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Optimizing a sequence of investments in a congested road network subject to strict Pareto optimality

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Abstract: Any improvement in an urban road network will cause some drivers to change routes and so impose increased congestion on others who have not changed. The shifts cause such complex interactions that an optimum sequence of investments can only be achieved by joint optimization, not by ranking projects that have been evaluated singly. Investments in a hypothetical congested network optimized by genetic algorithm (GA) give benefits to almost all drivers but there are disbenefits on some routes. The objective of this study has been to determine whether investments can be made strictly Pareto optimal which, in this context, means that nobody suffers as a result of a series of road projects. This is done with an added goal of eliminating disbenefits to improve equity: no traveller on any route to suffer any deterioration in route travel time in any of the years under consideration. A penalty is applied with a weight sufficient to drive route disbenefits to zero.

The GA seeks an optimal ordering of the 40 potential projects (one for each road link). The annual investment budgets are allocated to the projects in the GA order, with incomplete projects spilling into the following year. Each potential solution requires full assignments of traffic in each of eleven successive years. The network traffic assignment model is summarised as follows:

- the network has nine centres connected by 326 reasonable routes (over 40 road links);
- the number of alternative routes between an origin-destination pair varies from one to 70;
- the stochastic user equilibrium (SUE) traffic assignment method is used;
- traffic being assigned to routes by a logit function and summed over links;
- travel times are calculated using a BPR congestion delay function;
- route assignments are equilibrated by the method of successive averages;
- with traffic being reassigned in each of fourteen iterations and travel times recalculated.

The traffic congestion on links results in the initial logit assignments being substantially modified in the successive iterations, leading to an equilibrium for the particular GA generation. The magnitude of these calculations results in the GA taking considerable computing time to find an approximate optimum.

In the optimized schedule, twenty projects are at least partly completed during the ten investment years. The results from this hypothetical model suggest that a timetable of road investments may be one case where strict Pareto optimality can be achieved at no great cost. A ‘no losers’ outcome may be feasible with only a modest sacrifice of net benefits.

However a number of congested links will still take longer to traverse than previously – irritating drivers. Therefore reducing link delays in the otherwise optimized sequence of investments (subject to zero route time delays) has also been tested.

Whether road authorities do adjust investment sequences in order to reduce adverse impacts along the lines modelled is an empirical question for the administrative and political world. A similar question arises with respect to congestion effects on links. Even if trip times are not adversely affected by the traffic diversions resulting from road improvements, it has been shown that traffic on some links will be slower. Some authorities prefer plans which minimize such link delays, even at an appreciable cost in benefits.

These are real issues because beneficial investments are often endangered by a few potential losers campaigning against the proposal whereas the many potential winners are silent. If there are no losers then the clear benefit is likely to carry the day politically. The point of this study has been to establish that such an outcome may be possible with a moderate sacrifice of general benefits.

***Keywords**: Optimized road investments, genetic algorithm, strict Pareto optimality*

1. INTRODUCTION

When an urban road link is improved some drivers change routes and impose more congestion on others who have not changed. The latter will be losers from the upgrading, even though there will be a majority of winners and consequently a net benefit. A familiar example is a project which diverts traffic to a freeway or arterial, with the result that existing users suffer a deterioration in service level. The question of disbenefit from road projects has previously been discussed in terms of environmental harm (Lakshmanan *et al.*, 2001) and the issue of congestion disbenefits to some users of the network has attracted less attention.

1.1 Strict Pareto Optimality

The objective of this study has been to determine whether road investments can be strictly Pareto optimal: '… a resource allocation which cannot be changed to make someone better off without also making someone worse off' (Gravelle and Rees, 1981). Strict Pareto optimality here means at least someone benefits and nobody suffers as a result of a series of road investments. Within the strict Pareto criterion, the objective is to generate maximum benefits. However 'Pareto optimality' may be given a much broader meaning – effectively the compensation principle, which is not the same as strict Pareto optimality. For example, Gabriel *et al.* (2006) say: 'Since multiple conflicting objectives are considered, the goal is to find elements of or the entire Pareto optimal set (also known as efficient or nondominated set) …A Pareto optimal solution is one in which improvement of one objective must come at the expense of one of the other objectives.' Yang and Bell (1998) speak of the 'non-dominated or Pareto optimal alternatives' in the same sense.

