

List of Figures

2-1	The Modeling State-Space Problem _____	15
2-2	A Method to Reduce the Scale of Computational Demands _____	16
2-3	An Example Applying Scale Reduction to MesoNet Simulations _____	17
2-4	Reducing the Space of Model Responses using Correlation and/or Principal Components Analysis _____	21
3-1	Topology used for simulation experiments discussed in this study _____	38
4-1	Encoding Template for a 2^{11-5} Orthogonal Fractional Factorial Experiment Design ____	75
4-2	Enlargement of Sample Scatter Plot of Response y_7 vs. y_2 _____	80
4-3	Sample (and Partial) Table of Correlations among Response Pairs _____	80
4-4	Sample Histogram of Correlation Magnitudes among Response Pairs _____	81
4-5	Sample 6-x-6 Subset from a Combined Matrix of Scatter Plots and Correlation Values _____	82
4-6	Index-Index Plot Identifying Response Pairs with Correlation Magnitude above 0.65 _	83
4-7	Enlargement of a Sample Weight Vector for First Principal Component _____	84
4-8	Enlargement of a Sample Histogram for First Principal Component _____	85
4-9	Sample Main Effects Plot for Response y_{11} , average congestion window size _____	87
4-10	Sample Y-Y-X plot for Responses y_7 and y_{22} _____	88
4-11	Example Illustrating the Technique used to Summarize System Responses _____	102
4-12	Sample Data Summarization: 22 Responses for each of 64 Simulation Runs _____	103
4-13	Combined Matrix of Scatter Plots and Correlation Values for 22 Responses _____	103
4-14	Frequency Distribution of the Absolute Value of Correlations for All Pairs of Responses _____	104
4-15	Clustered Index-Index Plot for Correlation Pairs where $ \text{Correlation}(Y_i, Y_j) > 0.65$ ____	105
4-16	Histograms for 22 Principal Components _____	109
4-17	Weight Vectors for the First Four Principal Components _____	109
4-18	Main-Effects Plot for Response y_1 (Average Number of Active Flows) _____	112
4-19	Main-Effects Plot for Response y_{10} (Average Retransmission Rate) _____	114
4-20	Main-Effects Plot for Response y_{22} (Average Instantaneous Throughput for NN Flows) _____	115
4-21	Main-Effects Plot for Response y_{15} (Average Smoothed Round-Trip Time) _____	116
4-22	Main-Effects Plot for Response y_4 (Average Packets Output per Measurement Interval) _____	117
4-23	Main-Effects Plot for Response y_6 (Flows Completed per Measurement Interval) ____	117
4-24	Main-Effects Plot for Response y_{17} (Average Instantaneous Throughput of DD Flows) _____	118
4-25	Main-Effects Plot for Response y_{20} (Average Instantaneous Throughput of FF Flows) _____	119
4-26	Main-Effects Plot for PC1 (Network Congestion) _____	121
4-27	Main-Effects Plot for PC2 (Network Delay) _____	122
4-28	Main-Effects Plot for PC3 (Throughput for Advantaged Flows) _____	123
4-29	Main-Effects Plot for PC4 (Macroscopic Throughput) _____	124
4-30	Multi-factor Scatter Plot of Smoothed Round Trip Time (y_{15}) for each of the 11 Experiment Factors _____	130
4-31	Multi-factor Scatter Plot of Relative Queuing Delay (y_{16}) for Each Experiment Factor _____	131
4-32	Average Condition Ranking Displayed on Vertices of a Cube _____	133
5-1	Main Phases and Congestion Control Procedures in the Life of a TCP Flow _____	138
5-2	TCP Connection Establishment Procedures Leading to Connection Failure _____	140
5-3	TCP Connection Establishment Procedures Leading to Initiation of the Transfer Phase _____	141

5-4	Sample Change in Congestion Window over Time under Standard Slow Start and Congestion Avoidance _____	145
5-5	Sample Change in Congestion Window over Time under Limited Slow Start and Congestion Avoidance _____	146
5-6	Simulated Dumbbell Topology for MesoNet Verification Experiments _____	162
5-7	Change in <i>cwnd</i> vs. Time for Two TCP Flows (<i>rtt</i> = 42 ms) _____	163
5-8	Change in <i>cwnd</i> vs. Time for Two TCP Flows (<i>rtt</i> = 162 ms) _____	164
5-9	Change in <i>cwnd</i> vs. Time for Two TCP Flows (<i>rtt</i> = 324 ms) _____	165
5-10	Change in <i>cwnd</i> vs. Time for Two BIC Flows (<i>rtt</i> = 42 ms) _____	165
5-11	Change in <i>cwnd</i> vs. Time for Two BIC Flows (<i>rtt</i> = 162 ms) _____	166
5-12	Change in <i>cwnd</i> vs. Time for Two BIC Flows (<i>rtt</i> = 324 ms) _____	166
5-13	Change in <i>cwnd</i> vs. Time for Two CTCP Flows (<i>rtt</i> = 42 ms) _____	167
5-14	Change in <i>cwnd</i> vs. Time for Two CTCP Flows (<i>rtt</i> = 162 ms) _____	168
5-15	Change in <i>cwnd</i> vs. Time for Two CTCP Flows (<i>rtt</i> = 324 ms) _____	168
5-16	Change in <i>cwnd</i> vs. Time for Two FAST Flows (α -tuning enabled, <i>rtt</i> = 42 ms) _____	169
5-17	Change in <i>cwnd</i> vs. Time for Two FAST Flows (α -tuning enabled, <i>rtt</i> = 162 ms) _____	169
5-18	Change in <i>cwnd</i> vs. Time for Two FAST Flows (α -tuning enabled, <i>rtt</i> = 324 ms) _____	170
5-19	Change in <i>cwnd</i> vs. Time for Two FAST Flows (α_f = 80, <i>rtt</i> = 42 ms) _____	170
5-20	Change in <i>cwnd</i> vs. Time for Two FAST Flows (α_f = 80, <i>rtt</i> = 162 ms) _____	171
5-21	Change in <i>cwnd</i> vs. Time for Two FAST Flows (α_f = 80, <i>rtt</i> = 324 ms) _____	171
5-22	Change in <i>cwnd</i> vs. Time for Two FAST Flows (α_f = 200, <i>rtt</i> = 42 ms) _____	172
5-23	Change in <i>cwnd</i> vs. Time for Two FAST Flows (α_f = 200, <i>rtt</i> = 162 ms) _____	172
5-24	Change in <i>cwnd</i> vs. Time for Two FAST Flows (α_f = 200, <i>rtt</i> = 324 ms) _____	173
5-25	Change in <i>cwnd</i> vs. Time for Two HSTCP Flows (<i>rtt</i> = 42 ms) _____	174
5-26	Change in <i>cwnd</i> vs. Time for Two HSTCP Flows (<i>rtt</i> = 162 ms) _____	174
5-27	Change in <i>cwnd</i> vs. Time for Two HSTCP Flows (<i>rtt</i> = 324 ms) _____	175
5-28	Change in <i>cwnd</i> vs. Time for Two H-TCP Flows (<i>rtt</i> = 42 ms) _____	175
5-29	Change in <i>cwnd</i> vs. Time for Two H-TCP Flows (<i>rtt</i> = 162 ms) _____	176
5-30	Change in <i>cwnd</i> vs. Time for Two H-TCP Flows (<i>rtt</i> = 324 ms) _____	176
5-31	Change in <i>cwnd</i> vs. Time for Two Scalable TCP Flows (<i>rtt</i> = 42 ms) _____	177
5-32	Change in <i>cwnd</i> vs. Time for Two Scalable TCP Flows (<i>rtt</i> = 162 ms) _____	177
5-33	Change in <i>cwnd</i> vs. Time for Two Scalable TCP Flows (<i>rtt</i> = 324 ms) _____	178
6-1	Topology Adopted for Experiments _____	184
6-2	Scenario Adopted for Each Simulated Condition _____	188
6-3	Dendrogram Illustrating Clustering Based on Responses for Condition 4 During Time Period One _____	200
6-4	Cluster Analysis for 32 Conditions Using Data from Time Period One _____	201
6-5	Conditions Ordered from Least to Most Congested vs. Retransmission Rate _____	201
6-6	Distribution of Flow States over Three Time Periods under Condition 4 for Standard TCP _____	202
6-7	Distribution of Flow States over Three Time Periods under Condition 5 for Standard TCP _____	203
6-8	Cluster Analysis for Time Period One _____	203
6-9	Sample Plot Analyzing the Influence of Condition and Congestion Control Algorithm on the Average Number of Active Flows _____	204
6-10	Summary of Statistically Significant Outliers in Time Period One _____	206
6-11	Filtered Summary Plot for Time Period One Identifying Statistically Significant Outliers with Associated Relative Effect > 10% _____	207
6-12	Average Per-Flow Goodput on DD Flows for Seven Congestion Control Algorithms under Condition 4 over Three Time Periods _____	209
6-13	Number of Active DD Flows for Seven Congestion Control Algorithms under Condition 4 over Three Time Periods _____	210
6-14	Aggregate Packet Delivery Rate DD Flows for Seven Congestion Control Algorithms under Condition 4 over Three Time Periods _____	210

