, clearance *	1,631	1.95	-10.27	3.82	-0.93	-0.62	-1.11	0.46	-0.36
		brake performance *	1,369	2.70	-12.11	5.20	-0.56	-0.86	-0.74	0.22	-0.15
	hand brake	allowance *	12,796	1.41	-6.90	2.42	-0.27	-0.20	-0.17	0.23	0.19
		brake performance *	3,330	1.96	-9.63	4.35	-0.51	-1.05	-0.57	0.58	0.55
	hose pipe	leak, damage, attachment *	13,200	4.09	-12.81	5.67	-0.06	0.11	-0.45	-0.30	-0.61
	master cylinder	function, wear, damage	6,402	2.10	-9.71	3.80	0.11	-0.39	0.83	0.25	-0.20
		leak *	7,462	3.03	-11.27	-1.03	-0.06	0.05	0.33	0.48	0.57
	wheel cylinder	function, wear, damage	8,414	1.46	-6.39	2.69	-0.52	-1.36	-1.05	-0.31	-0.54
		leak *	15,749	1.49	-6.09	2.59	-0.58	-1.13	-0.85	0.15	-0.20
	disk caliper	function, wear, damage	16,875	2.47	-8.75	4.66	-0.24	-0.53	-0.42	0.08	0.00
		leak *	8,687	2.72	-10.14	4.37	-0.36	-0.36	-0.37	0.08	0.17
	brake dram and shoe	gap between dram and lining *	1,986	1.21	-7.55	2.81	-0.32	-1.24	-0.64	0.06	0.33
		sliding shoe wear, lightning wear *	4,819	2.90	-10.23	7.00	-0.34	-1.07	-0.19	-0.70	-0.97
		brake dram wear, damage	492	1.85	-12.44	4.63	-0.25	0.34	0.66	0.36	-2.10
	brake disk and pad	gap between disk and pad *	4,535	1.85	-8.82	4.46	-0.12	-0.11	0.12	0.07	-0.55
		brake pad wear *	77,035	2.09	-5.32	5.11	-0.26	-0.24	-0.27	0.17	-0.44
		brake disk wear, damage	16,990	1.57	-7.34	3.76	0.08	-0.05	-0.40	0.43	0.24
driving equipments	wheel cylinder	air pressure in tire *	20,112	1.32	-5.17	0.18	-0.34	-0.16	0.08	-0.08	0.01
		crack, damage *	7,264	1.43	-7.32	2.48	-0.05	0.17	0.55	-0.06	-0.36
		tread wear, unusual wear *	31,082	1.45	-5.90	3.46	-0.17	0.62	0.58	0.00	0.15
		looseness of wheel nut and bolt *	3,732	1.98	-8.50	3.17	-0.20	-1.03	-0.87	0.00	0.27
		backlash of front wheel bearing	5,689	2.80	-9.85	6.24	-0.15	-1.19	-1.51	-0.11	-0.60
		backlash of rear wheel bearing	1,769	2.25	-10.50	4.88	-0.52	-0.65	-0.77	0.31	0.63
buffering equipments	attaching and connection portion	looseness, backlash, damage	19,529	2.71	-9.34	4.54	0.07	-0.20	-0.87	0.18	0.34
	shock absorber	oil leak, damage	12,816	2.28	-8.80	4.34	0.00	-0.01	-0.96	-0.02	-0.11
power transmission	clutch	allowance, clearance *	1,374	2.30	-10.61	4.60	0.02	-0.33	-0.03	-5.73	2.18
	transmission	oil leak, oil volume *	17,707	1.73	-6.92	4.22	0.23	-0.24	-0.26	0.17	-0.11
	transfer	oil leak, oil volume *	2,402	1.89	-8.41	5.70	0.01	-3.26	-7.28	0.08	0.12
	propeller shaft	loose attachment *	1,312	3.39	-13.26	6.10	-0.12	-0.75	-3.67	0.15	0.91
	drive shaft	loose attachment *	675	2.56	-13.19	3.52	-0.61	-1.41	-0.14	1.73	1.57
