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# STRATEGIC VEHICLE FLEET MANAGEMENT - THE REPLACEMENT PROBLEM

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**ABSTRACT**. **Background**: Fleets constitute the most important production means in transportation. Their appropriate management is crucial for all companies having transportation duties. The paper is the third one of a series of three papers that the author dedicates to the strategic vehicle fleet management topic.

**Material and methods**: The paper discusses ways of building replacement strategies for companies' fleets of vehicles. It means deciding for how long to exploit particular vehicles in a fleet (the fleet replacement problem - FR). The essence of this problem lies in the minimization of vehicle / fleet exploitation costs by balancing ownership and utilization costs and taking into account budget limitations. In the paper an original mathematical model (an optimization method) allowing for the FR analysis is proposed.

**Results**: An application of the proposed optimization method in a real-life decision situation (the case study) within the Polish environment and the obtained solution are presented. The solution shows that there exist optimal exploitation periods of particular vehicles in a fleet. However, combination of them gives a replacement plan for an entire fleet violating budget constraints. But it is possible to adjust individual age to replacement of particular vehicles to fulfill budget constraints without losing economical optimality of a developed replacement plan for an entire fleet.

**Conclusions**: The paper is the last one of a series of three papers that the author dedicated to the strategic vehicle fleet management topic including the following managerial decision problems: MAKE-or-BUY, sizing / composition and replacement.

**Key words:** management, optimization, fleet, vehicle, transport, replacement.

"If you can afford to operate an old fleet you can afford to operate a less old one!" - Paul T. Lauria

## INTRODUCTION

The decision for how long to exploit particular vehicles in a fleet or when to dispose / replace them and by what type of a brand new or used vehicles, including selection of vehicles investment / acquisition option (e.g. to buy on cash, credit, lease or rent), is called a fleet replacement (FR) problem.

The FR problem can be considered on a level of single vehicles or on a level of entire fleets. It makes a significant difference in the way budget limitations are taken into account. Budget limitations mean available funds that can be spent on replacements of vehicles within a given time period (e.g. fiscal year). When single vehicles are considered budget limitations can be skipped or they just simply can't be taken into account since budgets are defined on a fleet level, not on a level of single


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vehicles. In contradiction, whereas entire fleets are considered budget limitations are crucial when developing replacement plans.

On a single vehicle level of considerations the essence of the FR problem is to exploit vehicles not too short and not too long. Too short exploitation periods result in high vehicle ownership costs, whereas too long exploitation periods result in high vehicle utilization costs. High ownership costs a caused by a steep decrease in a vehicles' residual value (RV) in early years of their exploitation life. High utilization costs a caused by technical condition deterioration and increased downtimes associated with it. While on an entire fleet level of considerations the essence of the FR problem is not to cause capital investment surges in time. It requires adjustments of an individual optimal age to replacement of particular vehicles in a fleet keeping capital investments within a predefined, reasonable range (budget limitations). The possibility of adjustment of an individual optimal age to replacement of particular vehicles is supported by relatively flat total (or unit) exploitation costs function around an optimal age to replacement being the decision variable.

## THE METHOD FOR SOLVING THE FR PROBLEM

Methods for solving the FR problem can be divided into the preventive and the failure based ones [Eilon, King, Hutchinson 1966; Glasser 1969; Jardine, Buzacott 1985]. But in the case of the preventive replacement methods it is necessary to define time to replacement, which is obvious in the case of the failure based methods since it is just a moment of a failure. There are two ways of defining that time (an exploitation period) when using the preventive based methods. They are: age based replacement [Glasser 1969] and group replacement [Nakagawa 1984]. Considering vehicles, including trucks, the preventive age based replacement methods can be applied. Instead of an age a cumulative utilization, e.g. mileage can be used as well.

Regardless if an age of a vehicle (an exploitation period) or a cumulative utilization (mileage) is used the general aim when planning replacement is to minimize overall exploitation costs, usually discounted ones. The majority of replacement methods are based on a comparison (a minimization of a sum that means balancing) of decreasing with time ownership costs (often depreciation costs only) and increasing with time utilization (operational and maintenance) costs [Britten 1971; Christer, Goodbody 1980]. As the author proved [Redmer 2009], while vehicles, especially trucks, are considered it is important to minimize unit (e.g. per one kilometer), discounted exploitation costs instead of a total exploitation costs (e.g. annual ones). It is caused by a decreasing with time utilization intensity of such vehicles.

