A NOVEL RATE-QUANTIZATION SOURCE MODELING FRAMEWORK FOR H.264/AVC

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ABSTRACT

How to perform rate control on emerging H.264/AVC, which includes the non-normative but widely accepted rate-distortion optimization (RDO) process, i.e., the rate-constrained motion estimation and mode decision, has become a challenging and difficult research issue. Usually, rate controller is useful at given residual signals to determine quantization parameter (QP). However, to perform RDO, a QP should first be predetermined. This leads to a classical chicken and egg dilemma. Therefore, how to understand and predict the coding behavior after RDO with different QPs is the core problem of the H.264/AVC rate controller. In this work, we attempt to adopt coding behaviors of customized residues that are extracted from part of RDO to forward estimate the coding behavior of RDO with different QPs. Experiments show that the proposed rate-quantization (R-Q) model is able to provide a more accurate estimation of the actual bit rate than existing MAD-based model in JM 10.2.

Index Terms— Rate control, Rate Distortion Optimization, Rate-Quantization model.

1. INTRODUCTION

In the last few years, rate controller has received a lot of attention and been widely studied, such as TM5 [1] for MPEG-2, TMN8 [2] for H.263 and VM-18 for MPEG-4, because the quality of the received video at the client site primarily depends on the efficiency of the rate control technique. The rate control scheme is expected to smooth out the varying bit rate of video source via adjusting QP, to prevent the client buffer from under/overflowing and to maximize the quality of the perceived video at the same time. Therefore, how to construct an accurate R-Q model becomes a key technique of the rate controller. Some variance/MAD[1]-based rate-estimation models such as in [1]-[7] derive the theoretical mathematical models to predict the actual bit rate based on the entropy theory. However, the variance/MAD itself is insufficient to describe the characteristics of the input source to estimate the actual source coding bit rate. All of above conventional R-D models mainly focus on how to model the actual bit rate at a given source residual signal. In some sense, that rate control scheme is only useful after the motion estimation (ME) is obtained.

On the other hand, in H.264/AVC standard, one of the core techniques is the RDO process, which includes a variable block size ME and a mode decision for RD-refinement. Furthermore, the best configuration of partition mode is determined from the one with the minimum Lagrange cost as a QP is given. It is worth noticing that the configuration of residual signal and motion vectors is a function of QP. This results in so-called chicken and egg dilemma [3] when rate controller is applied as well. Hence, it is difficult for the above R-D models to be directly employed in the H.264/AVC rate control framework.

To cope with the chicken and egg dilemma, in JM reference software [9], MAD of resultant residual of previous frames are used to estimate the MAD of resultant residual of the current frame by an adaptive linear model. Next, the estimated MAD is fed into a quadratic form [7] to construct the rate-estimation model. However, since the values of MAD between neighboring frames could dramatically fluctuate due to sudden scene changes, the coefficients of such an adaptive model are hard to deal with such abrupt scene changes. To reduce the impact of the scene changes, a more accurate MAD predictor [6] is proposed to enhance MAD-based R-Q model [3] by calculating the direct MAD (without ME) between reference frame and current frame. However, it still suffers from the same problem as mentioned [1][2][4][5][7].

In this work, we notice an interesting and important observation, i.e., the coding behavior of some customized residues (extracted from part of RDO) is quite similar with the coding behavior after the whole RDO process with different QPs. Thus, the intuition of our approach is to employ a linear combination of the estimated bitrate curves with customized residues to predict the actual bitrate curve after the whole RDO process. Experiments show that such a R-Q modeling framework provides a more accurate estimation of the actual bitrate than existing MAD-based model [3] does. In addition, it is worth noticing that when motion estimation is performed, we can extract customized residues to construct the proposed R-Q model and record reusable information for subsequent rate-constrained mode selection at the same time. Finally, a quantization-free rate-quantization (R-Q) source modeling framework is proposed to model customized residues as well. In short, the newly proposed source modeling framework can be easily implemented with lower computational complexity.

This paper is organized as follows. In Sec. 2, we first review the RDO process, and attempt to observe the coding behaviors of customized residues and RDO process, respectively. We will propose a new source modeling framework within the part of RDO process in Sec. 3. Then, in Sec. 4, we present a modified quantization-free R-Q modeling framework to customized residues.

[1] Mean Absolute Difference: MAD

Then, Sec. 5 and Sec. 6 are experimental results and conclusion, respectively.