		crack in joint dust boots, damage	26,642	3.84	-11.06	5.00	-0.20	-3.25	0.69	0.48	0.34
	differential	oil leak, oil volume	8,943	1.75	-6.81	5.24	0.01	-1.30	-7.39	-0.11	0.13
electric device	ignition device	spark plug *	34,601	1.59	-5.82	4.90	-0.13	-0.12	0.44	0.05	-0.13
		ignition timing *	481	2.63	-13.53	4.32	-0.37	0.52	0.08	-0.42	-0.05
		distributer cap *	2,538	3.44	-14.47	4.29	-0.07	0.21	0.82	0.84	0.22
	battery	terminal connection *	11,891	1.50	-7.31	1.60	-0.01	0.05	0.03	0.21	0.27
	electric wiring	loose attachment and damage	3,635	2.23	-10.07	3.38	-0.06	-0.20	-0.09	-0.11	0.40
engine	main unit	air cleaner element *	67,815	1.51	-4.40	4.71	-0.05	-0.08	-0.26	-0.01	-0.29
		air ventilation *	751	3.08	-13.31	3.37	-0.02	-0.43	-0.47	-0.52	-0.24
	lubricating device	oil leak *	44,009	2.71	-8.29	4.28	-0.07	-0.34	0.01	0.23	0.04
	fuel device	fuel leak	5,670	2.52	-10.48	2.32	0.41	-0.38	-1.03	0.54	0.46
	cooling device	looseness of fan belt, damage *	116,389	1.92	-4.96	4.60	-0.15	-0.02	-0.16	-0.04	-0.05
		water leak *	33,444	2.57	-8.51	4.33	-0.05	-0.35	-0.27	0.48	0.49
exhaust gas control equipments	blow-by gas reducing device	metering valve	271	2.88	-16.18	3.71	0.38	-0.09	1.12	1.07	1.84
		pipe damage	685	3.84	-18.39	3.73	0.35	0.65	0.76	2.05	2.32
	fuel evaporative emission reducing device	pipe damage	268	1.87	-14.78	-1.09	2.40	0.15	0.40	1.31	-1.28
		clog of charcoal canister, damage	159	3.21	-17.39	5.83	2.73	-0.29	-0.71	-0.40	-7.63
		check valve	80	2.87	-21.05	-10.44	1.54	-1.57	-0.53	6.62	-0.89
	carbon monoxide emission reducing device	joint looseness of catalytic exhaust gas reduction device, damage	1,014	1.35	-10.04	3.68	-0.63	0.22	-1.09	0.31	2.32
		secondary air supplier	314	1.40	-12.33	2.77	-0.19	2.02	0.94	-0.54	0.81
		exhaust gas recirculation device	313	1.09	-11.68	2.48	-0.31	0.94	2.18	-0.07	-1.81
		exhaust gas reduction during deceleration device	134	3.94	-18.03	-1.16	-0.56	0.68	1.40	-0.56	2.17
		pipe damage, connection	367	3.65	-17.29	2.51	0.18	0.78	1.31	0.43	1.66
	exhaust gas	CO	1,416	2.03	-10.97	2.77	-0.41	-0.23	0.10	0.35	0.62
		HC	1,088	2.12	-11.77	3.16	0.10	-0.01	0.25	0.28	0.67
		graphite	1,711	2.72	-10.63	4.72	-0.61	-2.10	-4.10	-0.57	-0.67
noise control equipments	exhaust pipe and muffler	loose attachment and damage *	9,276	2.59	-8.74	5.17	-0.50	-1.01	-1.00	-0.15	0.25
		muffler function	16,031	3.08	-9.41	4.39	-0.38	-1.34	-1.14	-0.13	-0.38
body	body	looseness, damage	4,075	1.96	-9.38	2.69	-0.30	0.06	-0.10	-0.03	0.05
number of samples			160,162								