6-15	Analyzing the Influence of Condition and Congestion Control Algorithm on the Average Goodput for DD Flows (y_9) during Time Period Two _____	211
6-16	Analyzing the Influence of Condition and Congestion Control Algorithm on Congestion Window Size during Time Period Three _____	212
6-17	Cluster Analysis Using Data from Time Period One – Algorithm 3 Excluded _____	213
6-18	Screenshot from DiVisa Animation of the Temporal Evolution of a MesoNet Simulation _____	214
6-19	Clustering for Time Period One – Annotated to Identify Distinctive Algorithm 3 _____	215
6-20	Clustering for Time Period One – Algorithm 3 Omitted _____	216
6-21	Condition-Response Summary for Time Period One _____	216
6-22	Filtered Summary Plot for Time Period One Identifying Statistically Significant Outliers with Associated Relative Effect > 10% _____	217
6-23	Detailed Analysis for Congestion Window Increase Rate in Time Period One _____	218
6-24	Detailed Analysis for Flow Completion Rate in Time Period One _____	218
6-25	Detailed Analysis for Retransmission Rate in Time Period One _____	219
6-26	Detailed Analysis for NN Flow Completion Rate in Time Period One _____	219
6-27	Detailed Analysis for Number of Connecting Flows in Time Period One _____	220
6-28	Clustering for Time Period Two – Annotated to Identify Distinctive Algorithm 3 _____	221
6-29	Clustering for Time Period Two – Algorithm 3 Omitted _____	221
6-30	Condition-Response Summary for Time Period Two _____	222
6-31	Filtered Summary Plot for Time Period Two Identifying Statistically Significant Outliers with Associated Relative Effect > 30% _____	222
6-32	Detailed Analysis for Congestion Window Increase Rate in Time Period Two _____	223
6-33	Detailed Analysis for Flow Completion Rate in Time Period Two _____	224
6-34	Detailed Analysis for Retransmission Rate in Time Period Two _____	225
6-35	Detailed Analysis for Average Goodput on DF Flows in Time Period Two _____	225
6-36	Detailed Analysis for Average Number of Active DF Flows in Time Period Two _____	226
6-37	Detailed Analysis for Average Number of Connecting Flows in Time Period Two _____	226
6-38	Detailed Analysis for Average Goodput on Long-lived Flow L1 in Time Period Two _____	227
6-39	Detailed Analysis for Average Goodput on Long-lived Flow L2 in Time Period Two _____	227
6-40	Clustering for Time Period Three – Annotated to Identify Distinctive Algorithm 3 _____	228
6-41	Clustering for Time Period Three – Algorithm 3 Omitted _____	229
6-42	Condition-Response Summary for Time Period Three _____	229
6-43	Filtered Summary Plot for Time Period Three Identifying Statistically Significant Outliers with Associated Relative Effect > 30% _____	230
6-44	Detailed Analysis for Congestion Window Increase Rate in Time Period Three _____	230
6-45	Detailed Analysis for Flow Completion Rate in Time Period Three _____	231
6-46	Detailed Analysis for Retransmission Rate in Time Period Three _____	231
6-47	Detailed Analysis for Average Goodput on DF Flows in Time Period Three _____	232
6-48	Detailed Analysis for Average Number of Active DF Flows in Time Period Three _____	232
6-49	Detailed Analysis for Average Number of Connecting Flows in Time Period Three _____	233
6-50	Detailed Analysis for Average Congestion Window Size in Time Period Three _____	233
6-51	Detailed Analysis for Average Goodput on Long-lived Flow L2 in Time Period Three _____	234
6-52	Clustering for Totals – Annotated to Identify Distinctive Algorithm 3 _____	235
6-53	Clustering for Totals – Algorithm 3 Omitted _____	236
6-54	Condition-Response Summary for Totals _____	236
6-55	Detailed Analysis for Aggregate Number of Flows Completed over 25-minute Scenario _____	237
6-56	Detailed Analysis for Average SYN Rate for Connecting Flows over 25-minute Scenario _____	237
6-57	Five Time Series Showing the Distribution of Flow States over Three Time Periods for Algorithm 1 (BIC) under Condition 12 _____	239
6-58	Five Time Series Showing the Distribution of Flow States over Three Time Periods for Algorithm 1 (BIC) under Condition 21 _____	240
6-59	Reproduction of Fig. 5-22, Showing Change in <i>cwnd</i> for Two FAST Flows ($a_F = 200$, $rtt = 42$ ms) _____	241