2. REVIEW R-D OPTIMIZATION PROCESS

2.1. Review R-D Optimization Process

In H.264/AVC standard [10], it supports a tree-structured hierarchical macroblock partitions. In JM reference software [9], a recommended Lagrange multiplier optimization technique [11] is adopted to offer a systematic way to select the optimal coding mode. For an inter macroblock, the rate-constrained variable block ME is first applied to find minimal prediction error by minimizing

$$J_{MxN}(mv, \lambda_{MOTION}) = D(s, c(mv)) + \lambda_{MOTION} \cdot R(mv - pmv), \qquad (1)$$

,where *mv* is the motion vector and *pmv* is the predicted motion vector. The rate term, i.e., $R(mv\text{-}pmv)$ computed by a lookup table, presents the relative bitrate of motion vector information. $D(s,c(mv))$ is the prediction error between the current block *s* and reference block *c*. Usually, $D(s,c(mv))$ is computed by sum of absolute differences (SAD) or sum of absolute differences after Hadamard transform (SATD). λ_{MOTION} is the Lagrange multiplier, which is given by

$$\lambda_{MOTION} = \sqrt{0.85 \cdot 2^{(QP-12)/3}} \qquad (2)$$

Thus, for a specified partition mode, the different motion vectors and residual signals might be selected with different QP as illustrated in Fig. 1.

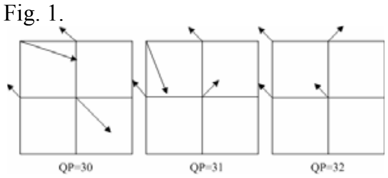

Fig. 1 The configuration of motion vectors and residual signals after rate-constrained variable block ME with different QP

Next, the rate-constrained mode selection is performed to figure out the coding mode with minimal distortion by minimizing

$$J(s, c, MODE \mid QP, \lambda_{MODE}) = D(s, c, MODE \mid QP) + \lambda_{MODE} \cdot R(s, c, MODE \mid QP) \qquad (3)$$

, where *MODE* is one of possible combination of partition modes. The distortion $D(s,c,MODE|QP)$ is computed by the sum of squared errors between the current block *s* and the reconstructed block *c*. $R(s,c,MODE|QP)$ is the number of bits for macroblock header, the *mv* and quantized transform coefficients with choosing *MODE*, and $\lambda_{MOTION} = \sqrt{\lambda_{MODE}}$.

Thus, with different QP, the different combination of motion vectors, residual signals and partition modes might be selected as shown in Fig. 2.

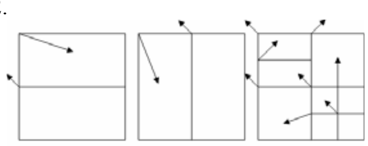

Fig. 2 The configuration of motion vectors, residual signals and partition modes after the rate-constrained mode selection for different QP

2.2. The Observation of Coding Behavior of Customized Residue

As we mentioned above, it is difficult to model the resultant bitrate of a frame after the RDO process under different QP conditions. The reason is that the final configuration of residual signal is unknown. So, the intuition of our approach is to observe the coding behavior of some customized residue of a frame with different QPs. We first apply the same partition mode (16x16, 8x8 and 4x4, respectively) to all MBs and set λ_{MOTION} to zero [2] to obtain two residues of a frame. Next, in Fig 3, we plot the actual bitrate curve of a frame after the RDO process with different QPs and the actual bitrate curves of customized residue (16x16, 8x8 and 4x4) of a frame with different QP. From Fig. 3, we observe that the bitrate curves of customized residues are very similar to the actual bitrate curve after the RDO process. Therefore, we conclude an interesting and important observation: the actual bitrate curve with the same partition mode is a proper estimation of the actual bitrate curve after the RDO process. Next, we are going to present how we use such important observation to construct the R-Q source modeling framework for H.264/AVC.

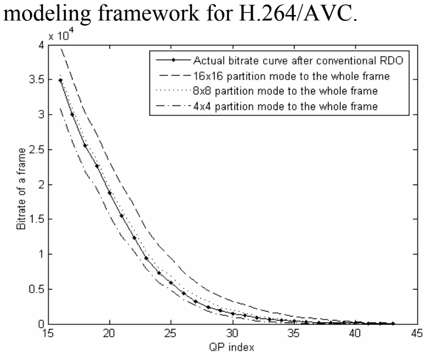

Fig. 3 Plots the $R_{RDO}(q)$, $R_{16x16}(q)$, $R_{8x8}(q)$ and $R_{4x4}(q)$.