🟧: 1% significant, 🟩: 5% significant, 🟦: 10%significant

Table 4 – Parameter estimates (compact vehicle)

equipment	inspection item		AIC	lambda	const	dist	insp	FR	FF	AT	MT
steering equipments	handle	handling trouble	1,343	2.10	-11.04	3.42	-0.22	-0.09	-0.43	0.03	0.22
	gear box	loose attachment	752	3.31	-13.81	3.72	-0.34	-0.33	-0.35	0.00	-0.43
	rod, arm	looseness, backlash, damage	14,797	3.12	-10.79	4.49	-0.23	-0.01	-0.89	0.12	0.26
		crackes in dust boots of pole joint	19,139	4.33	-12.43	4.27	-0.22	-0.14	0.41	-0.36	-0.30
	side slip		23,149	1.49	-5.49	2.52	-0.46	-0.19	-0.07	-0.22	0.00
	power steering	looseness, damage *	97,966	1.83	-4.87	3.20	-0.09	-0.30	-0.12	-0.13	-0.13
		oil leak and volume	21,402	2.72	-9.88	3.95	-0.04	0.02	0.01	0.14	-0.12
		loose attachment	484	1.92	-11.77	2.52	0.14	0.04	0.22	0.59	0.95
control equipments	brake pedal	allowance, clearance *	1,631	1.70	-9.25	3.27	-0.53	0.35	0.05	-0.09	0.06
		brake performance *	1,369	2.12	-10.52	3.71	-0.42	-0.36	-0.51	0.30	0.21
	hand brake	allowance *	12,796	1.49	-6.64	2.49	-0.39	-0.10	-0.18	-0.04	0.00
		brake performance *	3,330	2.69	-10.81	4.20	-0.53	-0.70	-0.93	0.00	0.88
	hose pipe	leak, damage, attachment *	13,200	4.25	-12.91	5.40	-0.32	0.13	-0.89	-0.34	-0.68
	master cylinder	function, wear, damage	6,402	2.07	-9.82	3.63	0.02	0.57	0.52	0.03	-0.06
		leak *	7,462	2.69	-10.51	2.98	0.00	0.78	0.23	0.06	0.12
	wheel cylinder	function, wear, damage	8,414	1.69	-6.59	3.04	-0.37	-0.23	0.35	-0.17	-0.04
		leak *	15,749	2.04	-6.77	2.81	-0.44	-0.33	0.52	-0.07	0.16
	disk caliper	function, wear, damage	16,875	2.30	-8.18	3.87	-0.12	-0.38	-0.67	-0.17	0.12
		leak *	8,687	2.48	-9.42	3.89	-0.34	0.04	-0.31	-0.08	-0.02
	brake dram and shoe	gap between dram and lining *	1,986	1.40	-6.84	2.85	-0.34	-0.45	-0.13	-0.27	-0.41
		sliding shoe wear, lightning wear *	4,819	2.42	-8.26	4.23	-0.30	-0.08	0.76	-0.23	-0.33
		brake dram wear, damage	492	1.85	-10.62	3.80	-0.16	-0.13	0.59	0.06	0.36
	brake disk and pad	gap between disk and pad *	4,535	1.64	-7.93	3.30	-0.33	-0.57	-0.47	-0.10	-0.13
		brake pad wear *	77,035	1.94	-4.97	4.35	-0.31	-0.18	-0.30	-0.01	-0.29
		brake disk wear, damage	16,990	1.75	-7.35	3.51	-0.11	-0.66	-0.80	0.30	0.07
driving equipments	wheel cylinder	air pressure in tire *	20,112	1.28	-4.94	0.11	-0.34	-0.29	-0.09	-0.15	-0.08
		crack, damage *	7,264	1.50	-7.18	0.55	-0.13	0.23	0.53	-0.09	-0.54
		tread wear, unusual wear *	31,082	1.41	-5.57	2.75	-0.08	0.52	0.80	-0.16	-0.26
		looseness of wheel nut and bolt *	3,732	1.62	-7.60	1.91	-0.03	-0.96	-0.93	-0.05	0.29
		backlash of front wheel bearing	5,689	2.61	-9.78	4.40	-0.32	-0.26	-1.43	-0.11	0.01
		backlash of rear wheel bearing	1,769	2.44	-10.34	3.83	-0.12	-0.89	0.14	0.08	0.46
buffering equipments	attaching and connection portion	looseness, backlash, damage	19,529	2.54	-8.84	4.12	-0.16	-0.48	-1.55	-0.01	0.15
	shock absorber	oil leak, damage	12,816	2.26	-8.65	3.75	-0.04	-0.40	-0.58	-0.14	0.03