6-60	Change in Congestion Window under FAST for Long-Lived Flow L2 during 500 Measurement Intervals within TP2 under Condition 21 _____	242
6-61	Change in Congestion Window under TCP Reno for Long-Lived Flow L2 during 500 Measurement Intervals within TP2 under Condition 21 _____	243
6-62	Change in Congestion Window under BIC for Long-Lived Flow L2 during 500 Measurement Intervals within TP2 under Condition 21 _____	243
6-63	Change in Congestion Window under CTCP for Long-Lived Flow L2 during 500 Measurement Intervals within TP2 under Condition 21 _____	244
6-64	Change in Congestion Window under HSTCP for Long-Lived Flow L2 during 500 Measurement Intervals within TP2 under Condition 21 _____	244
6-65	Change in Congestion Window under HTCP for Long-Lived Flow L2 during 500 Measurement Intervals within TP2 under Condition 21 _____	245
6-66	Change in Congestion Window under Scalable TCP for Long-Lived Flow L2 during 500 Measurement Intervals within TP2 under Condition 21 _____	245
6-67	Average Congestion Window Size of DD Flows during TP3 under Condition 12 for BIC, FAST, HSTCP, HTCP, Scalable TCP and TCP Reno _____	246
6-68	Average Congestion Window Size of DD Flows during TP3 under Condition 12 for CTCP _____	247
6-69	Comparing Congestion Window Size of Scalable TCP (STCP) and FAST with respect to Falling Congestion Window _____	249
7-1	Retransmission Rate vs. Simulated Conditions Ordered from Least to Most Congested _____	257
7-2	Change in Flow States over Three Time Periods under Condition 3 for Standard TCP _____	258
7-3	Change in Flow States over Three Time Periods under Condition 5 for Standard TCP _____	259
7-4	Cluster Analysis for Time Period One _____	260
7-5	Detailed Analysis of Retransmission Rate in Time Period One for All Algorithms _____	262
7-6	Detailed Analysis of Retransmission Rate in Time Period One when Excluding Responses for Algorithm 3 _____	263
7-7	Clustering for Time Period One – each sub-plot Annotated to Identify Distinctive Algorithms 3/8 _____	264
7-8	Condition-Response Summary for Time Period One _____	265
7-9	Condition-Response Summary for Time Period One – 10% Filter Applied _____	266
7-10	Detailed Analysis for Congestion Window Increase Rate Per Flow in Time Period One _____	267
7-11	Detailed Analysis for Flow Completion Rate in Time Period One _____	267
7-12	Detailed Analysis for Retransmission Rate in Time Period One _____	268
7-13	Detailed Analysis for Average Goodput on NN Flows in Time Period One _____	268
7-14	Detailed Analysis for NN Flow Completion Rate in Time Period One _____	269
7-15	Detailed Analysis for Number of Connecting Flows in Time Period One _____	269
7-16	Detailed Analysis for Average Packets Output Per 200 ms Interval in Time Period One _____	270
7-17	Detailed Analysis for Average Goodput on Long-lived Flow L2 in Time Period One _____	270
7-18	Detailed Analysis for Average Buffer Utilization at Router K0a in Time Period One _____	271
7-19	Cluster Analysis for Time Period Two – each sub-plot Annotated to Identify Distinctive Algorithms 3/8 _____	273
7-20	Condition-Response Summary for Time Period Two _____	273
7-21	Condition-Response Summary for Time Period Two – 30% Filter Applied _____	274
7-22	Detailed Analysis for Congestion Window Increase Rate in Time Period Two _____	274
7-23	Detailed Analysis for Packet Output Rate in Time Period Two _____	275
7-24	Detailed Analysis for Flow Completion Rate in Time Period Two _____	275
7-25	Detailed Analysis for Retransmission Rate in Time Period Two _____	276
7-26	Detailed Analysis for Average Goodput on FN Flows in Time Period Two _____	276
7-27	Detailed Analysis for Average FN Flow Completion Rate during Time Period Two _____	277
7-28	Detailed Analysis for Average Goodput on Long-lived Flow L2 in Time Period Two _____	277
7-29	Detailed Analysis for Average Number of Connecting Flows during Time Period Two _____	278
7-30	Detailed Analysis for Buffer Utilization at Router I0a during Time Period Two _____	278

7-31	Cluster Analysis for Time Period Three – each sub-plot Annotated to Identify Distinctive Algorithms 3/8 _____	280
7-32	Condition-Response Summary for Time Period Three _____	280
7-33	Condition-Response Summary for Time Period Three – 30% Filter Applied _____	281
7-34	Detailed Analysis of Congestion Window Increase Rate for Time Period Three _____	281
7-35	Detailed Analysis of Packet Output Rate for Time Period Three _____	282
7-36	Detailed Analysis of Congestion Window Size for Time Period Three _____	282
7-37	Detailed Analysis of Flow Completion Rate for Time Period Three _____	283
7-38	Detailed Analysis of Retransmission Rate for Time Period Three _____	283
7-39	Detailed Analysis of Average Goodput on Long-lived Flow L1 _____	284
7-40	Detailed Analysis of Buffer Utilization in Router C0a during Time Period Three _____	284
7-41	Detailed Analysis of Average Number of Connecting Flows during Time Period Three _____	285
7-42	Cluster Analysis for Totals – each sub-plot Annotated to Identify Distinctive Algorithms 3/8 _____	286
7-43	Condition-Response Summary for Totals _____	286
7-44	Detailed Analysis for Number of Packets Input during 25-minute Scenario _____	287
7-45	Detailed Analysis for Number of Packets Output during 25-minute Scenario _____	288
7-46	Detailed Analysis for Number of Flows Completed over 25-minute Scenario _____	288
7-47	Detailed Analysis for Average SYN Rate for Connecting Flows over 25-minute Scenario _____	289
7-48	Detailed Analysis for Average Goodput on Completed DD Flows over 25-minute Scenario _____	289
7-49	Change in Congestion Window under FAST-AT for Long-Lived Flow L2 during 500 Measurement Intervals within TP2 under Condition 21 _____	293
7-50	Change in Congestion Window under TCP Reno for Long-Lived Flow L2 during 500 Measurement Intervals within TP2 under Condition 21 _____	294
7-51	Goodput from $t=4500$ to $t=6500$ for each Congestion Control Algorithm on Long-Lived Flow L1 under Condition 8 _____	298
7-52	Goodput from $t=4500$ to $t=6500$ for each Congestion Control Algorithm on Long-Lived Flow L2 under Condition 8 _____	300
7-53	Goodput from $t=4500$ to $t=6500$ for each Congestion Control Algorithm on Long-Lived Flow L2 under Condition 8 _____	301
7-54	Goodput from $t=4500$ to $t=7500$ for each Congestion Control Algorithm on Long-Lived Flow L1 under Condition 14 _____	305
7-55	Goodput from $t=4500$ to $t=7500$ for each Congestion Control Algorithm on Long-Lived Flow L1 under Condition 28 _____	306
7-56	Goodput from $t=4500$ to $t=7500$ for each Congestion Control Algorithm on Long-Lived Flow L1 under Condition 32 _____	307
7-57	Goodput from $t=4500$ to $t=7500$ for each Congestion Control Algorithm on Long-Lived Flow L1 under Condition 21 _____	309
7-58	Average Congestion Window Size of DD Flows during TP3 under Condition 8 for BIC, FAST, FAST-AT, HSTCP, HTCP, Scalable TCP and TCP Reno _____	311
7-59	Average Congestion Window Size of DD Flows during TP3 under Condition 8 for CTCP _____	312
8-1	Conditions Ordered from Least to Most Congested (High Initial Slow-Start Threshold) _____	328
8-2	Conditions Ordered from Least to Most Congested (Low Initial Slow-Start Threshold) _____	328
8-3	Distribution of Flow States for Six Conditions (High Initial Slow-Start Threshold) _____	329
8-4	Distribution of Flow States for Six Conditions (Low Initial Slow-Start Threshold) _____	330
8-5	Illustration of Technique to Compute Means for Responses y_1 to y_{11} _____	334
8-6	Detailed Analysis of Retransmission Rate under High Initial Slow-Start Threshold _____	336
8-7	Average Goodput for Flows Using Alternate Congestion Control Algorithm and Flows Using TCP when Transferring Movies on a Very Fast Path with a Fast Interface Speed Given a Low Initial Slow-Start Threshold _____	337