The general drawback of the existing solution methods for the FR problem is that they assume a constant utilization of equipment, including vehicles, during its operational lifetime [Hartman 1999]. Moreover, the methods are focused on searching for an optimal, from the mathematical point of view, solutions. It results in replacement plans requiring varying with time investments, e.g. year-to-year. While in practice it is always better to avoid any expenditure surges.

As a result a generic formula for calculating the age to replacement $a^r_i$ of particular vehicles i (i = 1, 2, 3, …, I) in a fleet, the age that minimizes the average unit discounted fleet exploitation costs $UDC_{avr}$ and allows for fulfilling budget limitations in particular fiscal years fy (fy = 1, 2, 3, …) can be written as follows:

$$UDC_{avr}\left(a^{r}\right)=\frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\frac{CE_{ij}-GBV_{i}\cdot d_{ij}\cdot TR+UC_{F_{ij}}\left(a_{ij}\right)+UC_{V_{ij}}\left(a_{ij}\right)\cdot UI_{ij}\left(a_{ij}\right)+FP_{ij}\left(a_{ij}=a_{i}^{r}\right)-RV_{ij}\left(a_{ij}=a_{i}^{r}\right)}{(1+r)^{j}}}{\sum_{i=1}^{I}\sum_{j=1}^{J}UI_{ij}\left(a_{ij}\right)}$$

under the condition:

$$B_{fy}^{\min}\leq\sum_{i=1}^{I}\sum_{j=12\cdot(fy-1)+1}^{12\cdot fy}\left[CE_{ij}-GBV_{i}\cdot d_{ij}\cdot TR+FP_{ij}\left(a_{ij}=a_{i}^{r}\right)-RV_{ij}\left(a_{ij}=a_{i}^{r}\right)\right]\leq B_{fy}^{\max}$$

where:

| | |
|---|---|
| $UDC_{avr}(a^r)$ | average unit discounted fleet exploitation costs when replacing vehicles $i$ in a fleet at the age of $a^r_i$ [monetary unit – m.u./km], |
| $i$ | particular vehicles in a fleet; $i$ = 1, 2, 3, … $I$ [–], |
| $j$ | particular periods of analysis (e.g. months); $j$ = 1, 2, 3, … $J$ [time unit – t.u.], |
| $a_{ij}$ | age of vehicle $i$ in particular period of analysis $j$; $a_{ij} \in \langle$initial vehicle age when put into a fleet, $a^r_i \rangle$ [t.u.], |
| $a^r_i$ | age of vehicle $i$ to replacement – DECISION VARIABLES [t.u.], |
| $CE_{ij}$ | total capital expenditures associated with acquisition of vehicle $i$ incurred in particular periods of analysis $j$, e.g. leasing payments [m.u./t.u.], |
| $FP_{ij}(a_{ij} = a^r_i)$ | final payment associated with acquisition of vehicle $i$ incurred in the last period $j$ of its exploitation when $a_{ij} = a^r_i$ [m.u.], |
| $GBV_i$ | Gross Book Value of vehicle $i$ (e.g. net price) [m.u.], being a basis for depreciation expenses calculation, |
| $d_{ij}$ | depreciation rate of vehicle $i$ in particular periods of analysis $j$ [-/t.u.], |
| $TR$ | tax rate [-], |
| $UC_{Fij}(a_{ij})$ | utilization fixed costs of vehicle $i$ at the age of $a_{ij}$ in particular periods of analysis $j$ [m.u./t.u.], including costs associated with a vehicle only (e.g. without driver's salary):<br>– road taxes,<br>– insurance,<br>– permanent licenses, |
| $UC_{Vij}(a_{ij})$ | utilization unit variable costs of vehicle $i$ at the age of $a_{ij}$ in particular periods of analysis $j$ [m.u./km], including:<br>– fuel,<br>– maintenance (e.g. labor, spare parts, downtime, …),<br>– tires,<br>– one-time licenses,<br>– parking,<br>– phone calls,<br>– tolls (for roads, tunnels, bridges, ferries, …), |
| $UI_{ij}(a_{ij})$ | utilization intensity (mileage) of vehicle $i$ at the age of $a_{ij}$ in particular periods of analysis $j$ [km/t.u.], |
| $RV_i(a_{ij} = a^r_i)$ | residual (market) or scrap value of vehicle $i$ in the last period $j$ of its exploitation when $a_{ij} = a^r_i$ [m.u.], |
| $r$ | discount factor [-/t.u.], |
| $B^{min/max}_{fy}$ | fleet investment budget limitations (min / max) in particular fiscal years $fy$; $fy$ = 1, 2, 3, … [m.u./$fy$]. |