Flores (2002) makes recourse to the compensation principle even more explicit: '…it is important to recognize that most benefit-cost analysis focuses (a) on discrete changes and (b) attempts to establish whether or not a project is good. The applied goodness criterion is whether the change, supported by a cost allocation, could lead to a Pareto improvement, i.e. the Kaldor–Hicks compensation test …' Lakshmanan et al., (2001), speaking of road regulation, recognise the importance of distinguishing between potential and actual compensation: 'In theory, it is of course by definition always possible to construct a lump-sum redistribution of means, including the tax revenues, such that everyone is better off after optimal regulation… it is evident that difficulties related to, for instance, preference revelation and heterogeneity of road users may of course prevent actual tax redistribution schemes, aiming to turn potential Pareto improvements into strict Pareto improvements, from being practically implementable.'

In an area close to the topic of this paper, Shefer and Aviram (2005) give a particular slant: 'If no externalities exist, (notwithstanding congestion which generates negative externalities), then the transportation system's new equilibrium (steady state) will bring the average trip's time to a minimum. This new condition describes Wardrop's second principle of "system equilibrium" (or system optimal). It corresponds to "Pareto Optimum" such that no traveler can change route without increasing the total time traveled by all users, i.e., the average travel time will increase.'

1.2 Purpose of the Paper

A hypothetical model of a congested road network (Figure 1) is used to examine the incidence of motorists suffering from otherwise beneficial investments and to show that it may be possible for a sequence of road investments to be strictly Pareto optimal, without losing too many benefits – in a political sense. Strict Pareto optimality means that no traveller will suffer slower route travel time as a result of a sequence of road investments.

However it is likely that even with no deterioration in route travel time there will still be a number of congested links taking longer to traverse than previously. This may irritate many drivers. Therefore another option has also been tested: optimizing the sequence of road investments subject not only to the route time constraint but also to the restriction that link delays, summed over travellers, be reduced substantially.

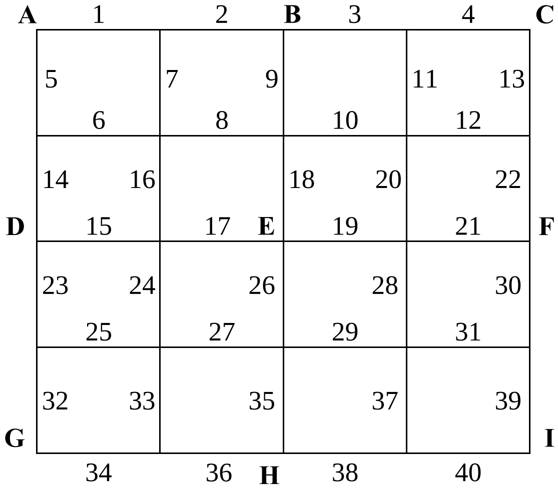

Figure 1. Road Network Connecting Nine Centres (A to I) - Link Numbers Shown.

2. THE MODEL

The model explores the possibility of strictly Pareto optimal investments and the differential impacts on users – the relative equity – of an optimized schedule of road upgrading investments. The stochastic user equilibrium (SUE) method is used, so that the traffic is distributed by a logit function and summed over links before the route assignments are equilibrated, subject to congestion, by the method of successive averages (Ortuzar and Willumsen, 2001). Deterministic user equilibrium (DUE) is the traditional and easy to apply assignment method but SUE is preferred here on the grounds that it provides for distributed responses to relative route times and so gives an appropriate representation of human heterogeneity, flexibility and variability. Kidokoro (2006) has considered the benefit implications of alternative models and expresses concern that DUE misrepresents heterogeneous road users.

Table 1. Hourly Traffic between Origin and Destination (OD) Centres

OD	Traffic	OD	Traffic	OD	Traffic	OD	Traffic
AB	1355	BD	421	CG	262	EG	507
AC	754	BE	789	CH	291	EH	947
AD	2549	BF	674	CI	640	EI	570
AE	749	BG	199	DE	1301	FG	546
AF	778	BH	248	DF	835	FH	914
AG	734	BI	238	DG	1750	FI	3300
AH	423	CD	362	DH	623	GH	1550
AI	439	CE	530	DI	410	GI	583
BC	1132	CF	2929	EF	1946	HI	1442

The nine centres are connected by 326 reasonable routes (via 40 road links) which involve no backtracking; of these, 18 have no alternatives. In other cases the number of alternative routes between an origin-destination pair varies from six to 70. The traffic congestion on links results in the initial logit assignments being substantially modified in the fourteen successive iterations leading to an approximate equilibrium.

