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Determining Optimal Time of Use Tariff Considering Demand Response Model

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Abstract- One of the most widely used demand response programs is Time of Use (TOU) pricing. Using proper tariffs for different load periods (peak, off-peak and middle periods) is vitally important for the implementation of TOU program. A suitable pricing should result in both the modification of load curve and customer satisfaction. In this paper, using modeling customer's reaction to tariffs, two new methods for optimal pricing of TOU program are proposed. The objectives of the proposed model are minimizing the customer costs and the maximizing the load factor. In this regard, given the maximum and minimum production costs for different periods, the optimal tariff for each period is determined through solving an optimization problem. The obtained results can clearly show the behavior of customers to the proposed tariffs and its effect on the load curve. The results of this study can help policy makers to consider the more suitable tariffs for TOU program in future.

Keywords- *Demand response model, load factor, time of use, optimal tariff*

I. INTRODUCTION

In recent years demand response (DR) have attracted a lot of attention [1]. Demand response programs are primarily motivated by cost-effectiveness of demand side options compared to supply side options. The implementation of DR programs leads to lowering of the peak, modification of the load curve, and in general, to more efficient operation of the system. Demand response programs are divided into incentive based programs and time based programs by the Federal Energy Regulatory Commission as shown in figure 1 [2].

Demand response programs provide many significant benefits including lowering electricity price and fluctuations in the market, postponing of generation, transmission and distribution development, improving the reliability and some incentive payment for participants in DR programs.

Time of use pricing program is the simplest and most practical time-based demand response programs. In Iran, TOU pricing system is currently being implemented, and the Iranian Ministry of Power expanding the implementation of this kind of demand side management program nationwide through installing smart meters (multi-tariffs).Peak shaving, valley filling, and load curve leveling are the most important objectives behind using TOU pricing [3]-[4].

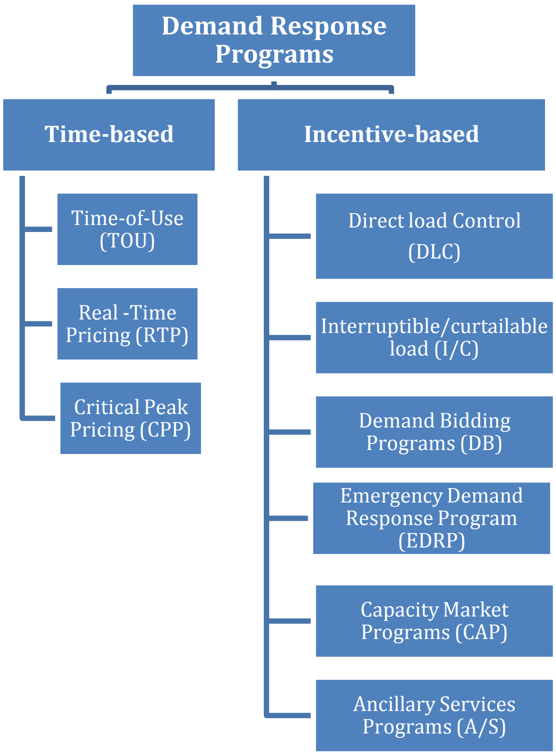

Figure 1. The classification of demand response programs

An important factor in the implementation of TOU pricing program, is using a suitable tariff, which has not received due attention in the literature. The determined tariffs for each period have a direct relationship with the final prices of electricity in each hour of a day. An optimal pricing should modify the load curve and bring about customers' satisfaction.

In the present study, two new methods for optimal pricing for TOU tariff are proposed. The customers' response to the tariffs is modeled using demand response relations. The first proposed model minimizes customer costs and the second maximizes the load factor. Moreover, we consider some essential constraints in our optimization problem to approach real conditions (More explanation is given in Section 3).

The remainder of this paper is organized as follows: in Section 2, some relevant studies are presented in brief. Section

3 presents the mathematical formulation of the proposed framework in detail. The results of the simulation are presented and analyzed in Section 4. Finally, the conclusions and discussions are presented.

II. Literature Review

Many research studies have been done on demand response so far. In what follows, the most important ones are summarized. In [5], demand response was defined and classified. Moreover, the related benefits and costs in using demand response were explained. In this reference, a model for investigating the effect of demand response on prices was developed. Also, some indices are introduced to evaluate DR effects. In [6], the dynamic economic dispatch problem which focuses on the supply side has been intelligently integrated with Time of Use program which focuses on the demand side.