power transmission	clutch	allowance, clearance *	1,374	2.14	-9.34	3.35	-0.56	0.02	-0.35	-3.88	1.34
	transmission	oil leak, oil volume *	17,707	1.69	-6.78	3.24	0.07	-0.07	-0.15	-0.01	-0.10
	transfer	oil leak, oil volume *	2,402	1.57	-7.92	3.15	0.10	-3.66	-5.85	-0.05	0.57
	propeller shaft	loose attachment *	1,312	2.68	-11.64	6.11	-0.62	-0.95	-13.78	0.18	0.19
	drive shaft	loose attachment *	675	3.04	-12.87	4.54	-0.27	-2.37	0.11	-0.41	-0.86
		crack in joint dust boots, damage	26,642	3.92	-10.23	4.46	-0.40	-3.79	0.42	-0.30	-0.40
	differential	oil leak, oil volume	8,943	1.65	-6.90	4.70	-0.04	-0.79	-8.37	-0.04	0.35
electric device	ignition device	spark plug *	34,601	1.36	-4.30	3.12	-0.02	-0.52	0.00	-0.04	-0.24
		ignition timing *	481	2.30	-12.94	2.16	-0.14	0.37	1.04	-0.21	0.90
		distributer cap *	2,538	2.78	-12.59	3.28	0.11	0.45	0.49	0.35	0.59
	battery	terminal connection *	11,891	1.46	-7.10	1.75	-0.08	-0.03	0.07	0.13	0.07
	electric wiring	loose attachment and damage	3,635	2.01	-9.51	2.65	-0.48	-0.21	-0.22	0.05	0.04
engine	main unit	air cleaner element *	67,815	1.49	-4.26	3.41	-0.03	-0.17	-0.21	-0.06	-0.14
		air ventilation *	751	2.53	-11.86	3.42	-0.26	-0.47	-0.72	0.07	0.31
	lubricating device	oil leak *	44,009	2.45	-7.20	3.72	-0.11	-0.52	-0.20	-0.03	-0.03
	fuel device	fuel leak	5,670	3.10	-11.61	4.59	-0.24	-0.16	-0.96	0.42	0.25
	cooling device	looseness of fan belt, damage *	116,389	1.94	-4.93	3.39	-0.18	-0.26	-0.12	-0.07	-0.03
		water leak *	33,444	2.11	-7.25	3.39	-0.14	-0.25	-0.12	0.18	0.12
exhaust gas control equipments	blow-by gas reducing device	metering valve	271	2.98	-14.11	2.61	-0.02	-1.35	0.16	-0.45	-0.27
		pipe damage	685	2.47	-13.59	3.20	0.20	1.16	1.70	0.11	-0.68
	fuel evaporative emission reducing device	pipe damage	268	2.46	-13.41	-0.09	-0.17	-0.65	1.69	0.08	0.18
		clog of charcoal canister, damage	159	2.56	-14.57	-1.34	0.65	0.01	0.22	-0.88	0.37
		check valve	80	2.81	-20.25	2.82	-1.41	4.11	5.43	0.35	-7.70
	carbon monoxide emission reducing device	joint looseness of catalytic exhaust gas reduction device, damage	1,014	1.25	-8.79	-6.89	-1.52	0.34	-0.71	0.21	0.98
		secondary air supplier	314	1.05	-10.62	2.40	0.35	0.14	-0.29	0.38	0.77
		exhaust gas recirculation device	313	1.24	-11.85	0.09	0.65	0.50	0.73	0.61	1.30
		exhaust gas reduction during deceleration device	134	3.87	-37.61	2.61	-1.08	-2.72	20.39	-0.22	-0.28
		pipe damage, connection	367	3.35	-14.77	0.81	0.02	-0.46	1.19	-0.47	-0.39
	exhaust gas	CO	1,416	2.83	-12.44	3.67	-0.25	0.23	0.85	0.26	0.53
		HC	1,088	2.35	-12.20	3.68	-0.27	0.90	1.04	0.19	0.76
		graphite	1,711	2.45	-11.01	4.15	-0.44	-0.62	-1.99	0.04	0.71
noise control equipments	exhaust pipe and muffler	loose attachment and damage *	9,276	2.76	-9.13	3.97	-0.30	-0.76	-0.87	-0.04	0.12
		muffler function	16,031	3.53	-10.65	3.87	-0.32	-0.71	-0.84	-0.06	0.12
body	body	looseness, damage	4,075	1.72	-8.65	2.25	-0.50	0.02	-0.12	-0.01	-0.07
number of samples			271,812								