The traffic between origin-destination pairs is shown in Table 1; traffic volumes have been specified so that they are approximately inversely related to distance between centres, as is normally the case. It is assumed that there is no change in traffic between centres over the whole period of the evaluation. This is different from the common pattern of traffic growth keeping up with road investment and even running ahead of it (Cervero and Hansen, 2002). The constant traffic assumption makes it relatively easy to explore and isolate a strict Pareto effect; traffic growth would complicate the analysis but in that case the improved service resulting from road projects with constant traffic could be matched by increasing the investment budget.

For simplicity, one potential upgrading project has been specified for each of the 40 links in the network (costs and changes in travel times shown in the Appendix). A conventional BPR congestion delay function has been used, with parameter values based on Sapkota (2004). If tt_0 is free speed travel time, v is hourly traffic flow and Q is hourly traffic capacity then travel time,

$$tt = tt_0\left\{1+0.6\left(\frac{v}{Q}\right)^{3.1}\right\} \tag{1}$$

The particular form of the logit distribution function used in the SUE model is based on the ratio of travel time to the minimum travel time (Taplin and Qiu, 1997). If C_{rs}^{k} is the time cost of traversing route k between origin r and destination s then the probability of choosing route k is expressed as:

$$p_{rs}^{k} = \frac{e^{\theta C_{rs}^{k}/C_{rs}^{\min}}}{\sum\limits_{k\in K_{rs}} e^{\theta C_{rs}^{k}/C_{rs}^{\min}}} \tag{2}$$

Benefits are calculated by the conventional rule-of-half (Gwilliam and Mackie, 1975). If T_{i0} is traffic on link i in the base year, T_{in} is link i traffic in year n, C_{i0} is time cost on link i in the base year and C_{in} is time cost on link i in year n then

$$\text{Benefit on link } i \text{ in year } n = 0.5(T_{i0} + T_{in})(C_{i0} - C_{in}). \tag{3}$$

The benefits, which begin in Year 2, are summed over all links for each year and these annual totals are discounted at seven per cent. The discounted sum of benefits and costs, the net present value, is the objective used in the genetic algorithm optimization. If investment were to cause a change in the network configuration then the benefit calculation would involve a more complete summation over traffic assigned to base and new networks, each multiplied by base and new costs (Qiu, 2000, Ch.5).

Construction of a particular project may be spread over two or three years, the costs being discounted accordingly. In these cases pro rata benefits accrue in each year following partial project completion. This is appropriate for projects to upgrade existing links, unlike new links or bridges where benefits would be deferred until final completion.

2.1 Impacts on Travellers

Traffic switching between the multiple reasonable routes has a major impact on both the benefits and disbenefits. The link impacts on travellers can be summarised as follows:

a) The existing travellers on the upgraded link experience some improvement in travel time but it is limited by the traffic diverted to it.
b) The existing travellers on the unimproved links forming elements of the routes now used by diverted traffic suffer a disbenefit.
c) The existing travellers on the links from which traffic has been diverted experience a benefit.
d) The diverted travellers experience benefits ranging from very small (just enough to induce a change) to fairly large.

These four effects are conceptually important even though the analyst simply assesses the aggregates from the traffic assignments before and after the link upgrading. In fact, it is virtually impossible to find a sequence of upgrading investments in a congested network which produce no link disbenefits. However the traveller is assumed to be concerned mainly with total trip time and so be satisfied if the total is at least as good as before. Thus it seems appropriate to focus primarily on a strict Pareto optimality constraint which requires that no trip in any year of the investment sequence shall take longer than before the investments begin. Nevertheless some drivers may be seriously annoyed by congestion on a link making it slower than previously; they might possibly see it as more equitable for the road construction authority to maximize benefits subject to the traffic weighted sum of link disbenefits being kept much smaller than in the case of strict Pareto optimality based on routes.

3. GENETIC ALGORITHM OPTIMIZATION

Genetic algorithm is now a well known way of finding an optimum or nearly optimum solution to a complex problem. Mathematical programming does not cope well with the complexity due to route switching, and ranking by separate cost-benefit ratios gives poor outcomes in the crucial early years of an investment sequence (Taplin *et al.*, 2005, Ch. 2). From the 40 potential projects, an investment timetable was determined for ten consecutive years, subject to an annual budget constraint. Each genetic algorithm search (using the Evolver add-in to Excel) was continued for about two hours to allow for the occasional improvement that can occur after a long period of no change. Because there is no mathematical guarantee of optimality, a number of runs were done for each problem specification.