3. PROPOSED RATE-QUANTIZATION SOURCE MODELING FRAMEWORK

Given the above important observation, we start to employ a linear combination of the estimated bitrates of the two partition modes of sizes 16x16 and 8x8 to model the actual bitrate[3].

$$R_{RDO}(q) \approx A(q) \cdot \hat{R}_{16x16}(q) + B(q) \cdot \hat{R}_{8x8}(q) + C(q), \qquad (4)$$

where $\hat{R}_{16x16}(q)$ and $\hat{R}_{8x8}(q)$ are the estimated bitrates with the same partition modes of sizes 16x16 and 8x8, respectively. $A(q)$, $B(q)$ and $C(q)$ are weighting coefficients obtained via the regression. That is, we need to obtain the residues of a frame with two partition modes of size 16x16 and 8x8 to estimate the corresponding bit rate.

In the RDO process, rate-constrained variable block ME is first applied to produce the best matched residue of each partition mode. Then, the best matched residue of each partition mode is fed into the rate-constrained mode selection to determine the best partition of a MB. In fact, the ME of each partition mode can be performed independently. Accordingly, we can partition rate-constrained variable block motion estimation into two parts, 16x16/8x8 ME and other block size ME, as illustrated in Fig. 4. In addition, it is worth noticing that when ME is performed, we can extract useful information for proposed R-Q modeling framework and record reusable information for subsequent rate-constrained mode

[2] If $\lambda_{MOTION}=0$, the configuration of residues and mv with different QP will be the same.

[3] In our experiments, we have tried several combinations of other partition modes. However, it does not provide a more accurate estimation of the actual bit rate.

selection at the same time. Specifically, when 16x16/8x8 ME is performed, we not only obtain residue of a MB with λ_{MOTION}=0, but also record its motion vectors, which can be used to recovery relative residue, with different λ_{MOTION}(QP). Hence, we can realize that such extraction of customized residues only costs little computational resource for the whole coding system. In next section, we are going to introduce a quantization-free rate modeling framework to estimate the bitrate of the customized residues with different QP for the newly proposed R-Q model framework.

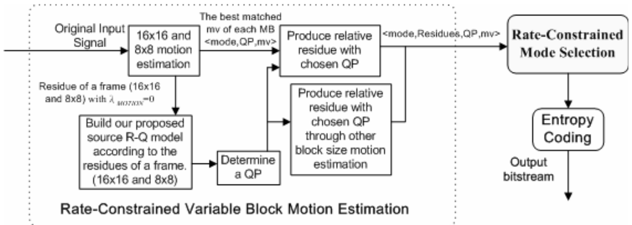

Fig. 4 The flowchart of the proposed R-Q modeling framework

4. A CHARACTERISTIC-BASED RATE MODELING FRAMEWORK

In [8], we have shown that there are three characteristics can be used to model coding bitrate of a frame when the source residual signal of a frame is given. They are the number of quantized nonzero coefficients, the sum of zeros before the last nonzero coefficient in zigzag scan and the sum of absolute quantized nonzero coefficients, denoted as $Q_C(q)$, $Q_Z(q)$ and $Q_L(q)$, respectively. The source bitrate of quantized residual signals of a frame can be model as:

$$\hat{R}_F(q) = \vec{W}_F(q) \cdot \vec{Q}_F(q), \qquad (5)$$

, where $\vec{W}_F(q)$ is a set of model coefficients obtained through regression method, and the characteristic vector is $\vec{Q}_F(q) = [Q_C(q)\, Q_L(q)\, Q_Z(q)\, 1]^T$. Note that the quantization process of H.264/AVC is different from conventional uniform quantizer. In the following, we present how to modify our previous modeling framework to fit into the emerging H.264/AVC encoder.

4.1. Review the Non-Uniform Quantizer of H.264/AVC

In this subsection, we first review the quantization scheme in H.264/AVC. For simplicity of discussion, herein, we take 4x4 luma AC coefficient quantization process as an example.