🟧: 1% significant, 🟩: 5% significant, 🟦: 10%significant

Table 5 – Parameter estimates (light vehicle)

equipment	inspection item		AIC	lambda	const	dist	insp	FR	FF	AT	MT
steering equipments	handle	handling trouble	593	1.97	-11.13	6.24	0.07	-15.07	-0.28	0.18	0.77
	gear box	loose attachment	191	3.17	-13.52	6.65	-0.62	-1.49	-1.01	-1.15	-3.97
	rod, arm	looseness, backlash, damage	3,341	3.12	-10.70	9.07	-0.39	-1.22	-0.86	-0.04	0.28
		crackes in dust boots of pole joint	8,874	4.31	-13.40	8.57	-0.12	-0.78	0.22	0.04	-0.21
	side slip		14,830	1.47	-5.20	3.99	-0.22	-0.76	-0.17	-0.29	-0.08
	power steering	looseness, damage *	33,455	1.70	-5.27	5.78	0.15	0.22	-0.51	0.07	-0.30
		oil leak and volume	1,852	2.18	-10.24	6.18	0.14	-0.39	-0.17	0.14	-0.16
		loose attachment	149	2.21	-11.54	0.57	-0.35	-6.78	-0.97	0.16	-5.57
control equipments	brake pedal	allowance, clearance *	1,899	2.18	-9.78	5.90	0.14	-8.01	-0.49	-0.58	-0.35
		brake performance *	1,458	2.23	-10.34	7.14	-0.32	-4.91	-0.71	0.32	0.33
	hand brake	allowance *	7,040	1.63	-7.58	3.16	-0.17	-0.34	0.22	0.54	0.23
		brake performance *	1,641	2.51	-10.90	8.31	-0.26	0.78	-0.77	0.03	0.43
	hose pipe	leak, damage, attachment *	1,583	4.37	-15.26	4.57	0.04	0.45	-0.01	-0.18	0.37
	master cylinder	function, wear, damage	2,105	2.23	-10.35	6.04	0.17	0.36	0.08	0.01	0.04
		leak *	6,168	1.81	-7.97	3.76	-0.14	-0.05	0.16	0.02	0.12
	wheel cylinder	function, wear, damage	26,189	1.72	-5.85	4.56	-0.13	-0.33	0.04	-0.05	-0.42
		leak *	43,687	2.06	-5.81	3.79	-0.24	-0.77	0.15	-0.50	-0.30
	disk caliper	function, wear, damage	8,520	2.43	-8.50	7.61	-0.04	-0.73	-0.78	-0.41	-0.09
		leak *	4,875	2.16	-9.06	6.18	0.23	-0.37	-0.07	-0.24	0.01
	brake dram and shoe	gap between dram and lining *	3,354	1.82	-7.86	3.81	0.04	-0.61	-0.26	-0.06	-0.17
		sliding shoe wear, lightning wear *	10,838	2.93	-8.82	8.96	-0.10	-1.38	-0.73	0.11	-0.32
		brake dram wear, damage	922	2.50	-11.03	9.13	-0.57	-11.50	-1.28	-0.25	-1.10
	brake disk and pad	gap between disk and pad *	1,789	2.01	-9.33	7.50	0.22	0.09	-0.39	0.03	-0.02
		brake pad wear *	30,621	1.50	-4.11	0.02	-0.09	-0.01	-0.07	-0.03	0.00
		brake disk wear, damage	4,233	1.51	-7.45	6.75	-0.58	-3.53	-0.93	0.59	0.45
driving equipments	wheel cylinder	air pressure in tire *	12,219	1.42	-5.29	0.68	-0.10	-0.07	-0.01	0.04	-0.11
		crack, damage *	3,917	1.61	-7.82	2.46	0.23	0.40	0.68	-0.06	-0.88
		tread wear, unusual wear *	17,996	1.57	-6.13	5.14	-0.03	0.61	0.89	-0.03	-0.23
		looseness of wheel nut and bolt *	1,760	2.49	-9.63	1.59	-0.18	-9.96	-0.54	-0.15	-0.08
		backlash of front wheel bearing	3,027	2.42	-9.42	8.72	-0.28	-2.28	-0.62	0.08	-0.09
		backlash of rear wheel bearing	2,806	2.24	-9.35	7.29	0.03	-0.65	-0.14	-0.21	0.25
buffering equipments	attaching and connection portion	looseness, backlash, damage	5,422	2.98	-10.12	6.35	0.24	-2.10	-0.96	-0.20	0.15
	shock absorber	oil leak, damage	3,516	2.67	-10.26	7.50	-0.06	-0.64	-0.56	-0.15	-0.19