4. SOLUTIONS COMPARED

The best unconstrained solution, measured as the value of travel time improvement less project costs, has a net present value of $23.34 million but some drivers suffer route time disbenefits to a discounted value of $13,046, mainly occurring in Year 2 – the first year of benefits – when the impacts of only a few projects are felt. In three cases, AC, BC and CF, the base traffic cannot escape the effect of additional traffic because there is only one route. Figure 2 gives an approximate indication of the sizes of the investments and their sequence plotted on the network diagram. The time profile of project expenditures is shown in Table 2(a).

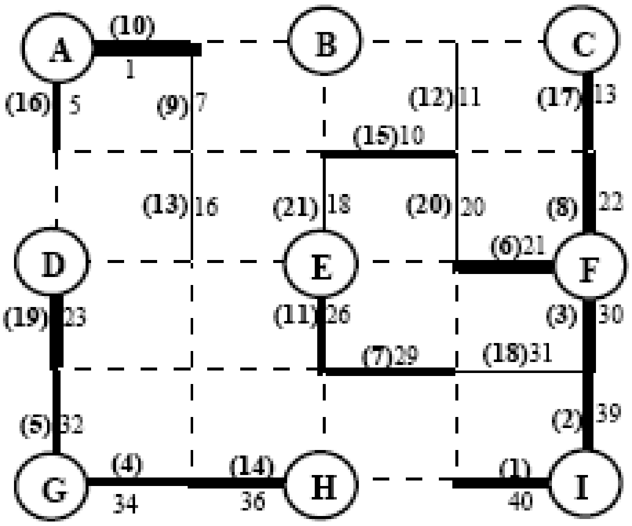

Figure 2. Unconstrained Optimum (construction sequence numbers in brackets – line width indicates approx. expenditure).

The procedure to obtain a strictly Pareto constrained solution was to re-run the GA search with a penalty imposed on the discounted NPV equal to the sum of undiscounted negatives in routes. This was sufficient to drive the sum of penalties to zero. Thus the Pareto constrained solution in Table 2(b) results in no route suffering any increase in travel time. This is a considerable planning feat and took substantial computer search time. It means that travellers on routes to which traffic has been diverted as a result of upgradings anywhere in the network suffer no deterioration in travel time in any of the years modelled. The net present value has been reduced to $19.00 million. In the constrained case there are still discounted link disbenefits of $176,000, a little less than the $185,000 in the unconstrained result. However drivers who suffer slower times on the affected links in the constrained (Pareto) case have them offset by faster times on other links on their routes.

Table 2. Time Profile of Project Expenditure, $M (annual budget $12M) – [project number = link number]

(a) Unconstrained optimum (NPV = $23.34 million)

Project:	**40**	**39**	**30**	**34**	**32**	**21**	**29**	**22**	**7**	**1**	**26**	**11**	**16**	**36**	**10**	**5**	**13**	**31**	**23**	**20**	**18**
Year 1	5.4	6.6																			
Year 2		0.4	11.6																		
Year 3			1.4	3.0	2.2	5.4															
Year 4						10.9	1.1														
Year 5							1.8	10.2													
Year 6								4.2	1.3	6.6											
Year 7										4.6	3.3	1.2	1.2	1.6							
Year 8														2.8	2.3	6.9					
Year 9																0.7	8.0	1.4	1.8		
Year 10																			10.1	1.2	0.7
Total	5.4	7.0	13.0	3.0	2.2	16.2	3.0	14.3	1.3	11.2	3.3	1.2	1.2	4.4	2.3	7.6	8.0	1.4	11.9	1.2	0.7

(b) Constrained Pareto optimum: no route disbenefits (NPV = $19.00 million)

Project:	**37**	**29**	**32**	**34**	**39**	**40**	**16**	**30**	**5**	**21**	**22**	**1**	**36**	**7**	**28**	**12**	**23**	**13**	**20**	**31**
Year 1	3.7	3.0	2.2	3.0	0.2															
Year 2					6.9	5.1														
Year 3						0.2	1.2	10.5												
Year 4								2.5	7.6	1.9										
Year 5										12.0										
Year 6										2.4	9.6									
Year 7											4.7	7.3								
Year 8												3.9	4.4	1.3	1.4	1.1				
Year 9																1.5	10.5			
Year 10																	1.4	8.0	1.2	1.3
Total	3.7	3.0	2.2	3.0	7.0	5.4	1.2	13.0	7.6	16.2	14.3	11.2	4.4	1.3	1.4	2.6	11.9	8.0	1.2	1.3

A noticeable effect of the Pareto constraint on routes (Table 2(b)) is that four small projects are implemented in Year 1 and a small part of one of the large projects, in contrast to two large projects in Year 1 in the unconstrained optimum. Three of the projects in the unconstrained optimum are omitted from the constrained optimum and are replaced by three others.