To avoid the operation of division [11], each coefficient at (i, j), $0 \le i, j \le 3$, denoted as $X_q(i,j)$ is quantized by

$$X_q(i,j) = sign\{x(i,j)\} \cdot (|x(i,j)| \cdot A(Q_M, i, j) + f >> qbits), \qquad (6)$$

where $qbits = 15 + \lfloor q/6 \rfloor$, f=λ •2^{qbits}, Q_M=q mod 6, and $A(Q_M,i,j)$=$M(Q_M,r)$ in which r=0 for (i,j) ={(0,0),(0,2),(2,0),(2,2)},r=1 for (i,j) = {(1,1),(1,3),(3,1),(3,3)}, and r=2, otherwise, with

$$M(Q_M,r) = \begin{bmatrix} 13107 & 5243 & 8066 \\ 11916 & 4660 & 7490 \\ 10082 & 4194 & 6554 \\ 9362 & 3647 & 5825 \\ 8192 & 3355 & 5243 \\ 7282 & 2893 & 4559 \end{bmatrix}. \qquad (7)$$

Here, we understand that the value of each quantized coefficient $X_q(i,j)$ is strongly associated with the weighting value of its position and quantization parameter.

4.2. Characteristic-based Extraction Framework for H.264/AVC

First, we need to build a histogram to extract three characteristics of the input source. As we stated before, the value of each quantized coefficient $X_q(i,j)$ is strongly associated with the weighting value of its position. Hence, three types of histograms (r=0~2) of a frame are needed $D_0(x)$, $D_1(x)$ and $D_2(x)$, respectively. In addition, we equivalently rewrite Eq. (6) as:

$$X_q(i,j) = sign\{x(i,j)\} \cdot \left\lceil \frac{|x(i,j)| + \Delta(q,r)}{Qstep(q,r)} \right\rceil, \qquad (8)$$

, where $\Delta(q,r)$ is $\lambda \cdot 2^{qbits} / M(Q_M, r)$ and $Qstep(q,r)$ is $2^{qbits} / M(Q_M, r)$.

Of course, when any transform coefficient $|x(i,j)|$ is less than $T(Q_M, r) = (1-\lambda) \cdot 2^{qbits} / M(Q_M, r)$, $|x(i,j)|$ will be quantized to zero. Consequently, the number of quantized nonzero coefficients $Q_C(q_i)$ can be easily obtained by following recursive formula:

$$Q_{C,r}(q=0) = \sum_{|x| \ge T(Q_M, r)} D_r(x) \qquad (9)$$

$$Q_{C,r}(q) = Q_{C,r}(q-1) - \sum_{T(Q_M - 1, r) \le |x| \le T(Q_M, r)} D_r(x) \qquad (10)$$

$$Q_C(q) = \sum_{r=0}^{2} Q_{C,r}(q) \qquad (11)$$

In addition, the sum of absolute quantized nonzero coefficients $Q_L(q)$ could be computed by:

$$Q_L(q) = \sum_{r=0}^{2} \sum_{n=1}^{Q_{C,r}(q)} \left\lceil \frac{|x_n| + \Delta(q,r)}{Qstep(q,r)} \right\rceil \qquad (12)$$

Note that for each item $\left\lceil \frac{|x_n| + \Delta(q,r)}{Qstep(q,r)} \right\rceil$ in Eq. (12), there is a dynamically stuffing value α_n over [0,1) need to be padded by a ceiling operation, if we apply division on $|x_n|$. To reduce a large of divisions, Eq, (12) can be presented as:

$$\sum_{r=0}^{2} \left(\sum_{n=1}^{Q_{C,r}(q)} \frac{|x_n| + \Delta(q,r)}{Qstep(q,r)} + \sum_{n=1}^{Q_{C,r}(q)} \alpha_n \right) \qquad (13)$$

Then, we sum up all absolute values of nonzero coefficients in advance, i.e. the item $\sum_{n=1}^{Q_{C,r}(q)} |x_n|$, denoted as $Q_{SANZ,r}(q)$, and α_n is set to 0.5. Hence, Eq. (13) can be approximated by

$$\sum_{r=0}^{2} \left(\frac{Q_{SANZ,r}(q) + Q_{C,r}(q) \cdot \Delta(q,r)}{Qstep(q)} + 0.5 \cdot Q_{C,r}(q) \right) \qquad (14)$$

Since $Q_L(q)$ is a function of $Q_{SANZ,r}(q)$and $Q_{C,r}(q)$, prior to calculating $Q_L(q)$, we need know the information of $Q_{SANZ,r}(q)$. Also, $Q_{SANZ,r}(q)$ is computed by recursive formula:

$$Q_{SANZ,r}(q=0) = \sum_{|x| \ge T(Q_M, r)} \sum_{1}^{D_r(x)} x \qquad (15)$$

$$Q_{SANZ,r}(q) = Q_{SANZ,r}(q-1) - \sum_{T(Q_M - 1, r) \le |x| \le T(Q_M, r)} \sum_{1}^{D_r(x)} x \qquad (16)$$