The authors in [7], evaluated the control algorithms for the implementation of demand response in a smart residential building. They developed a model to assess the effect of demand response strategies using various time-of-use electricity tariffs. Reference [8] proposes an economic model for the demand response which can explain the change in consumption pattern of consumers. The objective function of the model is to maximize the customer utility. The results of this paper demonstrate the efficiency of the proposed model in explaining the change in consumption pattern.

In [9], a novel method to design Time-of-Use tariffs for domestic customers has been proposed using the Gaussian Mixture Model clustering technique. To demonstrate the effectiveness of the proposed method, an example study in the UK case is carried out. In [10], a dynamic energy management framework is used to simulate automated residential demand response, based on energy consumption models. The models estimate the residential demand using a novel approach that quantifies consumer energy use behavior. The simulations quantitatively show the impact of demand response programs against different time-varying electricity price.

Reference [11], incorporates real-time pricing demand response program in the short-term decision of a distribution company. The objective is to maximize the expected profit of distribution Company and it is a mixed integer linear programming problem. In [12], the authors studied the effects of two different demand response programs in assumed scenarios. In this study, some criteria were used to make comparisons between different scenarios such as: peak load, the customer's used energy, load factor, and peak to valley distance. Moreover, strategic success index was used to determine the most optimal program.

In [13], the researcher used the historical data of price and electricity consumption in the TOU program to analyze the customer behavior. In [14], a new method for quantification of the load cooperation in the electricity market was proposed. In this method, a model for customers' behavior in changing his demand was developed during the market clearing process. Based on the findings obtained, an increase in the load shift, can reduce the market clearing. Reference [15], investigated the optimization of TOU pricing programs. The simulation done in this study showed that TOU programs could effectively reduce the load peak, thus smoothing the load curve.

III. The Proposed Method

The main objective of the present study is to propose a new method for determining the optimal tariff at different periods of peak, off-peak, and middle loads using the demand response model. In fact, the optimal prices for these three different load periods are determined through simulating the customer's reaction to the tariffs. It is assumed that the system operator knows the minimum and maximum electricity production costs for these three load periods.

A. *Demand Response Model*

In [16], customer benefit function was used to develop an economic model for demand response. The proposed model clearly demonstrates that the consumption of participants changes with the changes in price. This model and other advanced models derived from it have been used in many research studies to analyze demand response programs [12] and [17]-[19]. In the present study, this DR model is used as follow:

$$d_e(h) = \gamma \times d_0\{1 + \sum_{k=1}^{24} E(h,k) \times \frac{[\rho(k) - \rho_0(k)]}{\rho_0(k)}\} h = 1,2,\ldots,24 \quad (1)$$

Where:

γ:The level of participation in TOU program in percentage

d_e (h):The elastic demand at hour h after implementation TOU program (MWh)

d0(h): The initial demand at hour h before implementation TOU program (MWh)

E(h,k):Price elasticity between hour handhourk.

ρ(k):The electricity tariff for hourk in (Rial/MWh)

ρ0(k): The initial price at k hour(Rial/MWh)

In general, the infra-structures for the implementation of TOU pricing programs are not available for all customers. Moreover, some customers are not willing to participate in this program. Therefore, in the present study parameter γ represents the participation percentage of the customers in the TOU program. The simulations were carried out for a participation percentage between %5 to %35. The total electricity demand d(h), after the implementation of TOU pricing program can be calculated through the following equation:

$$d(h) = (1 - \gamma) \times d_0(h) + d_e(h) \qquad h = 1,2,\ldots,24 \quad (2)$$

B. *The Proposed Objective Function*

Method 1: Minimizing Customer Costs

From the perspective of the customer, the desirable pricing is one which imposes minimal cost on him. The electricity cost for the customer is sum of multiplying his electricity consumption in each hour by the electricity price rate for that hour. In the first proposed objective function for determining electricity tariffs, the customer costs are minimized through equation 3. By substituting d_e (h) from equation (1) and eliminating the first term which is constant, the objective function to minimize customer costs will be equal to second line in equation 3.