Figure 3 gives a spatial view of the changes resulting from the route constraint. As shown in Table 2, most of the projects are the same but the implementation sequence differs. The unconstrained Year 1 investment in two large projects (40 and 39) generated maximum benefits but imposed disbenefits in Year 2 on 25 routes between seven centres. Deferring them to Year 2 (Table 2(b)) and implementing smaller projects first is sufficient to moderate the traffic diversions causing the delays on those 25 routes. Rescheduling and replacement has also eliminated the smaller route disbenefits in Years 3 to 8.

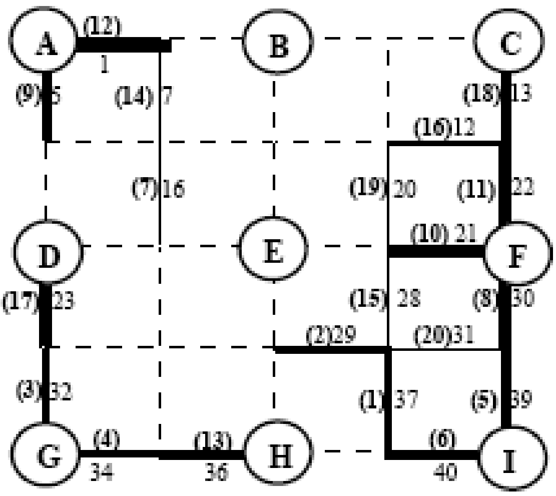

Figure 3. Optimum Constrained to No Route Disbenefits – (line width indicates approximate expenditure).

4.1 Delays on Links

The third problem was to add the goal of substantially reducing link delays. It is not feasible to eliminate all of them but they can be made much less than in the solution constrained only to no route disbenefits. The procedure was to impose a heavy computing penalty on the discounted value of the link delays; the penalty on route disbenefits was also maintained to ensure that there would be none of these. The penalty on link disbenefits was arbitrarily chosen after a little experimentation to allow a solution with a positive net present value (NPV) of the whole investment schedule. The remaining penalty in the computation result was removed from the NPV.

Table 3. Time Profile of Project Expenditure, $M, Constrained Pareto optimum with added constraint: Reduced Link Delays (NPV = $10.38 million)

Project:	**10**	**20**	**40**	**8**	**37**	**13**	**30**	**18**	**22**	**34**	**32**	**28**	**15**	**39**	**21**	**5**	**7**	**12**	**26**	**23**
Year 1	2.3	1.2	5.4	1.7	1.3															
Year 2					2.3	8.0	1.7													
Year 3							11.4	0.6												
Year 4								4.1	7.9											
Year 5									6.5	3.0	2.2	0.3								
Year 6												1.0	9.2	1.8						
Year 7														5.3	6.7					
Year 8															9.5	2.5				
Year 9																5.1	1.3	2.6	3.0	
Year 10																			0.3	11.7
Total	2.3	1.2	5.4	1.7	3.7	8.0	13.0	4.8	14.3	3.0	2.2	1.4	9.2	7.0	16.2	7.6	1.3	2.6	3.3	11.7

When link disbenefits are constrained they are reduced to $41,700 as compared to the $175,700 and $184,600 in the route constrained and unconstrained results (Table 2). The loss of total benefits in this link constrained case is $12.96 million compared with $4.34 million in the route constrained case. Table 3 shows that six of the projects in the unconstrained optimum schedule are omitted in the link constrained case and five are added. There is a very considerable reordering of projects.

5. CONCLUSION AND DISCUSSION

The analysis reported in this paper has demonstrated that minimising disbenefits in order to improve equity can run alongside formal cost-benefit evaluation. The evidence of the hypothetical model suggests that a timetable of road investments may be one of the few cases where strict Pareto optimality, meaning that everyone benefits and nobody suffers, can be achieved at no great cost. We have interpreted the strict Pareto condition in the road context as the requirement that trip (route) times should be at least as good as before the sequence of upgrading investments is undertaken. An added limitation, that there should be little deterioration in link travel times, has also been considered. Such a condition might appear equitable if drivers are particularly concerned by congestion making any link slower to traverse.