At last, the sum of zeros before the last nonzero coefficient in zigzag scan $Q_Z(q)$ can be obtained through the sum of $Q_{Z,4x4}(q)$ (the sum of zeros before the last nonzero coefficient in zigzag scan in 4x4 block), which can be obtained by subtracting the number of nonzero coefficients from $P_{LAST,q}$. (the position of last nonzero coefficients in 4x4 block). We note that the newly proposed R-Q model for H.264/AVC does not perform any quantization process. Hence, the major computational complexity is on building three kinds of histograms and on above recursive formulas. The important point to note is that our R-Q source modeling framework only needs additive operations, e.g., comparison, addition, subtraction. That is, the proposed R-Q model can be easily implemented with lower computational complexity.

5. EXPERIMENT RESULT

The proposed R-Q modeling framework is implemented in JM 10.2. The relative prediction error is defined as "the ratio of the accumulation estimation errors to the total of bitrates of coded frames":

$$E = \sum_{\text{all coded frames}} | R_o(q) - R_e(q) | \Big/ \sum_{\text{all coded frames}} R_o(q) \qquad (17)$$

,where R_o and R_e are the actual coding bitrate and the estimated bitrate, respectively. In our experiments, the encoding frame is fixed at 10 fps. Frame type is set to IPPP. The first I frame is encoded with QP=32. The number of reference frame is set to 6. We perform rate controller recommended in [3]. Then construct the proposed R-Q model at the same time. In Table 1, we can see that proposed R-Q model has a substantial improvement compared to MAD-based R-Q model [3] from high activity sequence "foreman" to low activity sequence "Salesman". In Fig. 5, we also plot the estimated rate curves of "carphone" and "foreman", with QP=21 and QP=27, respectively, in temporal from Table 1. We can also see that the estimated bitrate curve is more close to the actual coding bitrate curve compared with MAD-based R-Q model [3].

6. CONCLUSION

In this work, we observed that coding behaviors of customized residues are very similar with the coding behavior of RDO with different QPs. We employ this important observation to model the coding behavior of the input source after RDO with different QP. Experimental results show that the proposed R-Q model has a substantial improvement to existing MAD-based R-Q model for JM 10.2 [3] in terms of accuracy of bit rate.

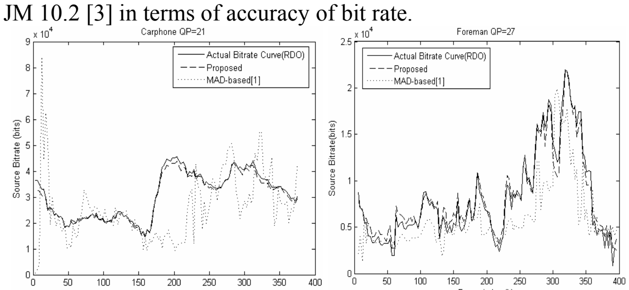

Fig. 5 The number of bits among actual rate curve (RDO), proposed rate curve and MAD-based rate curve for continuous p-frames of carphone.qcif and foreman.qcif, respectively.

Table. 1 The relative prediction error defined as Eq. (17) from high activity sequence "foreman" to low activity sequence "Salesman" with different QP and different bandwith, performing rate control in [1].