## THE CASE STUDY - SOLVING THE FR PROBLEM IN POLISH CIRCUMSTANCES

Let's consider a fleet composed of 20 EURO5 semi-trucks (truck-tractors) heaving Gross Book Value of 325000 Polish zlotys each (1 zloty = 3.8 USD = 4.0 EUR - the exchange rate dated 16.04.2015 by the National Bank of Poland), and leased as a brand new ones 4.5 years ago (being currently at the age of 54 months). The leasing, that is a 5-year long financial one, lasts within the next 6 months with no final payments. The leasing monthly payments are constant and equal to 6000 zlotys. Vehicles are depreciated under the rate of 17% annually that gives the 86-month depreciation period. The company, that is a non-transportation company operating the analyzed fleet for international transports, pays tax at the rate of 19%.

The following parameters: fixed utilization costs, variable utilization costs, residual value and utilization intensity, characterizing particular vehicles, vary with time of their exploitation. Moreover, since particular vehicles are utilized with different intensity their variable utilization costs changes with time under different rates. Average values of the particular parameters are as follows (assuming a straight line changes with time):

– annual fixed utilization costs for a brand new vehicle equal to 18000 zlotys and decrease with time (by 3.0% per year),
– unit variable utilization costs for a brand new vehicle equal to 2.1 zlotys per kilometer and increase with time differently for particular vehicles (see Table 1),
– utilization intensity (monthly mileage) is different for particular vehicles (see Table 1) and decreases with time (by 2.5% per year),
– residual value of a vehicle at the end of the leasing period (for 5-year old vehicle) equals to 50% of its GBV and decrease further with time (by 5.0% per year).

Assumed values of the age to replacement $a^r_i$ for all vehicles in the fleet are 5 at minimum to 10 years at maximum (60 to 120 months).

Table 1. Parameters heaving individual values for particular vehicles
Tabela 1. Parametry posiadające indywidualne wartości dla każdego z pojazdów

| **Vehicle *i*** | **Monthly mileage for a brand new vehicles** | **Variable utilization costs' annual increases** |
|---|---|---|
| | **[km/month]** | **[%/year]** |
| **1** | 8000 | 1,7% |
| **2** | 8200 | 1,7% |
| **3** | 8400 | 1,7% |
| **4** | 8600 | 1,8% |
| **5** | 8800 | 1,8% |
| **6** | 9000 | 1,8% |
| **7** | 9200 | 1,9% |
| **8** | 9400 | 1,9% |
| **9** | 9600 | 1,9% |
| **10** | 9800 | 2,0% |
| **11** | 10000 | 2,0% |
| **12** | 10200 | 2,0% |
| **13** | 10400 | 2,2% |
| **14** | 10600 | 2,2% |
| **15** | 10800 | 2,2% |
| **16** | 11000 | 2,3% |
| **17** | 11200 | 2,3% |
| **18** | 11400 | 2,3% |
| **19** | 11600 | 2,4% |
| **20** | 11800 | 2,4% |

Using the proposed above mathematical model of the FR problem, the above described data and a professional solver for the MS Excel the problem has been solved.