8-8	Principal Components Analysis of Goodputs given High Slow-Start Threshold _____	338
8-9	Illustration of Biplot of PC1 vs. PC2 and Related Clustering _____	339
8-10	Scatter Plot of $y16(u)/100$ vs. $y2(u)/100$ for Movies Transferred over a Very Fast Path with Fast Interface Speed Given a High Initial Slow-Start Threshold; FAST Alternate Congestion Control Algorithm _____	340
8-11	Bar Graph for Movies Transferred over a Very Fast Path with Fast Interface Speed given a High Initial Slow-Start Threshold during Condition 21 (Most Congested) _____	340
8-12	Rank Matrix for Algorithm 7 (Scalable TCP) – High Initial Slow-Start Threshold _____	341
8-13	Average Number of Active Flows under High Initial Slow-Start Threshold _____	343
8-14	Average Number of Connecting Flows under High Initial Slow-Start Threshold _____	344
8-15	Average Rate of Flow Completion under High Initial Slow-Start Threshold _____	344
8-16	Average Flow Retransmission Rate under High Initial Slow-Start Threshold _____	345
8-17	Average Smoothed Round-Trip Time under High Initial Slow-Start Threshold _____	345
8-18	Aggregate Flows Completed under High Initial Slow-Start Threshold _____	346
8-19	Web Objects as Proportion of Flows Completed under High Initial Slow-Start Threshold _____	346
8-20	Average Flow Congestion Window Size under High Initial Slow-Start Threshold _____	347
8-21	Average Number of Active Flows under Low Initial Slow-Start Threshold _____	348
8-22	Average Number of Connecting Flows under Low Initial Slow-Start Threshold _____	349
8-23	Average Rate of Flow Completion under Low Initial Slow-Start Threshold _____	349
8-24	Average Flow Retransmission Rate under Low Initial Slow-Start Threshold _____	350
8-25	Average Smoothed Round-Trip Time under Low Initial Slow-Start Threshold _____	350
8-26	Aggregate Flows Completed under Low Initial Slow-Start Threshold _____	351
8-27	Web Objects as Proportion of Flows Completed under Low Initial Slow-Start Threshold _____	352
8-28	Average Flow Congestion Window Size under Low Initial Slow-Start Threshold _____	352
8-29	Average Goodput on Movies (High Initial Slow-Start Threshold) _____	355
8-30	Average Goodput on Service Packs (High Initial Slow-Start Threshold) _____	356
8-31	Average Goodput on Documents (High Initial Slow-Start Threshold) _____	356
8-32	Average Goodput on Web Objects (High Initial Slow-Start Threshold) _____	357
8-33	Principal Component 1 vs. Principal Component 2 from Average Goodput Data (High Initial Slow-Start Threshold) _____	357
8-34	Scatter Plot of Goodput on TCP Flows vs. Non-TCP Flows for Movies Transferred on Very Fast Paths with Fast Interfaces (High Initial Slow-Start Threshold) _____	358
8-35	32 Bar Graphs (one for each Simulated Condition) plotting Goodput on TCP Flows vs. Non-TCP Flows for Movies Transferred on Very Fast Paths with Fast Interfaces (High Initial Slow-Start Threshold) _____	359
8-36	Scatter Plot of Goodput on TCP Flows vs. Non-TCP Flows for Service Packs Transferred on Very Fast Paths with Fast Interfaces (High Initial Slow-Start Threshold) _____	360
8-37	Scatter Plot of Goodput on TCP Flows vs. Non-TCP Flows for Documents Transferred on Very Fast Paths with Fast Interfaces (High Initial Slow-Start Threshold) _____	360
8-38	Average Goodput on Movies (Low Initial Slow-Start Threshold) _____	363
8-39	Average Goodput on Service Packs (Low Initial Slow-Start Threshold) _____	363
8-40	Average Goodput on Documents (Low Initial Slow-Start Threshold) _____	364
8-41	Average Goodput on Web Objects (Low Initial Slow-Start Threshold) _____	364
8-42	Principal Component 1 vs. Principal Component 2 for Average Goodput Data (Low Initial Slow-Start Threshold) _____	365
8-43	Scatter Plot of Goodput on TCP Flows vs. Non-TCP Flows for Movies Transferred on Very Fast Paths with Fast Interfaces (Low Initial Slow-Start Threshold) _____	366
8-44	32 Bar Graphs (one for each simulated condition) plotting Goodput on TCP Flows vs. Non-TCP Flows for Movies Transferred on Very Fast Paths with Fast Interfaces (Low Initial Slow-Start Threshold) _____	367