The important question is how much total benefit is sacrificed in order to achieve equity and strict Pareto optimality? In all solutions the annual budget constraint makes the present value of investments the same, at $84.28 million. The sacrifice to achieve strict Pareto optimality with respect to route travel times is 4.03% of total feasible benefits. Clearly this is the result for a particular case and another would give a different percentage loss of benefits. Nevertheless the model network provides a large enough basis for the analysis to indicate that strict Pareto optimality may be feasible in most circumstances.

In another calculation, based on Table 2, the disbenefits that have been eliminated in the strictly Pareto optimum case (with respect to route times) are found to be only 0.3% of the benefits that have been lost in order to achieve this result. The more extreme case with reduced link disbenefits, as well as zero route disbenefits, results in 12.0% of total benefits being lost and a link disbenefit reduction which is 1.1% of the lost benefits (based on Table 2).

In the broadest sense, these results have a political meaning. They raise the following question: given that it is possible to achieve strict Pareto optimality, how much aggregate benefit is the community prepared to sacrifice in order to achieve this result? The findings of this paper based on simulated results can only be indicative but one can ask whether sacrificing four percent of the feasible benefits is too much to pay? This is not like the trick of notionally compensating losers without any loss of benefits whatever. Such compensating payments are not made in reality whereas the ‘no losers’ outcome would be a reality in the strictly Pareto constrained case.

Whether road authorities sometimes adjust investment sequences in order to reduce adverse impacts along the lines examined here is an empirical question for the real administrative and political world. A similar question arises with respect to congestion effects on links. Even if trip times are not adversely affected by the traffic diversions resulting from road improvements, it has been shown that traffic on some links will be slower. It is just possible that authorities may prefer forward plans which minimise such link delays even at a high cost in total benefits.

These questions are real because potential investments that would result in many winners but a few losers are often endangered because the potential losers campaign against the proposal whereas the potential winners are silent. If there are no losers then the clear benefit is likely to carry the day politically. The point of this study has been to establish that such an outcome is possible with a moderate sacrifice of general benefits.

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Appendix: Projects (One per Link) and Link Travel Times in Minutes

Link	Project Cost $M	Free Speed Trip Time		Congested Time, No Projects	**Link**	Project Cost $M	Free Speed Trip Time		Congested Time, No Projects
		Base	With Project				Base	With Project	
1	11.20	2.00	1.93	11.87	**21**	16.24	2.19	2.11	18.49
2	11.92	2.15	2.07	6.02	**22**	14.32	2.12	2.05	18.64
3	7.36	1.88	1.83	5.13	**23**	11.92	1.98	1.86	7.55
4	8.72	2.01	1.95	7.72	**24**	2.80	2.16	2.11	2.60
5	7.60	1.96	1.92	14.30	**25**	2.56	2.07	2.02	2.37
6	1.26	1.85	1.82	1.98	**26**	3.28	1.97	1.90	4.46
7	1.28	2.09	2.04	2.73	**27**	5.12	1.92	1.87	2.85
8	1.72	1.97	1.93	3.14	**28**	1.36	2.03	2.00	2.56
9	6.20	2.05	1.98	4.33	**29**	2.96	2.20	2.12	3.65
10	2.34	1.96	1.90	3.20	**30**	13.04	1.71	1.64	18.71
11	1.25	2.06	2.01	2.69	**31**	1.44	2.22	2.15	2.34
12	2.60	2.09	2.01	2.22	**32**	2.16	1.75	1.71	6.96
13	8.00	1.88	1.84	11.71	**33**	1.52	2.15	2.10	2.54
14	5.24	1.87	1.84	9.94	**34**	3.04	1.81	1.75	6.41
15	9.20	2.01	1.95	7.89	**35**	5.68	2.25	2.18	5.59
16	1.23	1.84	1.80	2.46	**36**	4.40	1.78	1.70	5.67
17	6.52	1.95	1.91	6.01	**37**	3.68	2.06	2.01	3.09
18	4.76	1.92	1.87	4.30	**38**	8.16	1.92	1.85	6.17
19	11.68	2.01	1.95	8.37	**39**	7.04	1.78	1.70	14.54
20	1.24	2.09	2.04	2.51	**40**	5.36	1.88	1.81	9.37