power transmission	clutch	allowance, clearance *	1,502	2.68	-11.53	5.57	0.53	1.07	0.02	-4.26	0.79
	transmission	oil leak, oil volume *	6,405	1.78	-7.13	5.80	-0.11	0.56	-0.31	0.17	-0.57
	transfer	oil leak, oil volume *	889	1.92	-8.22	4.83	-0.50	-0.94	-7.79	-0.37	-0.10
	propeller shaft	loose attachment *	123	3.57	-14.09	4.68	1.21	-12.67	-9.59	-0.85	-8.10
	drive shaft	loose attachment *	1,086	3.26	-12.96	8.06	0.02	-1.91	0.21	-0.07	-1.04
		crack in joint dust boots, damage	41,087	3.96	-10.17	7.74	-0.32	-0.64	0.57	-0.40	-0.46
	differential	oil leak, oil volume	2,655	2.27	-8.11	10.04	-0.10	-0.10	-5.25	-0.15	-0.58
electric device	ignition device	spark plug *	28,808	1.54	-4.69	6.29	0.11	-0.19	-0.24	0.22	0.05
		ignition timing *	733	3.28	-13.81	3.06	0.05	1.04	0.21	-0.34	0.72
		distributer cap *	1,789	3.61	-13.63	9.42	-0.20	-4.33	-0.05	-0.15	-0.14
	battery	terminal connection *	6,323	1.61	-7.44	2.18	0.15	-0.15	0.12	0.11	0.09
	electric wiring	loose attachment and damage	2,249	2.16	-9.60	3.37	-0.02	0.93	-0.20	-0.16	-0.27
engine	main unit	air cleaner element *	26,448	1.68	-5.19	6.85	-0.01	-0.46	-0.09	0.02	-0.01
		air ventilation *	819	2.61	-11.70	5.25	-1.25	-10.39	-0.46	0.04	0.39
	lubricating device	oil leak *	29,872	2.53	-7.15	6.98	-0.15	-0.71	-0.47	-0.02	-0.32
	fuel device	fuel leak	873	3.65	-14.10	6.35	0.45	-3.12	-0.68	0.25	0.18
	cooling device	looseness of fan belt, damage *	66,781	2.35	-5.26	6.06	-0.11	-0.16	-0.36	-0.09	-0.15
		water leak *	19,685	2.21	-7.35	6.33	-0.03	0.02	-0.13	0.13	-0.33
exhaust gas control equipments	blow-by gas reducing device	metering valve	903	2.42	-10.50	1.49	-0.46	-4.68	-0.90	0.01	-1.35
		pipe damage	323	2.17	-12.55	4.38	-0.49	1.57	0.11	0.58	1.22
	fuel evaporative emission reducing device	pipe damage	138	2.35	-13.98	3.63	0.01	-18.35	0.55	-0.30	0.68
		clog of charcoal canister, damage	72	5.99	-29.65	-1.21	-4.75	-0.77	7.76	0.04	-6.60
		check valve	84	2.82	-12.08	-12.84	-5.81	-9.53	-9.73	-6.41	0.89
	carbon monoxide emission reducing device	joint looseness of catalytic exhaust gas reduction device, damage	432	2.41	-11.86	5.03	-0.02	-16.87	-0.98	0.27	0.37
		secondary air supplier	57	0.53	-10.23	0.15	-7.50	-3.09	-0.37	-5.98	2.57
		exhaust gas recirculation device	134	6.66	-21.90	-5.35	-9.70	-1.68	-0.25	-9.68	-6.23
		exhaust gas reduction during deceleration device	180	2.87	-27.11	-4.31	1.48	-1.16	13.21	0.44	-10.25
		pipe damage, connection	384	2.79	-13.36	3.91	-0.15	-6.62	0.24	-0.55	0.23
	exhaust gas	CO	3,707	3.24	-12.32	5.48	0.08	-2.12	0.85	-0.69	-0.05
		HC	1,847	3.10	-12.63	5.27	0.22	-3.71	0.62	-0.79	-0.17
		graphite	-	-	-	-	-	-	-	-	-
noise control equipments	exhaust pipe and muffler	loose attachment and damage *	6,195	2.66	-8.65	6.55	-0.09	-2.86	-0.96	0.02	-0.10
		muffler function	18,797	2.85	-8.05	4.85	-0.20	-1.27	-0.89	-0.04	0.03
body	body	looseness, damage	2,885	1.67	-8.30	2.95	-0.02	0.12	-0.13	-0.19	0.24
number of samples			79,904								