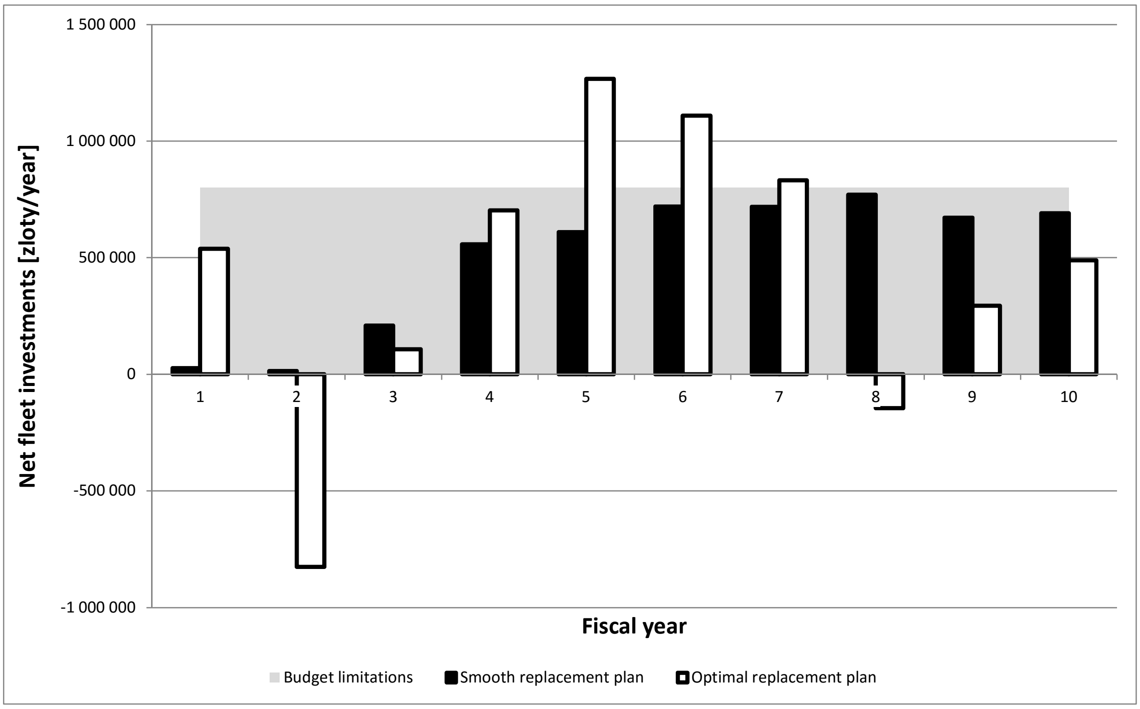
Two different solutions of the problem have been found. The solutions named "optimal" and "smooth" one. The optimal solution means a replacement plan constructed based on the optimal age to replacement calculated separately for each one vehicle in the fleet. In this solution the budget constraint has been relaxed (skipped). The smooth solution means a replacement plan constructed based on the age to replacement calculated for particular vehicles in the fleet simultaneously (at the same time) trying to keep investment expenditures in the range of 0 to 800 000 zlotys per year (the budget).

The results are presented in Fig. 1 and Table 2.

Table 2. Selected solutions of the analyzed FR problem
Tabela 2. Wybrane rozwiązania analizowanego problemu wymiany taboru

| **Vehicle *i*** | **Age to replacement of vehicle *i* – $a^r_i$ [month]** | |
|---|---|---|
| | **Smooth solution** | **Optimal solution** |
| **1** | 101 | 96 |
| **2** | 101 | 96 |
| **3** | 77 | 89 |
| **4** | 77 | 89 |
| **5** | 60 | 89 |
| **6** | 69 | 83 |
| **7** | 101 | 83 |
| **8** | 89 | 83 |
| **9** | 101 | 78 |
| **10** | 101 | 78 |
| **11** | 120 | 78 |
| **12** | 63 | 73 |
| **13** | 89 | 73 |
| **14** | 120 | 73 |
| **15** | 69 | 69 |
| **16** | 101 | 69 |
| **17** | 60 | 69 |
| **18** | 63 | 69 |
| **19** | 77 | 65 |
| **20** | 63 | 62 |
| **Average age to replacement – $a^r_i$ [month]** | **85** | **78** |
| **Average unit fleet exploitation costs – $UDC_{avr}$ ($a^r$) [zloty/km]** | | |
| **discounted** ($r$ = 1.3% per year) | **1.54** | **1.53** |
| **not discounted** | **2.65** | **2.63** |
| **Average discounted total annual fleet exploitation costs [million zloty/year]** | **3.30** | **3.30** |
| **Average discounted total annual net fleet investments [million zloty/year]** | **0.46** | **0.40** |
| **Average total annual fleet mileage [million km/year]** | **2.20** | **2.20** |