8-45	Scatter Plot of Goodput on TCP Flows vs. Non-TCP Flows for Service Packs Transferred on Very Fast Paths with Fast Interfaces (Low Initial Slow-Start Threshold) _____	368
8-46	Bar Graphs plotting Goodput on TCP Flows vs. Non-TCP Flows for Service Packs Transferred on Very Fast Paths with Fast Interfaces (Low Initial Slow-Start Threshold) _____	368
8-47	Scatter Plot of Goodput on TCP Flows vs. Non-TCP Flows for Documents Transferred on Very Fast Paths with Fast Interfaces (Low Initial Slow-Start Threshold) _____	369
8-48	32 Bar Graphs plotting Goodput on TCP Flows vs. Non-TCP Flows for Service Packs Transferred on Very Fast Paths with Fast Interfaces (Low Initial Slow-Start Threshold) _____	369
8-49	Goodput Rank Matrix – $y_2(u)$ – BIC (High Initial Slow-Start Threshold) _____	372
8-50	Goodput Rank Matrix – $y_2(u)$ – CTCP (High Initial Slow-Start Threshold) _____	373
8-51	Goodput Rank Matrix – $y_2(u)$ – FAST (High Initial Slow-Start Threshold) _____	373
8-52	Goodput Rank Matrix – $y_2(u)$ – FAST-AT (High Initial Slow-Start Threshold) _____	374
8-53	Goodput Rank Matrix – $y_2(u)$ – HSTCP (High Initial Slow-Start Threshold) _____	374
8-54	Goodput Rank Matrix – $y_2(u)$ – HTCP (High Initial Slow-Start Threshold) _____	375
8-55	Goodput Rank Matrix – $y_2(u)$ – Scalable TCP (High Initial Slow-Start Threshold) _____	375
8-56	TCP Goodput Rank Matrix – $y_{16}(u)$ – BIC (High Initial Slow-Start Threshold) _____	376
8-57	TCP Goodput Rank Matrix – $y_{16}(u)$ – CTCP (High Initial Slow-Start Threshold) _____	376
8-58	TCP Goodput Rank Matrix – $y_{16}(u)$ – FAST (High Initial Slow-Start Threshold) _____	377
8-59	TCP Goodput Rank Matrix – $y_{16}(u)$ – FAST-AT (High Initial Slow-Start Threshold) _____	377
8-60	TCP Goodput Rank Matrix – $y_{16}(u)$ – HSTCP (High Initial Slow-Start Threshold) _____	378
8-61	TCP Goodput Rank Matrix – $y_{16}(u)$ – HTCP (High Initial Slow-Start Threshold) _____	378
8-62	TCP Goodput Rank Matrix – $y_{16}(u)$ – Scalable TCP (High Initial Slow-Start Threshold) _____	379
8-63	Goodput Rank Matrix – $y_2(u)$ – BIC (Low Initial Slow-Start Threshold) _____	380
8-64	Goodput Rank Matrix – $y_2(u)$ – CTCP (Low Initial Slow-Start Threshold) _____	381
8-65	Goodput Rank Matrix – $y_2(u)$ – FAST (Low Initial Slow-Start Threshold) _____	381
8-66	Goodput Rank Matrix – $y_2(u)$ – FAST-AT (Low Initial Slow-Start Threshold) _____	382
8-67	Goodput Rank Matrix – $y_2(u)$ – HSTCP (Low Initial Slow-Start Threshold) _____	382
8-68	Goodput Rank Matrix – $y_2(u)$ – HTCP (Low Initial Slow-Start Threshold) _____	383
8-69	Goodput Rank Matrix – $y_2(u)$ – Scalable TCP (Low Initial Slow-Start Threshold) _____	383
8-70	TCP Goodput Rank Matrix – $y_{16}(u)$ – BIC (Low Initial Slow-Start Threshold) _____	384
8-71	TCP Goodput Rank Matrix – $y_{16}(u)$ – CTCP (Low Initial Slow-Start Threshold) _____	384
8-72	TCP Goodput Rank Matrix – $y_{16}(u)$ – FAST (Low Initial Slow-Start Threshold) _____	385
8-73	TCP Goodput Rank Matrix – $y_{16}(u)$ – FAST-AT (Low Initial Slow-Start Threshold) _____	385
8-74	TCP Goodput Rank Matrix – $y_{16}(u)$ – HSTCP (Low Initial Slow-Start Threshold) _____	386
8-75	TCP Goodput Rank Matrix – $y_{16}(u)$ – HTCP (Low Initial Slow-Start Threshold) _____	386
8-76	TCP Goodput Rank Matrix – $y_{16}(u)$ – Scalable TCP (Low Initial Slow-Start Threshold) _____	387
8-77	Average vs. Standard Deviation in Goodput Rank (High Initial Slow-Start Threshold) _____	388
8-78	Average vs. Standard Deviation in Goodput Rank Low Initial Slow-Start Threshold) _____	389
9-1	Conditions Ordered Least to Most Congested under High Initial Slow-Start Threshold _____	399
9-2	Distribution of Flow States for Six Conditions with Increasing Congestion _____	399
9-3	Average Number of Connecting Flows under High Initial Slow-Start Threshold _____	402
9-4	Average Retransmission Rate under High Initial Slow-Start Threshold _____	403
9-5	Average Flow Completion Rate under High Initial Slow-Start Threshold _____	404
9-6	Aggregate Flows Completed under High Initial Slow-Start Threshold _____	404
9-7	Average Smoothed Round-Trip Time under High Initial Slow-Start Threshold _____	405
9-8	Web Objects as Proportion of Flows Completed under High Initial Slow-Start Threshold _____	405
9-9	Movies as Proportion of Flows Completed under High Initial Slow-Start Threshold _____	406

9-10	Average Flow Congestion Window Size under High Initial Slow-Start Threshold _____	406
9-11	Average Goodputs on Movies under Combinations of Path Class and Interface Speed _____	409
9-12	Average Goodputs on Service Packs under Combinations of Path Class and Interface Speed _____	409
9-13	Average Goodputs on Documents under Combinations of Path Class and Interface Speed _____	410
9-14	Average Goodputs on Web Objects under Combinations of Path Class and Interface Speed _____	410
9-15	Principal Component 1 vs. Principal Component 2 from Average Goodput Data in a Large, Fast Network and High Initial Slow-Start Threshold _____	411
9-16	Goodput on TCP Flows vs. Non-TCP Flows for Movies on Very Fast Paths with Fast Interfaces in a Large, Fast Network with High Initial Slow-Start Threshold _____	412
9-17	Bar Graphs plotting Goodput Differences on TCP Flows vs. Non-TCP Flows for Movies Transferred on Very Fast Paths with Fast Interfaces in a Large, Fast Network with a High Initial Slow-Start Threshold _____	413
9-18	Goodput on TCP Flows vs. Non-TCP Flows for Movies on Fast Paths with Fast Interfaces in a Large, Fast Network with High Initial Slow-Start Threshold _____	414
9-19	Bar Graphs plotting Goodput Differences on TCP Flows vs. Non-TCP Flows for Movies Transferred on Fast Paths with Fast Interfaces in a Large, Fast Network with High Initial Slow-Start Threshold _____	414
9-20	Goodput on TCP Flows vs. Non-TCP Flows for Service Packs on Fast Paths with Fast Interfaces in a Large, Fast Network with High Initial Slow-Start Threshold _____	415
9-21	Bar Graphs plotting Goodput Differences on TCP Flows vs. Non-TCP Flows for Service Packs Transferred on Fast Paths with Fast Interfaces in a Large, Fast Network with High Initial Slow-Start Threshold _____	415
9-22	Goodput Rank Matrix – $y_2(u)$ – BIC (Large, Fast Network, High Initial Slow-Start) _____	418
9-23	Goodput Rank Matrix – $y_2(u)$ – CTCP (Large, Fast Network, High Initial Slow-Start) _____	419
9-24	Goodput Rank Matrix – $y_2(u)$ – FAST (Large, Fast Network, High Initial Slow-Start) _____	419
9-25	Goodput Rank Matrix – $y_2(u)$ – FAST-AT (Large, Fast Network, High Initial Slow-Start) _____	420
9-26	Goodput Rank Matrix – $y_2(u)$ – HSTCP (Large, Fast Network, High Initial Slow-Start) _____	420
9-27	Goodput Rank Matrix – $y_2(u)$ – HTCP (Large, Fast Network, High Initial Slow-Start) _____	421
9-28	Goodput Rank Matrix – $y_2(u)$ – Scalable (Large, Fast Network, High Initial Slow-Start) _____	421
9-29	Goodput Rank Matrix – $y_{16}(u)$ – BIC (Large, Fast Network, High Initial Slow-Start) _____	422
9-30	Goodput Rank Matrix – $y_{16}(u)$ – CTCP (Large, Fast Network, High Initial Slow-Start) _____	422
9-31	Goodput Rank Matrix – $y_{16}(u)$ – FAST (Large, Fast Network, High Initial Slow-Start) _____	423
9-32	Goodput Rank Matrix – $y_{16}(u)$ – FAST-AT (Large, Fast Network, High Initial Slow-Start) _____	423
9-33	Goodput Rank Matrix – $y_{16}(u)$ – HSTCP (Large, Fast Network, High Initial Slow-Start) _____	424
9-34	Goodput Rank Matrix – $y_{16}(u)$ – HTCP (Large, Fast Network, High Initial Slow-Start) _____	424
9-35	Goodput Rank Matrix – $y_{16}(u)$ – Scalable (Large, Fast Network, High Initial Slow-Start) _____	425
9-36	Average vs. Standard Deviation in Goodput Rank (Large, Fast Network, High Initial Slow-Start Threshold) _____	426
A-1	Response curves of two hypothetical TCP variants TCP0 and TCP1 and the graph of a hypothetical packet loss function _____	471
A-2	Response curve for CUBIC with a $\pm 50\%$ error region vs. TCP Reno _____	477
A-3	Response curve for CTCP with a $\pm 50\%$ error region vs. TCP Reno _____	478
A-4	Response curves for CUBIC and CTCP with corresponding error regions _____	479