🟧: 1% significant, 🟩: 5% significant, 🟦: 10%significant

Fourth, the parameter estimates vary widely among inspected items and vehicle types. This result indicates that the committee's estimates of failure rate curves are possibly strongly biased due to the ignoring of differences in deterioration mechanism among inspected items. Further, the estimates of the negative impact caused by the revision of the current I/M program may be strongly biased. As previously mentioned, the committee estimated the relationship between the number of vehicles with failure and the size of negative effects caused by vehicle transportation, to be more precise, traffic death toll, traffic congestion length, and emission of exhaust gases. And the set of inspected items relevant with the traffic accident are thought to be different from the set of those relevant with the emission of exhaust gases. The ignoring of differences in deterioration mechanism may cause the biases in the estimates of the negative impacts of the current I/M program revision.

Finally, comparing the observed and estimated failure curves (Note: we are not showing them in this paper), we can see that they are fitting well for the pairs of item and vehicle type that their sample size is large, and for younger aged vehicles. There are two reasons why the fitting is good for younger aged vehicles. One reason is that the number of samples is large for younger aged vehicles, compared with older aged vehicles. The other reason is that older aged vehicles are more fraught with uncertainty in our modelling of I/M history.

Increase in failure rates

Here, let us estimate the increase in failure rate under the revision scenario of the I/M program. We consider the scenario of extending only the first inspection time period from three years to four years. This scenario is the same with that considered by the committee. To compare the result with that by the committee, we use the same definition of failure by the committee, and we estimate the ratio of vehicles that at least one inspected item does not meet the standard.

Following the idea summarized in Figure 4, the failure rate of any items at each age before and after the revision can be given by the probabilities shown in Table 6, where $F_{ij}(t)$ is the distribution function of Weibull proportional hazard model. We denote the failure rate of item j of vehicle i with t years age by $P_{ij}(t)$. Then, we calculate the failure rate of vehicle i with t years age, that is, the probability that vehicle i with t years age has at least one item that does not meet the standard, as follows:

$$P_i(t) = 1 - \prod_j \left(1 - P_{ij}(t)\right). \tag{16}$$

In deriving Eq.(16), we are assuming the dependence of deterioration among items. Further, we calculate the average failure ratio of vehicles with t years age as follows:

$$P(t) = \frac{1}{\left|\{i \in I \mid t_i = t\}\right|} \sum_{i \in \{i \in I \mid t_i = t\}} P_i(t). \tag{17}$$

We cannot calculate $P(t)$ in Eq.(17) for the vehicles with the ages of 1,2,4,6,8,10,12 and 14 years since only the vehicles just before inspection were surveyed. Therefore, we estimate

Table 6 – Failure rate of each item at any ages

age	before revision	after revision
1	$F_{ij}(1)$	$F_{ij}(1)$
2	$F_{ij}(2)$	$F_{ij}(2)$
3	$F_{ij}(3)$	$F_{ij}(3)$
4	$F_{ij}(3)\cdot F_{ij}(1)+\left[F_{ij}(4)-F_{ij}(3)\right]$	$F_{ij}(4)$
5	$F_{ij}(3)\cdot F_{ij}(2)+\left[F_{ij}(5)-F_{ij}(3)\right]$	$F_{ij}(4)\cdot F_{ij}(1)+\left[F_{ij}(5)-F_{ij}(4)\right]$
6	$F_{ij}(3)\cdot F_{ij}(2)\cdot F_{ij}(1)+F_{ij}(3)\left[F_{ij}(3)-F_{ij}(2)\right]$ $+\left[F_{ij}(5)-F_{ij}(3)\right]F_{ij}(1)+\left[F_{ij}(6)-F_{ij}(5)\right]$	$F_{ij}(4)\cdot F_{ij}(2)+\left[F_{ij}(6)-F_{ij}(4)\right]$
7	$F_{ij}(3)\cdot F_{ij}(2)\cdot F_{ij}(2)+F_{ij}(3)\left[F_{ij}(4)-F_{ij}(2)\right]$ $+\left[F_{ij}(5)-F_{ij}(3)\right]F_{ij}(2)+\left[F_{ij}(7)-F_{ij}(5)\right]$	$F_{ij}(4)\cdot F_{ij}(2)\cdot F_{ij}(1)+F_{ij}(4)\left[F_{ij}(3)-F_{ij}(2)\right]$ $+\left[F_{ij}(6)-F_{ij}(4)\right]F_{ij}(1)+\left[F_{ij}(7)-F_{ij}(5)\right]$
:	:	:

Table 7 – Failure rate of each vehicle type at any ages

age	normal		compact		light	
	before	after	before	after	before	after
0	0	0	0	0	0	0
1	0.079	0.079	0.092	0.092	0.091	0.091
2	0.235	0.235	0.261	0.261	0.272	0.272
3	0.422	0.422	0.453	0.453	0.485	0.485
4	0.300	0.599	0.316	0.630	0.362	0.673
5	0.553	0.351	0.577	0.371	0.637	0.424
6	0.400	0.614	0.423	0.641	0.484	0.706
7	0.669	0.438	0.699	0.468	0.763	0.529
8	0.474	0.710	0.511	0.744	0.571	0.804
9	0.745	0.503	0.783	0.545	0.834	0.598
10	0.532	0.774	0.575	0.811	0.622	0.855
11	0.791	0.547	0.831	0.594	0.865	0.630
12	0.570	0.812	0.614	0.848	0.642	0.875
13	0.820	0.578	0.856	0.622	0.871	0.636
14	0.597	0.836	0.633	0.865	0.644	0.876
15	0.841	0.605	0.867	0.638	0.866	0.633

the number of vehicles with those ages by interpolation. The estimated failure rates of vehicles of any age are summarized in Table 7.

From Table 7, we can see that the failure rates are not monotonic for age. Although deterioration curve of each item is monotonic, due to the effects of maintenance done depending on the results of check, the failure rate of the following year of inspection falls from the previous year and its curve becomes non-monotonic. By summing the products of share and failure rate of vehicles at each year age, total ratio of vehicles in failure can be calculated. Further, by subtracting the number of vehicles with failure before the revision from that after the revision, we can calculate the increase in the number of vehicles with failure. Since the statistics of the number of light vehicles cannot be found, we calculate and show only the results of the normal and compact vehicles. The results are shown in Table 8. In the committee's estimation, only the increase in the failure rate of vehicles with four years of age was shown in the final report, and it was estimated to be a 10.6% increase. Technically our results and committee's results are uncomparable due to the difference between what we estimated and what the committee estimated. (Note: Although the increase in failure rate of vehicles with four years age can be calculated from our results, due to the lack of monotonicity, it cannot be compared with that by the committee's.) However the gap between two estimates is enough to make us insist that the committee's estimates were overestimated.

Table 8 – Increase in failure rate under revision scenario

	normal	compact
increase in failure rate	1.60%	1.37%

CONCLUSION

Vehicles are highly important in almost all aspects of our human society, and vehicles I/M programs are indispensable to reduce the social cost caused by motor traffic, such as traffic accidents, air pollution and global warming, etc. In this study, we examined the previous estimation by the committee, and pointed out that they have three major problems in the estimation of failure rate of vehicles. Then, we proposed a model of incorporating I/M history of a vehicle, and estimated the deterioration curves of all the inspected items using the same data as used by the committee. Finally, we calculated the increase in failure rate of vehicles under revision scenario. The results are summarized as follows:

1. For any pairs of inspected item and types, age deterioration is occurring, and most of them can be represented by the accelerated hazard model. Only some items of exhaust gas equipments can be represented by the constant hazard model.

2. For more than 55 of the 67 inspected items, running deterioration is occurring. Most of items, for which running deterioration is not occurring, are of exhaust gas equipments.

3. If the first inspection time period were extended from three years to four years under the current Japan's I/M program, the failure rate would increase by 1.60% for normal type vehicles, and by 1.37% for compact type vehicles. The committee's estimate, 10.6 percent increase in the failure rate of vehicles under the revision scenario, is possibly significant overestimation.

The above results have considerable value in quantifying the impacts of the revision of Japan's current I/M program. And they have value in deepening the understanding of vehicles' deterioration mechanism, too. Most countries are thought to have some kind of product and usage standards of vehicles, and they are deemed similar to some extent. The above results give some useful information to the researchers and administrative officials in this field.

Finally, we point out some topics to be tackled in the future. First, the assumption of the independence of the deterioration of inspected items should be relaxed. A copula approach is proposed for multivariate survival analysis (cf. Klein and Moeschberger, 2003). In this approach, single variate survival models same as those estimated in this study are estimated. Then, a copula function representing the interdependence structure of the multivariates is estimated. Since the data size (sample size) is large, this approach is thought to be effective in conserving the cost of statistical analysis. Identifying the interdependence structure of inspected items is valuable for the understanding of the complex deterioration mechanism of vehicles, composed of many equipments and affected by many factors. If we do not need to estimate the impacts of the revision of I/M program, other statistical techniques, such as Bayesian network analysis, may be powerful for the identification of interdependence structure. Second, attrition bias should be removed. Since vehicles with failure are more likely to be renewed, the sampled vehicles old years of age are thought to be more durable than vehicles with average durability. Therefore, our results may be underestimating the deterioration curves to some extent. Third, the assumption of perfect recover after maintenance should be removed. This assumption is thought to be removed by using frailty models in survival analysis.

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