$$\begin{aligned} Min\ Cost &= (1-\gamma)\sum_{h=1}^{24}\rho_0(h)d_0(h) + \sum_{h=1}^{24}\rho(h)d_e(h) \\ &\equiv Min\sum_{h=1}^{24}\left(\gamma.\rho(h).d_0(h).\sum_{k=1}^{24}\left\{E(h,k).\frac{[\rho(k)-\rho_0(k)]}{\rho_0(k)}\right\}\right) \end{aligned} \quad (3)$$

Method 2: Maximizing Load Factor

- For a system operator, a pricing program which smoother's the load curve is more desirable. A frequently used parameter to evaluate the levelness of the load curve is load factor. The load factor calculated through dividing the average daily load by the load peak. Thus, in the second method proposed here, the equation (4) is used to calculate the maximum load factor

$$Max\ \ LF = \frac{\frac{\sum_{h=1}^{24} d(h)}{24}}{\underset{h}{Max}\{d(h)\}} \quad (4)$$

$$= Max\left(\frac{\frac{1}{24}.\left(\sum_{h=1}^{24}\begin{matrix}(1-\gamma).d_0(h)+ \\ \gamma.d_0(h).\sum_{k=1}^{24}E(h,k).\frac{[\rho(k)-\rho_0(k)]}{\rho_0(k)}\end{matrix}\right)}{\underset{h}{Max}\left\{\begin{matrix}(1-\gamma).d_0(h)+ \\ \gamma.d_0(h).\sum_{k=1}^{24}E(h,k).\frac{[\rho(k)-\rho_0(k)]}{\rho_0(k)}\end{matrix}\right\}}\right)$$

- The variable to be found in the above optimization equations is the tariff set for the TOU pricing program at the time of use (p(k)).

Constraints of both objective functions

For both of the objective functions, some limitations are considered, all of which are presented as equations below to avoid repetition. In fact, each of these objective functions along with their limitations form an optimization equation which need to be solved. These constraints are explained below.

$$d_e(h) \ge 0 \quad h = 1,2,...,24 \quad (5)$$

$$\underset{h}{Max}\{d(h)\} \le \underset{h}{Max}\{d_0(h)\} \quad (6)$$

$$|d(h) - d_0(h)| \le 0.3 \times d_0(h) \quad h = 1,2,...,24 \quad (7)$$

$$\sum_{h=1}^{24} d(h) \ge \sum_{h=1}^{24} d_0(h) \quad (8)$$

The magnitudes of d(h) and d_e(h) can be obtained using equations 1 and 2.Mathematically, d_e (h)can have a negative value. So, it seems necessary to add a limitation such as (5) in the optimization process. This means that, the customers who are sensitive to prices, even at their highest level of responsiveness, cannot reduce their electricity consumption less than zero. According to equation 6, the pricing should be performed in a way that daily peak does not exceed its peak before the implementation of TOU program. Based on equation 7, it is assumed that the reduction in the customers' consumption after the implementation of the TOU program is not more than %30 of their consumption per hour before the implementation of the program. This is due to the fact that a large increase seems quite illogical and improbable. Based on equation 8, the daily energy consumption of the customers after the implementation of the pricing system must not be less than that before the program, since the purpose of the implementation of TOU pricing program is to shift demand from peak hours to off-peak hours rather than to reduce energy consumption. The prices in the three periods are limited to their lower band and the upper band as presented in Equations (9)-(11):

$$\rho_o^{Min} \le \rho(h) \le \rho_o^{Max} \quad \forall h \in \text{offpeak period} \quad (9)$$

$$\rho_m^{Min} \le \rho(h) \le \rho_m^{Max} \quad \forall h \in \text{middle period} \quad (10)$$

$$\rho_p^{Min} \le \rho(h) \le \rho_p^{Max} \quad \forall h \in \text{peak period} \quad (11)$$

The equality constraints of the optimization problem are as equations (12)-(14). These equations express that tariff ρ(h) in each period type (off-peak, middle and peak) is the same.

$$\rho(h) = \rho(k) \quad \forall h,k \in \text{offpeak period} \quad (12)$$

$$\rho(h) = \rho(k) \quad \forall h,k \in \text{middle period} \quad (13)$$

$$\rho(h) = \rho(k) \quad \forall h,k \in \text{peak period} \quad (14)$$

The objective of optimization in the second method is only to enhance the load factor. The optimization process does not have any effect on controlling customer costs. So, in some cases there may be huge increases in customer costs. Therefore, in the second method, a limitation as (9) is added to the process:

$$Cost \le 1.02 \times Cost_0 \quad (Cost_0 = \sum_{h=1}^{24}\rho_0(h) \times d_0(h)) \quad (15)$$