B-1	Experiment Topology _____	484
B-2	Changes in RTT Fairness with Increasing Buffer Size _____	489
B-3	Changes in Throughput Fairness with Increasing Buffer Size _____	490
B-4	Changes in Average Throughput with Increasing Buffer Size _____	491
C-1	Combined Matrix of Scatter Plots and Correlation Values for 22 Responses _____	500
C-2	Frequency Distribution of the Absolute Value of Correlations for All Pairs of Responses _____	501
C-3	Index-Index Plot for Correlation Pairs where $ \text{Correlation}(Y_i, Y_j) > 0.65$ _____	502
C-4	Histograms for 22 Principal Components _____	503
C-5	Weight Vectors for the First Four Principal Components _____	503
C-6	Main Effects Plots for Top Four Principal Components _____	504
C-7	Y-Y-X plot for Responses y7 and y22 _____	506
C-8	Main-Effects Plot for Response y1 (Average Number of Active Flows) _____	507
C-9	Main-Effects Plot for Response y10 (Average Retransmission Rate) _____	508
C-10	Main-Effects Plot for Response y11 (Average Congestion Window Size) _____	509
C-11	Main-Effects Plot for Response y22 (Average Throughput on NN Flows) _____	510
C-12	Main-Effects Plot for Response y15 (Average Smoothed Round-Trip Time) _____	511
C-13	Main-Effects Plot for Response y4 (Average Packets Output per Measurement Interval) _____	512
C-14	Main-Effects Plot for Response y6 (Flows Completed per Measurement Interval) _____	513
C-15	Main-Effects Plot for Response y17 (Average Instantaneous Throughput on DD Flows) _____	514
C-16	Main-Effects Plot for Response y20 (Average Instantaneous Throughput on FF Flows) _____	515
C-17	Average Condition Ranking Displayed on Vertices of a Cube _____	518
D-1	Sample Ordered Data Plot _____	524
D-2	Sample Multi-factor Scatter Plot _____	526
D-3	Sample Main Effects Plot _____	527
D-4	Sample Interaction Effects Matrix _____	528
D-5	Sample Block Plots _____	529
D-6	Sample Youden Plot _____	530
D-7	Sample Effects Plot _____	531
D-8	Sample Half-Normal Probability Plot of Effects _____	532
D-9	Sample Cumulative Residual Standard Deviation Plot _____	533
D-10	Sample Contour Plot of Two Dominant Factors _____	534

List of Tables

3-1	Link Propagation Delays in the Base Simulated Topology _____	41
3-2	Routes across the Backbone from Source (S) to Destination (D) Domain _____	41
3-3	Specification of Values for Parameter SOURCE_TYPE _____	48
3-4	Summary of Aggregate Measures Reported by MesoNet _____	53
3-5	Summary of Flow-Class Measures Reported by MesoNet _____	56
3-6	Summary of Long-Lived Flow Measures Reported by MesoNet _____	58
3-7	Summary of Measures Reported by MesoNet for Each Router _____	59
3-8	Summary of Added Measures Reported by MesoNet for Access Routers _____	60
3-9	Characteristic Performance for MesoNet in Two Experiments _____	68
3-10	Processing Requirements for MesoNet in Two Experiments _____	69
3-11	Memory Requirements for MesoNet in Two Experiments _____	69
4-1	Responses Characterizing Macroscopic Network Behavior _____	78
4-2	Responses Characterizing Instantaneous Throughput for Active Flows by Flow Class _____	79
4-3	Identity and Purpose of 10 Plots in the 10-Step Graphical Analysis _____	86
4-4	Simulation-Control Parameters _____	90
4-5	Parameters Controlling User Behavior _____	90
4-6	Parameters Adapting Network Characteristics _____	91
4-7	Parameters Altering Properties of Sources and Receivers _____	92
4-8	Parameters Controlling Source Startup Pattern _____	92
4-9	Parameters Related to TCP Operation _____	93
4-10	Recap of Sensitivity Analysis Factors and Mapping to MesoNet Parameters _____	93
4-11	Two-Level Settings for Each of 11 Factors in Sensitivity Analysis _____	94
4-12	Relationship among the Speed of Backbone Routers and Other Router Types _____	95
4-13	Relation between Factors and Number and Distribution of Sources _____	97
4-14	Relation between Factors and Number and Distribution of Receivers _____	97
4-15	Relation between Factors and Distribution of Flow Classes _____	97
4-16	Buffers for Combinations of Round-Trip Propagation Delay (x1) and Capacity (x2) _____	98
4-17	Characteristics of Processors Executing Simulation Runs _____	99
4-18	Execution Time Required for Each Simulation Run _____	101
4-19	Responses Selected for Investigation in Sensitivity Analysis _____	107
4-20	Responses Composing Principal Component One _____	109
4-21	Responses Composing Principal Component Two _____	109
4-22	Responses Composing Principal Component Three _____	109
4-23	Responses Composing Principal Component Four _____	110
4-24	Definition of Major Principal Components in Model Response _____	119
4-25	Rank Analysis based on Domain Expertise _____	127
4-26	Rank Analysis based on Principal Components Analysis _____	127
4-27	Mapping of Factor Settings to Eight Three-Factor Conditions _____	131
4-28	Average Response Values for Each Three-Factor Condition _____	131
4-29	Ranking for Each Condition vs. Each Response _____	132
4-30	Changes in Ranking Attributable to Each Factor _____	132
5-1	Definition of Symbols Used to Model Connection Establishment Procedures _____	141
5-2	Definition of Symbols Used to Model Slow-Start Procedures _____	142
5-3	Symbols and Definitions Used to Model BIC Congestion Avoidance Procedures _____	147
5-4	Symbols and Definitions Used to Model CTCP Congestion Avoidance Procedures _____	150
5-5	Symbols and Definitions Used to Model FAST Congestion Avoidance Procedures _____	153
5-6	Symbols and Definitions Used to Model HSTCP Congestion Avoidance Procedures _____	155
5-7	Symbols and Definitions Used to Model H-TCP Congestion Avoidance Procedures _____	156
5-8	Symbols and Definitions Used to Model Scalable TCP Congestion Avoidance Procedures _____	158