Source: author's research




Source: author's research

Fig. 1. The net fleet investments in comparison to the available budget for fleet replacement
Rys. 1. Wydatki inwestycyjne netto w stosunku do założonego budżetu na wymianę floty

As it is shown in Table 2 both solutions are very similar, equally good, when taking into account the average unit fleet exploitation costs they result in (less than 1% difference). Moreover, the average age to replacement is similar in both solutions as well. It is around 7 years of exploitation to the moment of replacement (based on the optimal solution 6.5 years and on the smooth one 7.1 years - precisely). The significant difference is when taking into account budget limitations and net fleet investments the both solutions result in within particular fiscal years. The net fleet investments are defined as a difference between funds that according to a given FR problem solution (a replacement plan) have to be spent on vehicles' purchases (e.g. leasing payments) less all possible allowances (e.g. depreciation resulting in a tax shield and a residual value resulting in incomes when selling a vehicle). Fig. 1 proves that the optimal solution from the budget limitations point of view is a significantly worse solution for the company operating analyzed fleet than the smooth one. The optimal solution results in the net fleet investments varying much from year to year within the range of minus 825 000 to plus 1 267 000 zlotys per one fiscal year. Moreover, this solution requires high expenditures in the first one fiscal year (538 000 zlotys). On the contrary, the smooth solution does not cause capital investment surges in time, requires small expenditures in the first three fiscal years (83 000 zlotys on average) and the expenditures in the further years are relatively flat (within the range of 558 000 to 770 000 zlotys per year).

## CONCLUSIONS

Summarizing not only presented above considerations of the FR problem, but also two other, important strategic fleet management problems that are the Make-or-Buy (MoB) and the fleet sizing / composition (FS/FC) discussed in the two previously published by the author papers (Redmer 2014; Redmer 2015), one can draw the fallowing conclusions:

- The FR problem: the best (in this case a smooth one meaning relatively flat capital investments in particular fiscal years) solution of the problem is very similar to its other solutions (e.g. an optimal one meaning combination of the optimal ages to replacement of particular vehicles in a fleet) resulting in very equal average unit fleet exploitation costs and average age of vehicles to replacement; best solution of the problem can match budget limitations on fleet investments while it is a problem in other solutions; best solution of the problem requires lower expenditures in the first years of a replacement plan than other solutions; best solution does not cause capital fleet investment surges in time while other solutions do.
- The FS/FC problem: best (in this case an optimal one meaning appropriate number of vehicles of particular types in a fleet) solution of the problem can be significantly better than its other solutions (e.g. a smooth meaning the same number of vehicles of particular types in a fleet, or a random ones) resulting in a higher utilization of a fleet that is always the most economical; the total size of a fleet in best solution can be higher than in other solutions of the problem but better fitted; best solution of the problem results in a low number of vehicle types in a fleet, that is easier to manage; best solution (fleet composition) is sensitive to any changes in vehicle types in a fleet that decreases the fleet utilization ratio.
- The MoB problem: best (in this case an optimal one) solution of the problem can result in a significant reduction of the total transportation costs; usually a mix of the MAKE and the BUY options constitute the best solution; sometimes, solution based mostly on the MAKE option can also reduce total transportation costs, however such a solution requires significant investments and is very risky; less risky, requiring lower investments seems to be solution based on the MAKE option but putting into a fleet used vehicles only; best solution is relatively sensitive to changes (increases) of the unit operating costs of company's "own" vehicles reducing significantly any savings the MAKE option can result in; when the MAKE option is going to be applied there is always a risk

associated with an ineffective utilization of company's "own" fleet.