The lower band and the upper band for the prices in the three periods are presented in table 1 below:

TABLE I. THE RANGE OF PRICES IN DIFFERENT PERIODS (RIALS/MWH)

	Off-peak	Middle	Peak
lower band	40000	90000	150000
upper band	70000	130000	300000

Considering the objective functions and the relevant limitations, both of the optimization problems are non-linear. In this study, the simulations of these two optimization problems were performed using the optimization tools available on Matlab software.

IV. SIMULATION RESULTS

- To examine the efficiency of the proposed methods, the load curve data of the Iranian electricity grid in peak day is utilized [20]. This daily load curve is illustrated in figure 2.

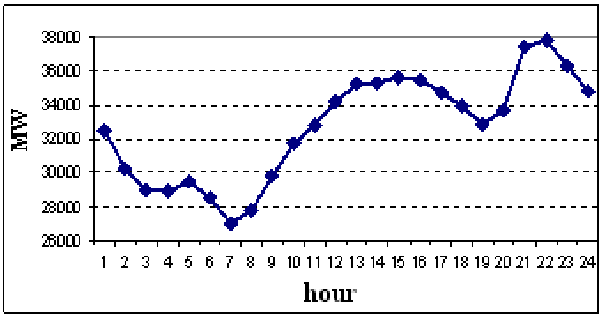

Figure 2. The daily load curve for peak day of Iran

- As shown in Figure 2, the period between 1to 8 is considered as off-peak period, the one between 9 to 20 as middle period, and the one between 21 to 24 as peak period. In the simulation performed, it is assumed that the values of elasticities presented are as Table 2.

TABLE II. SELF AND CROSS ELASTICITY

	Off-peak	Middle	Peak
Off-peak	- 0.1	0.01	0.012
Middle	0.01	- 0.1	0.016
Peak	0.012	0.016	- 0.1

- Initially, as an illustration, the changes in the daily load curve due to the implementation of the demand response program are presented. The results obtained for %10 and %20 customer participation in the TOU pricing program are shown in figure 3 and 4, respectively. The primary peak was 37770 MW and the primary load factor was %86.6.

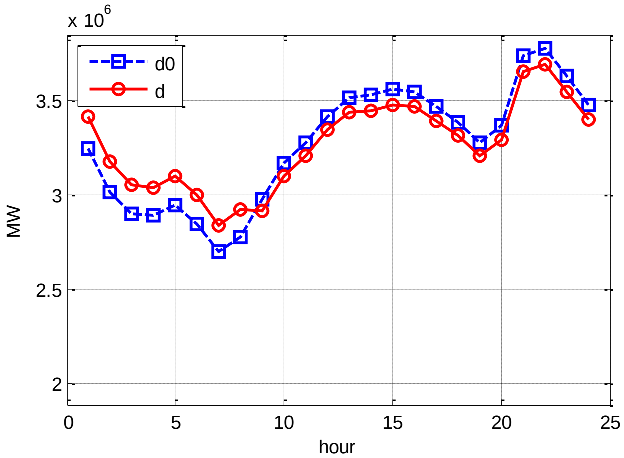

Figure 3. Load curve before and after the implementation of TOU program for γ = %10

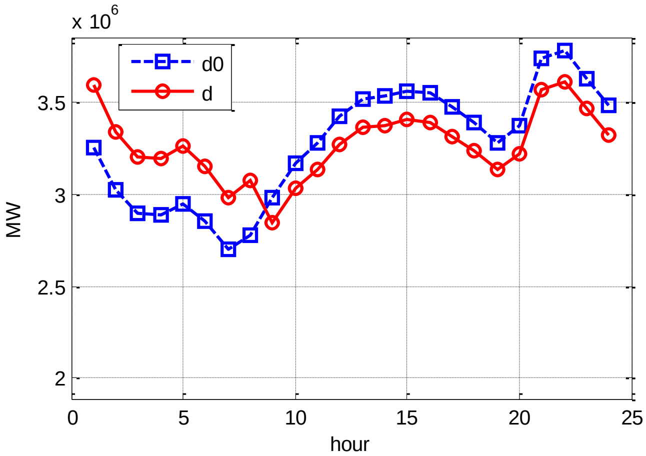

Figure 4. Load curve before and after the implementation of TOU program for γ=%20