E	**Foreman**		**Carphone**		**Salesman**	
	Coded Frames=133,		**Coded Frames=127,**		**Coded Frames=149,**	
	R=54,000,k=2		**R=34,000, k=2**		**R=54,000, k=2**	
	Proposed	**MAD**	**Proposed**	**MAD**	**Proposed**	**MAD**
q_{0}	0.0003996	0.119680	0.000328	0.140200	0.0001755	0.0400940
q_{1}	0.0004002	0.101210	0.000327	0.118630	0.0001643	0.0332970
q_{2}	0.0004082	0.075721	0.000298	0.089687	0.0001295	0.0241370
q_{3}	0.0003931	0.067414	0.000288	0.080092	0.0001100	0.0211400
q_{4}	0.0003729	0.053661	0.000249	0.064913	0.0001251	0.0165250
q_{5}	0.0003525	0.043763	0.000242	0.053242	0.0001687	0.0133220
q_{6}	0.0002989	0.036962	0.000223	0.045759	0.0002550	0.0112810
q_{7}	0.0002449	0.031375	0.000214	0.039393	0.0003183	0.0096140
q_{8}	0.0001750	0.022978	0.000206	0.029575	0.0003833	0.0072999
q_{9}	0.0001423	0.020437	0.000192	0.026537	0.0004008	0.0067946
q_{10}	0.0001378	0.015769	0.000183	0.020898	0.0004459	0.0060782
q_{11}	0.0001358	0.012650	0.000166	0.017028	0.0005015	0.0056990
q_{12}	0.0001804	0.010372	0.000166	0.014148	0.0005805	0.0054618
q_{13}	0.0002037	0.008707	0.000176	0.011978	0.0005642	0.0053004
q_{14}	0.0002438	0.005981	0.000187	0.008369	0.0005402	0.0051014
q_{15}	0.0002451	0.005441	0.000181	0.007564	0.0004999	0.0049923
q_{16}	0.0002385	0.004167	0.000166	0.005647	0.0005297	0.0048547
q_{17}	0.0002530	0.003563	0.000150	0.004552	0.0006787	0.0046424
q_{18}	0.0003254	0.003259	0.000147	0.003889	0.0013490	0.0041161
q_{19}	0.0003940	0.003055	0.000150	0.003338	0.0019141	0.0037917
q_{20}	0.0004242	0.002998	0.000149	0.002774	0.0028379	0.0035162
q_{21}	0.0002788	0.002938	0.000232	0.002706	0.0037238	0.0034217
q_{22}	0.0002273	0.003072	0.000282	0.002758	0.0018903	0.0034003
q_{23}	0.0002251	0.003054	0.000341	0.002946	0.0026078	0.0034209
q_{24}	0.0003391	0.002919	0.000315	0.003071	0.0019218	0.0037128
q_{25}	0.0003703	0.002892	0.000364	0.003276	0.0024891	0.0039344
q_{26}	0.0004914	0.002929	0.000408	0.003700	0.0014057	0.0042459
q_{27}	0.0007078	0.002718	0.000522	0.003634	0.0041161	0.0046682
q_{28}	0.0009227	0.002899	0.000655	0.003822	0.0016998	0.0050950
q_{29}	0.0012299	0.003074	0.000760	0.003855	0.0055003	0.0057811
q_{30}	0.0015844	0.003317	0.000795	0.003884	0.0016650	0.0064294
q_{31}	0.0019224	0.003676	0.000896	0.003820	0.0036125	0.0068428
q_{32}	0.0023280	0.004613	0.000936	0.003766	0.0022277	0.0075722
q_{33}	0.0026820	0.005470	0.001176	0.003350	0.0019429	0.0087892
q_{34}	0.0027156	0.006495	0.001141	0.003253	0.0020666	0.0096867
q_{35}	0.0029524	0.007732	0.001354	0.003304	0.0021344	0.0114260
q_{36}	0.0032895	0.009023	0.001542	0.003317	0.0034715	0.0134860
q_{37}	0.0036180	0.009896	0.001996	0.003351	0.0032824	0.0150890
q_{38}	0.0040536	0.011740	0.002580	0.003731	0.0067860	0.0186700
q_{39}	0.0045944	0.013129	0.003038	0.004333	0.0076614	0.0230570
q_{40}	0.0049785	0.015303	0.003684	0.005276	0.0103690	0.0269690
q_{41}	0.0057924	0.017434	0.004178	0.006526	0.0117460	0.0331030
q_{42}	0.0058760	0.021210	0.005065	0.008407	0.0100940	0.0400740
q_{43}	0.0064603	0.023852	0.005100	0.010068	0.0141400	0.0517800
q_{44}	0.0064102	0.027966	0.005363	0.012669	0.0208920	0.0661230
q_{45}	0.0074101	0.035174	0.006014	0.016740	0.0156650	0.0828410
q_{46}	0.0078608	0.040793	0.005795	0.019785	0.0269730	0.0997440
q_{47}	0.0081455	0.047438	0.006524	0.025751	0.0147060	0.1142100
q_{48}	0.0087610	0.057811	0.006638	0.031396	0.0212480	0.1372600
q_{49}	0.0085795	0.066197	0.007163	0.036668	0.0141050	0.1869700
q_{50}	0.0086730	0.073325	0.007342	0.042211	0.0172230	0.1937600
q_{51}	0.0081665	0.081225	0.007393	0.050450	0.0134570	0.2046800

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