5-9	Capacity of the Dumbbell Topology with Various Round-Trip Times _____	179
5-10	Link and Buffer Utilizations for Simulated Congestion Control Mechanisms _____	180
5-11	Bandwidth Fairness (Jain's Index) for Simulated Congestion Control Mechanisms _____	180
6-1	Congestion Control Mechanisms Compared _____	183
6-2	Definition of Three Path Classes _____	184
6-3	Robustness Factors Selected for Comparing Congestion Control Mechanisms _____	185
6-4	Fixed Network Parameters _____	185
6-5	Domain View of Router Speeds _____	186
6-6	Path Propagation Delays Simulated _____	186
6-7	Buffer Sizes Simulated _____	186
6-8	Fixed Parameters Related to Sources and Receivers _____	187
6-9	Number of Simulated Sources _____	187
6-10	Fixed Simulation Control Parameters _____	187
6-11	Fixed Parameters Specifying Simulated User Traffic _____	188
6-12	Fixed Parameters Specifying Long-Lived Flows _____	189
6-13	Template Specifying a 2^{6-1} Orthogonal Fractional Factorial Design _____	190
6-14	Instantiated Robustness Conditions for 2^{6-1} Experiment Design _____	191
6-15	Responses Characterizing Macroscopic Behavior _____	191
6-16	Responses Characterizing User Experience on Very Fast Paths _____	192
6-17	Responses Characterizing User Experience on Fast Paths _____	192
6-18	Responses Characterizing User Experience on Typical Paths _____	193
6-19	Responses Characterizing User Experience on Long-Lived Flows _____	193
6-20	Responses Characterizing Buffer Usage in Directly Connected Access Routers _____	193
6-21	Aggregate Responses Characterizing Macroscopic Behavior _____	194
6-22	Responses Characterizing User Experience for Completed Flows on Very Fast Paths _____	194
6-23	Responses Characterizing User Experience for Completed Flows on Fast Paths _____	194
6-24	Responses Characterizing User Experience for Completed Flows on Typical Paths _____	195
6-25	Responses Characterizing Distribution of Flows among Backbone Routers _____	195
6-26	Characteristics of Compute Servers Used to Execute the Simulations _____	196
6-27	Processing Requirements for Simulations Mapped to Specific Compute Servers _____	196
6-28	Characterization of the Number of Flows and Data Packets Simulated _____	197
6-29	Format Adopted for Each Time-Period Data File _____	197
6-30	Format Adopted for Reporting Aggregate Measures _____	198
6-31	Flows Completed per 200 ms interval and Total Completions for DD Flows in Time Period Two under Condition 4 _____	211
6-32	Average, Minimum and Maximum Goodput on DD Flows for Each Congestion Control Algorithm during TP2 when Averaged over All 32 Conditions _____	240
7-1	Congestion Control Mechanisms Compared _____	253
7-2	Robustness Factors Adopted for Comparing Congestion Control Mechanisms _____	254
7-3	Fixed Parameters Related to Sources and Receivers _____	255
7-4	Instantiated Robustness Conditions _____	255
7-5	Domain View of Router Speeds _____	256
7-6	Number of Simulated Sources _____	256
7-7	Buffer Sizes Simulated _____	256
7-8	Comparing Resource Requirements for Simulating the FAST Congestion Control Algorithm in a Large, Fast Network and a Scaled-Down Network _____	261
7-9	Comparing Number of Simulated Flows and Packets for a Large, Fast Network and a Scaled-Down Network under All Congestion Control Algorithms _____	261
7-10	Goodputs on DD Flows Averaged over all 32 Conditions for Each Time Period _____	292
7-11	Per Flow Goodputs for Long-Lived Flow L1 Averaged over all 32 Conditions for Each Time Period _____	295
7-12	Per Flow Goodputs for Long-Lived Flow L2 Averaged over all 32 Conditions for Each Time Period _____	295

7-13	Per Flow Goodputs for Long-Lived Flow L3 Averaged over all 32 Conditions for Each Time Period _____	295
7-14	Time until Long-Lived Flows Reach Maximum Transfer Rate in TP1 for Condition 8 _____	296
7-15	Time until Long-Lived Flows Recover Maximum Transfer Rate in TP3 for Condition 8 _____	297
7-16	Average Goodput for Each Congestion Control Algorithm on Three Long-Lived Flows during TP2 under Condition 8 _____	302
7-17	Time until Long-Lived Flow L1 Reaches Maximum Transfer Rate in TP1 for Three Uncongested Conditions _____	303
7-18	Time until Long-Lived Flow L1 Recovers Maximum Transfer Rate in TP3 for Three Uncongested Conditions _____	303
7-19	Average Goodput on Long-Lived Flow L1 for Each Congestion Control Algorithm under Each of Three Uncongested Conditions _____	308
7-20	Average Goodput on Long-Lived Flow L1 for Each Congestion Control Algorithm in Each of the Three Time Periods under Most Congested Condition 21 _____	308
8-1	Alternate Congestion Control Regimes Compared _____	316
8-2	Robustness Factors Adopted for Comparing Congestion Control Mechanisms _____	317
8-3	Probability Distributions for Files of Various Sizes _____	318
8-4	Fixed Parameters for Sizing Files _____	318
8-5	Four Dimensions Defining Flow Groups _____	318
8-6	Flow Group Identifiers Assigned Based on Three-Dimensional Classification _____	319
8-7	Computing Target Minimums for Document Transfers with Combinations of Flow Traits _____	321
8-8	Fixed Network Parameters _____	322
8-9	Fixed Source and Receiver Parameters _____	323
8-10	Proportion of Sources and Receivers Placed under Specific Router Classes _____	323
8-11	Probability of Flows Transiting Specific Path Classes _____	323
8-12	Fixed Simulation Control Parameters _____	324
8-13	Two-Factor 2^{9-4} Orthogonal Fractional Factorial Design Template _____	325
8-14	The 32 Simulated Conditions used to compare Each Combination of Congestion Control Algorithm and Initial-Slow Start Threshold _____	326
8-15	Simulated Router Speeds _____	327
8-16	Number of Simulated Sources _____	327
8-17	Simulated Propagation Delays _____	327
8-18	Characterization of Simulated Buffer Sizes _____	327
8-19	Measured Responses Characterizing Macroscopic Network Behavior _____	331
8-20	Measured Responses Characterizing User Experience for Each Flow Group _____	332
8-21	Comparing Resource Requirements for Simulating One Hour of Network Operation under 32 Conditions with High and Low Initial Slow-Start Thresholds _____	333
8-22	Comparing Flows Completed and Data Packets Sent when Simulating One Hour of Network Operation under 32 Conditions with High and Low Initial Slow-Start Thresholds _____	333
8-23	Data Format Summarizing Responses y1 to y16 for All Algorithms and Conditions _____	334
8-24	Data Format Summarizing User Experience for One Flow Group _____	335
8-25	Data Format Summarizing User Experience for One Flow Group under All Algorithms and Conditions _____	335
8-26	Average Goodput per Flow Group under Each Alternate Congestion Control Algorithm (High Initial Slow-Start Threshold) _____	353
8-27	Average Goodput per Flow Group on TCP Flows Competing with Each Alternate Congestion Control Algorithm (High Initial Slow-Start Threshold) _____	354
8-28	Average Goodput per Flow Group under Each Alternate Congestion Control Algorithm (Low Initial Slow-Start Threshold) _____	361
8-29	Average Goodput per Flow Group on TCP Flows Competing with Each Alternate Congestion Control Algorithm (Low Initial Slow-Start Threshold) _____	362