- Based on the results obtained, if %10 of the customers participates in the program, the load peak decreases by %2.2 and reaches 36931 MW. In addition, the load factor reach to %88.6
- As shown in figure 4, if there is a customer participation of% 20, the load peak experiences a reduction of %4.5 and reaches 36072 megawatts and the load factor with a considerable increase reach to % 90.7.
- The simulations for different values of γ varying from %0 to %35 with steps of %5 are performed. The results obtained when γ=0 show the system condition before the implementation of TOU pricing program (base case). The details of results for all simulations are provided in Tables A1 and A2 in the appendix. In all curves and tables, method one means the minimization of customer costs while method two refers to maximization of load factor.
- In table 3, the optimal prices determined based on the simulations for both methods, for different participation levels, are presented.

TABLE III. THE OPTIMAL PRICING TARIFFS (103RIALS/MWH)

	Off-peak tariff		Middle tariff		Peak tariff	
γ(%)	Method 1	Method 2	Method 1	Method 2	Method 1	Method 2
0	40	57.3	117.08	104.15	150	296.14
5	40	50.4	117.08	107.08	150	282.70
10	40	40	117.08	111.87	150	254.72
15	40	40	117.08	112.84	150	235.16
20	40	40	117.08	113.39	150	224.25
25	40	41.3	117.08	113.45	150	214.29
30	43.58	48.9	90	112.57	150	182.15

- As can be seen, in the method 1, the electricity price for peak hours is constant while in the method 2, it decreases as the customer participation increases. As the peak tariff decreases, the imposed costs on the customer are expected to fall. The following curves illustrate this fact. Figure 5 shows the percentage of change in the electricity cost for the participants in the TOU programs against the imposed costs before the implementation of the program.

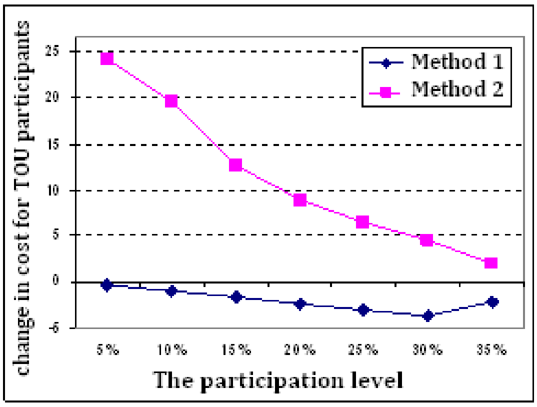

Figure 5. The change in electricity cost for DR participants in terms of γ

A careful look at figure 5 reveals that the first method always results in a reduction in the electricity costs for the participants. This result is logically expected considering the objective function of the first method that is, minimizing customer costs. The reason why the customer costs are high in the second method, especially for low customer participations, is that few participants play a role in increasing the load factor of the electricity network. However, when the customer participation improves, the customer costs decreases significantly. With the same token, in the first method, when the rate of customer participation in the TOU pricing program approaches %35, there is a meaningful change in the trend of the customer cost graph in which there is a significant increase in the consumed energy (Table A2 in the appendix).

Figure 6 presents the changes in customer costs for all participants for different values of γ. All the cost rates are normalized with the base cost so that comparisons can made easily. As shown in figure 6, for all values of γ, the first method imposes a lower total cost for the customers.

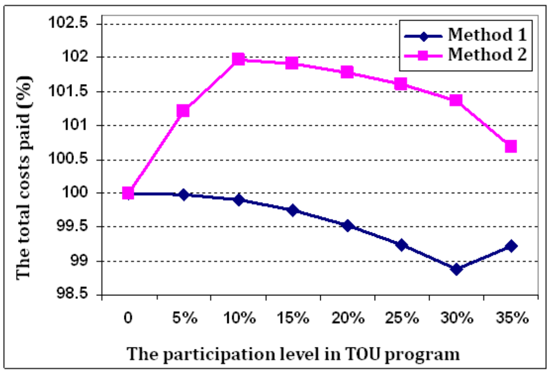

Figure 6. The change in total costs for customers in terms of γ parameter

Moreover, compared to changes shown in figure 5, those in figure 6 fluctuate in a more limited range. For example, for a customer participation of 10 percent, in the second method, the total costs increase just by %2. However, the same customer participation rate in TOU program is associated with an increase of %20 percent in customer costs (Figure 5). The same holds true for the results obtained for the first method.