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# STRATEGICZNE ZARZĄDZANIE TABOREM SAMOCHODOWYM - PROBLEM WYMIANY

**STRESZCZENIE**. **Wstęp**: Floty pojazdów stanowią podstawowy środek produkcji w transporcie. Prawidłowe zarządzanie nimi jest zatem kluczowe dla wszystkich firm realizujących przewozy. Niniejszy artykuł jest trzecim z serii trzech, jakie autor chce poświęcić tematyce strategicznego zarządzania taborem samochodowym.
**Metody**: W artykule omówiono sposoby kształtowania strategii wymiany flot samochodowych przedsiębiorstw. To znaczy ustalenia, jak długo poszczególne pojazdy we flocie mają być eksploatowane (problem wymiany - FR). Istota problemu leży w minimalizacji kosztów eksploatacji pojazdu / floty poprzez znalezienie równowagi pomiędzy kosztami posiadani a kosztami użytkowania z uwzględnieniem ograniczeń budżetowych. W artykule zaproponowano autorską, matematyczną metodę (model optymalizacyjny) pozwalającą na prowadzenie analiz typu FR.
**Rezultaty**: W artykule zaprezentowano zastosowanie opracowanej metody na rzeczywistym przykładzie problemu decyzyjnego w warunkach polskich oraz uzyskane rezultaty. Rezultaty te pokazały, że istnieje optymalny okres eksploatacji każdego z pojazdów we flocie. Jednak kombinacja tych okresów daje plan wymiany dla całej floty niespełniający ograniczeń budżetowych. Jest jednak możliwe dostosowanie indywidualnych okresów eksploatacji poszczególnych pojazdów we flocie tak, by spełnić ograniczenia budżetowe i jednocześnie zachować optymalność / efektywność ekonomiczną uzyskanego rozwiązania, planu wymiany dla całej floty.
**Wnioski**: Niniejszy artykuł jest ostatnim z serii trzech, które autor poświęcił tematyce strategicznego zarządzania taborem samochodowym z uwzględnieniem takich menedżerskich problemów decyzyjnych, jak: MAKE-or-BUY, liczebność / kompozycja i wymiana floty.

**Słowa kluczowe:** zarządzanie, optymalizacja, flota, pojazd, transport, wymiana.

# STRATEGISCHES FAHRZEUGFLOTTENMANAGEMENT - DAS PROBLEM DES FLOTTENERSATZES

**ZUSAMMENFASSUNG. Einleitung**: Fahrzeugflotten und Fuhrparks stellen die grundlegenden Produktionsmittel im Transportwesen dar. Ein angemessenes Flottenmanagement ist für alle Transportunternehmen und -firmen von großem Belang. Der vorliegende Artikel ist der dritte von dreien, die der Autor dem strategischen Fahrzeugflottenmanagement widmet.
**Methoden**: Dieser Artikel beschreibt Möglichkeiten für Unternehmen, die Erneuerung ihres Fuhrparks zu planen. Dies beinhaltet die Entscheidung darüber, für welche Nutzungsdauer unterschiedliche Fahrzeuge einer Flotte aufrechterhalten werden sollen (the fleet replacement problem - FR).
Der Kern dieses Problems liegt in der Minimierung der Flottenkosten, indem die Fahrzeugbeschaffung und -nutzungskosten unter bestimmten Budgetlimitierungen ausbalanciert werden. Im vorliegenden Artikel wird dabei ein ursprünglich mathematisches Modell (Optimierungsmethode) zur FR-Analyse vorgestellt.
**Ergebnisse**: Es werden die Umsetzung und Ergebnisse einer Anwendung der vorgestellten Optimierungsmethode im Rahmen eines Feldversuchs in Polen präsentiert. Die Lösung zeigt auf, dass eine optimale Nutzungsdauer für bestimmte Fahrzeugtypen innerhalb eines Fuhrparks existiert. Allerdings führt eine Kombination der einzelnen Nutzungsdauer zu einer Überschreitung des Zielbudgets. Es ist allerdings möglich dieses durch Anpassung des Ersatzzeitpunkts einzelner Fahrzeuge aufrechtzuerhalten und gleichzeitig einen ökonomisch optimalen Plan zum Flottenersatz zu ermitteln.
**Fazit**: Dieser Artikel ist der letzte von der dreiteiligen Serie des Autors über verschiedene Belange der strategischen Flottenplanung wie: Eigenfertigung oder Fremdbezug von Fahrzeugflotten, Größe und Zusammensetzung eines Fuhrparks sowie die Nutzungsdauer und der Ersatz von Fahrzeugen.

**Codewörter:** Management, Optimierung, Fahrzeugflotten, Fahrzeuge, Transport, Flottenersatz.

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