8-30	Range of Goodput Differences (%) for Flow Groups under High and Low Initial Slow-Start Threshold _____	370
8-31	Summary Average and Standard Deviation in Goodput and TCP Goodput Rank for All Congestion Control Algorithms (High Initial Slow-Start Threshold) _____	379
8-32	Summary Average and Standard Deviation in Goodput and TCP Goodput Rank for All Congestion Control Algorithms (Low Initial Slow-Start Threshold) _____	387
9-1	Comparison of Experiment with Congestion Control Algorithms in a Small Network vs. Experiment in a Large, Fast Network _____	395
9-2	Robustness Factors Adopted for Comparing Congestion Control Mechanisms _____	396
9-3	Key Fixed Factors Adopted for Comparing Congestion Control Mechanisms _____	396
9-4	Two-Level 2 ⁹⁻⁴ Orthogonal Fractional Factorial Design _____	397
9-5	Simulated Router Speeds _____	398
9-6	Number of Simulated Sources _____	398
9-7	Characterization of Simulated Buffer Sizes _____	398
9-8	Comparing Resource Requirements for Simulating a Small Network and a Large, Fast Network _____	400
9-9	Comparing Number of Simulated Flows and Packets for a Small Network and a Large, Fast Network _____	401
9-10	Average Goodput per Flow Group under Each Alternate Congestion Control Algorithm for a Large, Fast Network with High Initial Slow-Start Threshold _____	407
9-11	Average Goodput per Flow Group on TCP Flows Competing with Each Alternate Algorithm for a Large, Fast Network with High Initial Slow-Start Threshold _____	408
9-12	Range of Goodput Differences (%) for Flow Groups under High Initial Slow-Start Threshold for Small, Slow Network and for Large, Fast Network _____	416
9-13	Summary Average and Standard Deviation in Goodput Rankings for Flows using Alternate Congestion Control Algorithms and for Competing TCP Flows (Large, Fast Network, High Initial Slow-Start Threshold) _____	425
10-1	Comparing Four Characteristics of Individual Alternate Congestion Control Algorithms _____	436
A-1	Estimated throughput for CUBIC in p/ms for 1000 concurrent flows on a link with a 122 p/ms capacity (for 1 KB packets) _____	480
A-2	Estimated throughput for CTCP in p/ms for 1000 concurrent flows on a link with a 122 p/ms capacity (for 1KB packets) _____	480
A-3	Estimated throughput for TCP Reno in p/ms for 1000 concurrent flows on a link with a 122 p/ms capacity (for 1 KB packets) _____	480
B-1	One-Way Propagation Delay on Each Link in the Simulated Topology _____	485
B-2	Characteristics of Three Flow Sets Simulated in the Experiment _____	486
B-3	MesoNet Parameter Settings for the Experiment _____	486
B-4	Domain View of the Simulated Network Characteristics _____	487
B-5	Configuration of Compute Server for Simulations _____	488
B-6	Resource Requirements for Simulations _____	488
C-1	Two-Level Settings for Each of 11 Factors in Sensitivity Analysis _____	494
C-2	Selected Fixed Parameters _____	495
C-3	Router Speeds by Router Class for Each Level of Network Speed (x2) _____	495
C-4	Average Buffer Size by Router Class for Specific Combinations of Propagation Delay (x1), Network Speed (x2) and Buffer-Sizing Algorithm (x3) _____	495
C-5	Relation between Factors and Number and Distribution of Sources _____	496
C-6	Relation between Factors and Number and Distribution of Receivers _____	497
C-7	Relation between Factors and Distribution of Flow Classes _____	497
C-8	Responses Characterizing Macroscopic Network Behavior _____	498
C-9	Responses Characterizing Average Instantaneous Throughput by Flow Class _____	498

C-10	Configuration of Compute Servers for Simulations _____	499
C-11	Execution Time Required for Each Simulation Run _____	499
C-12	Responses Selected for Investigation in Sensitivity Analysis _____	506
C-13	Rank Analysis of Sensitivity Analysis Responses _____	516
C-14	Mapping of Factor Settings to Eight Conditions _____	517
C-15	Average Response Values for Each Condition _____	517
C-16	Ranking for Each Condition vs. Each Response _____	518
C-17	Changes in Ranking Attributable to Each Factor _____	519
D-1	Identity and Purpose of 10 Plots in the 10-Step Graphical Analysis _____	523

Table of Acronyms

Acronym	Definition
ACK	Acknowledgment
AvFSWO	Average File Size for Web Objects
AvThT	Average Think Time
AWND	Advertised Window
BIC	Binary Increase Congestion control
BRS	Backbone Router Speed
C	Capacity
CA	Cellular Automata
CAC	Correlation Analysis and Clustering
CPU	Central Processing Unit
CRTO	Current Retransmission Time Out
CTCP	Compound TCP
CWND	Congestion Window
DES	Discrete-Event Simulation
DT	Data segment (or packet)
DWND	Delay Window (used by CTCP)
FAST	Fast Active Queue Management Scalable TCP
FAST-AT	Fast Active Queue Management Scalable TCP with Alpha Tuning
GB	Gigabytes (Giga denotes billion)
Gbps	Gigabits per second (Giga denotes billion)
GENI	Global Environment for Network Innovation
GHz	Giga Hertz (Giga denotes billion)
HSTCP	High Speed TCP
HTCP	Hamilton TCP
ICCRG	Internet Congestion Control Research Group
IP	Internet Protocol
IRTF	Internet Research Task Force
ISP	Internet Service Provider
ITL	Information Technology Laboratory
Kbytes	Kilobytes
Kbytes	Kilobytes
MB	Megabytes
Mbps	Megabits per second
Mbytes	Megabytes
MCMP	Multicore Multiprocessor
NAK	Negative Acknowledgment
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
OFF	Orthogonal Fractional Factorial
P2P	Peer-to-Peer

PC	Personal Computer
PC	Principal Component
PCA	Principal Components Analysis
PDM	Propagation Delay in Milliseconds
POP	Point Of Presence
ppts	packets per time step
pps	packets per second
p/ms	packets per millisecond
PrFH	Probability of a Fast Host
PrLF	Probability of a Larger File
QSA	Queue Sizing Algorithm
RDist	Receiver Distribution
RTO	Retransmission Time Out
RTT	Round Trip Time
RWND	Receiver Window
SD	Standard Deviation
SDist	Source Distribution
SFSR	Scaling For Sources and Receivers
SLX	Simulation Language with eXtensibility
SQR	Square Root
SQRT	Square Root
SRTT	Smoothed Round Trip Time
SST	slow start threshold
STCP	Scalable TCP
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
WEB	World-wide Web