The changes in system load factor for changes in customer participation in TOU program are presented in figure 7. As shown, for participation rates lower than %20, the pricing using the second method results in better load factors. However for γ> 0.2, the first method of pricing is more suitable. Based on the results obtained, an increase in the customer participation rate does not always lead to better load factors. The non-linear nature of the load factor equation is the most important factor accounting for the unpredictability of its behavior. At best, the load factor can increase up to %92.7.

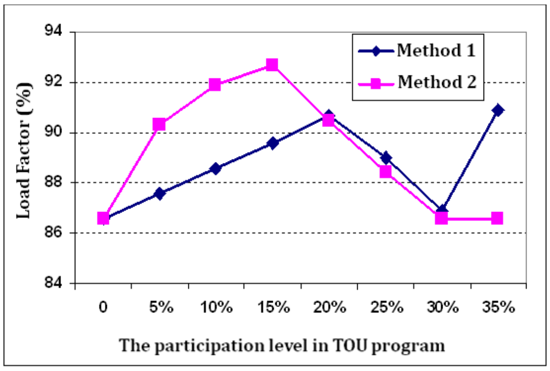

Figure 7. The changes in load factor in terms of γ parameter

V. CONCLUSION

A suitable pricing tariff for different hours is one of the most important issues in the implementation of a TOU program. In this study, two new methods for optimization of prices were proposed for a TOU pricing program. The efficiency of these two methods was studied through developing a model for the customers' behavior within a demand response framework. As expected, the first method was considered more suitable by the customers due to the significant decrease in the electricity costs. This seems quite logical in that the cost imposed on the customers is negatively correlated with the customer participation level in the program. Based on the results obtained in this study, when the customer participation was below %20, the second method produced a higher load factor compared to the first method. However, as the customer participation level increased, the difference between the two methods faded away, that is, both methods produced similar results. Moreover, the results revealed that an increase in the customer participation level was not necessarily accompanied with an increase in load factor, a findings which can be accounted for by the non-linearity of the load factor equation. The participants in the TOU program had a reduction of up to 30% in their electricity costs. However, when all the customers were taken into account, this decrease was about 3%. This is owing to the fact that the number of participants in the program was rather low. The proposed model in this study and its results can be used by policy makers to select the most suitable pricing tariff, so that there can be a balance between the objectives set by the system operator and the customer's satisfaction.

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APPENDIX

TABLE A1. SIMULATION RESULTS FOR ALL COSTOMERS

	Load factor (%)		**Total cost (10^9Rial)**		**Consumed energy (MWh)**	
γ (%)	**Method 1**	**Method 2**	**Method 1**	**Method 2**	**Method 1**	**Method 2**
0	86.6	86.6	78.48	78.49	784860	784860
5	87.6	90.3	78.47	79.44	784860	784860
10	88.6	91.9	78.40	80.03	784860	784860
15	89.6	92.7	78.28	79.98	784860	784860
20	90.7	90.5	78.11	79.89	784860	784860
25	89	88.4	77.89	79.76	784860	784860
30	86.9	86.6	77.61	79.56	784860	784860
35	90.9	86.6	77.88	79.02	823763	784860

TABLE A2. SIMULATION RESULTS FOR PARTICIPATING CUSTOMERS IN TOU PROGRAM

	Total cost (10^9Rial)		**Consumed energy (MWh)**		**Cost/Energy (10^3Rial/MWh)**	
γ (%)	**Method 1**	**Method 2**	**Method 1**	**Method 2**	**Method 1**	**Method 2**
5	3.91	4.88	39243	39243	99.62	124.25
10	7.77	9.39	78487	78487	98.95	119.63
15	11.6	13.3	117730	117730	98.28	112.69
20	15.3	17.1	156974	156974	97.61	108.94
25	19.0	20.9	196217	196217	96.94	106.46
30	22.7	24.6	235461	235461	96.27	104.57
35	26.9	28.0	313713	274705	85.62	101.94